Advanced Materials for Clean and Sustainable Energy and Mobility

EMIRI key R&I priorities

EMIRI
Energy Materials Industrial Research Initiative
TECHNOLOGY ROADMAP

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Introduction

In the face of the 21st century's global energy challenges, Europe has set ambitious targets: to decrease by 2030 greenhouse gas emissions by 40% compared to 1990, and to achieve a carbon-neutral economy by 2050. This will require a combination of different technologies within the energy system; from energy harvesting, to energy storage, as well as technologies that improve the energy efficiency of end uses. Europe has already made significant steps. The share of renewable energy has increased from 8.5% in 2005 to 17.5% in 2017 – enabled by harvesting and storage technologies – while energy efficiency of end-use sectors increased by 30% compared to 1990. Achieving these ambitious targets will require further investments in advanced materials R&I – which represent up to 80% of technology components costs. These investments will not only provide an environmental benefit, but will also strengthen the economy – the RES and energy efficiency sectors employ more than 2 million people in the EU – and create a competitive advantage for Europe in a future where clean technologies are indispensable.

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6 Glossary

Battery Energy Storage

BEV	Battery Electric Vehicle
BIPV	Building Integrated PV
COP	Conference of the Parties
CSP	Concentrated Solar Power
ES	Energy Storage
EV	Electric Vehicle
GHG	Greenhouse Gases
HEV	Hybrid Electric Vehicle
LCOE	Levelised Cost of Electricity
LIB	Lithium-ion Batteries
OEM	Original Equipment Manufacturer
PHEV	Plug-in Hybrid Electric Vehicle
PV	Photovoltaic
RES	Renewable Energy Sources
UNFCCC	United Nations Framework Convention on Climate Change
ZSM	Zero Strain Materials

Hydrogen for Stationary Applications and CCU

AKE	Alkaline Electrolyser
CCS	Carbon Capture and Storage
CHP	Carbon Heat and Power
CCU	Carbon Capture and Utilisation
FC	Fuel Cells
P2F	Power to Fuels
P2I	Power to Industry
P2H	Power to Hydrogen
P2P	Power to Power
PEM FC	Proton Exchange Membrane Fuel Cell
PEME	Proton Exchange Membrane Electrolyser
SMR	Steam-methane Reforming
SOE	Solid Oxide Electrolyser
SOFC	Solid Oxide Fuel Cell

Hydrogen for Mobility

AEM	Anion Exchange Membrane
AEMFC	Anion Exchange Membrane Fuel Cells
AFC	Alkaline Fuel Cell
BEV	Battery Electric Vehicle
BOP	Balance of Plant
FC	Fuel cell
FCEV	Fuel Cell Electric Vehicle
HC	Hydrocarbons
HT-PEM	High Temperature PEM
ICE	Internal Combustion Engine
LT-PEM	Low Temperature PEM
MDFC	Molten Carbonate Fuel Cell
OEM	Original Equipment Manufacturer
PAFC	Phosphoric Acid Fuel Cell
PEM	Polymer Electrolyte Membrane/Proton Exchange Membrane
PPP	Public Private Partnership
SOFC	Solid Oxide Fuel Cell
R&A	Repair & Maintenance
D&A	Depreciation & Amortisation
CCM	Catalyst Coated Membrane

Solar energy harvesting

BIPV	Building Integrated Photovoltaics
BSF	Back Surface Field
CSP	Concentrated Solar Power
DoE	Department of Energy
DoI	Declaration of Intent
IEA	International Energy Agency
ITRPV	International Technology Roadmap for Photovoltaics
FTE	Full Time Equivalent
HCPV	High Concentration Photovoltaics
IBC	Interdigitated Back-Contact
MJ	Multi Junction
OPV	Organic Photovoltaics
PEB	Plus Energy Buildings
PERC	Passivated Emitter and Rear Cell
PV	Photovoltaic
R&D	Research and Development
RES	Renewable Energy Sources
SHJ	Silicon Hetero Junction
VRE	Variable Renewable Energy
ZEB	Zero Energy Buildings

Wind energy harvesting

FRP	Fibre Reinforced Polymers
PET	Polyethylene Terephthalate

Building energy performance

CAGR	Compound Annual Growth Rate
CFL	Compact Fluorescent Lamp
EC	Electrochromic
EPBD	Energy Performance Buildings Directive
EPS	Expanded Polystyrene
ITO	Indium Tin Oxide
LED	Light-emitting Diode
LC	Liquid Crystal
OLED	Organic LED
PCM	Phase Change Material
PDLC	Polymer Dispersed Liquid Crystal
PIR	Polyisocyanurate
PU	Polyurethane
SHGC	Solar Heat Gaining Coefficient
SPD	Suspended Particle Device
TCM	Thermochemical Storage
TES	Thermal Energy Storage
XPS	Extruded Polystyrene

Lightweight Technologies

AHSS	Advanced High Strength Alloys
FRP	Fibre Reinforced Polymers
CF	Carbon fibres
GF	Glass fibres
NF	Natural Fibres
AF	Aremid Fibres
ICE	Internal Combustion Engine
EoL	End of Life
SUV	Sport Utility Vehicle
OEM	Original Equipment Manufacturer

Forward

EMIRI driving research, innovation and competitiveness across the advanced materials industry for the benefit of Clean and Sustainable Energy and Mobility

The advanced materials industry (Chemicals, Polymers, Metals and alloys, Glass, Ceramics, Composites, ...) is renowned as one of the leading technology sectors in Europe. It generates innovation that benefits society at large providing more than 2.5 million direct jobs (and around four times more in indirect jobs along the various value chains), and contributes to more than 650 billion euros of Europe's gross domestic product. Home to approximately 40.000 companies, European advanced materials industry plays a key role in serving society's need for clean and sustainable energy and mobility in Europe, and all over the world. The impact of the industry on the wider European economy is significant and must be sustained.

The advanced materials demand for clean energy and sustainable mobility is anticipated to grow continuously until 2050 and beyond, also satisfying an increasing request for safer, more affordable and environmentally friendly solutions. Industrial competition is fierce, not only from established world regions, but also from new, strong challengers. In this context, there are vast amounts to be done in the research and innovation field to provide a differentiating competitive advantage for the EU in this market.

Advanced materials at the heart of clean techs

High-performance advanced materials are at the core of the technological innovations needed to reach a sustainable and climate-neutral economy and society. Such materials are a part of the solution to our global challenges, offering better performance in their use, at lower cost, resource and energy requirements, and improved sustainability at the end-of-life of the products. The development of these new materials has to manage the scarcity of resources and be part of a circular economy value chain which will contribute to Europe's competitiveness in a context of increased sustainability standards.

With the imperative to change our energy technology mix, to respond to the challenge of decarbonisation and of the security of energy supply, research and innovation investments to improve the competitiveness, performances and environmental footprint of advanced materials for clean and sustainable energy and mobility technologies are more than ever needed for Europe to compete in the global market and support the delivery of a prosperous, modern, competitive and climate-neutral economy by 2050.

History shows that it takes about 10 – 15 years of R&I activities before the required advanced materials are developed and are ready for market uptake. Together, the Industry & the European Commission need to partner up to accelerate the innovation in the field. EU has a strong position in research, but there is unfortunately a large gap between the technology base and the industrial uptake. The extensive market uptake is due to long capital-intensive development times in combination with substantial technology and commercialization risks. These factors make it difficult for new materials to make the journey from the lab to industrial scale production and the markets.

One of the key activities of EMIRI is to identify research and innovation areas where new advanced materials can really make the difference in the clean and sustainable energy and mobility sectors. EMIRI will further on aid to lead the way for these early stage technologies and materials to industry growth and market.

Since 2012, EMIRI, the Energy Materials Industrial Research Initiative, is representing more than 50 organizations (industry, research, associations) active in advanced materials for clean and sustainable energy & mobility technologies. EMIRI contributes to industrial leadership of developers, producers and key users of advanced materials by shaping innovation, manufacturing and energy policy framework at European level. In the frame of Horizon 2020, EMIRI closely collaborated with European Commission to develop an Innovation Pillar on advanced Materials & nanotech for clean energy & clean mobility technologies. Since then there have been many changes and developments that affect the energy and mobility sectors directly and indirectly. These justify the release of this new multi-annual technology roadmap which is adapted to meet the new challenges. We invite all public and private stakeholders in European advanced materials, energy and mobility sectors to consider the revised priorities set out in this document in their future research and innovation programmes.

Dr. Egbert LOX
Chairman of EMIRI
Senior Vice President
Government Affairs, Umicore

Vision

Europe faces a number of serious challenges, where further investments and supportive measures in research and innovation are needed to create and deploy new solutions and to transform global threats into new opportunities for European businesses and societies.

1. Major challenges; huge opportunities

Europe faces a number of serious challenges, where further investments and supportive measures in research and innovation are needed to create and deploy new solutions and to transform global threats into new opportunities for European businesses and societies.

Climate change is one of the dominant and most urgent issues of our time. It brings unprecedented challenges, in a world where a rapidly growing global population, unsustainable production, increasing mobility and changing consumption patterns put the spotlight on **planetary boundaries**, with mounting pressures on ecosystems and natural resources. Our consumption of energy is of particular concern, as the development and use of sustainable energy sources and systems are struggling to keep up with rising global demand. The impact of climate change will continue to increase across the globe unless global warming is limited to 1.5 ºC, as defined in the objectives of the Paris Agreement. The need to transition to a carbon-neutral economy is more pressing than ever; the United Nations Intergovernmental Panel on Climate Change has assessed that while the limitation of global warming is possible, doing so will require unprecedented changes in our ways of life, towards sustainable societies and economies.

In a context of **resource scarcity**, our societies also need urgently to transition towards sustainable circular economy business models, aiming to maintain the value of products, materials and resources in the economy for as long as possible, and at minimising the generation of waste. **Europe's future prosperity** is jeopardised by increased global competition. The autonomy of Europe's industry is compromised by reliance on imported raw materials and key technologies. However, while climate change and the transition towards sustainable development will affect many aspects of today's European societies and industries, the transition to new technologies, including digitalisation, represents almost unlimited possibilities for innovation. On the other side, climate change and the transition towards sustainable development also raises legitimate concerns about the impact on employment, the quality of jobs in the future, and the ethical and wider implications for the society as a whole. As the technological developments become more and more important for ensuring prosperity and sustainable growth, Europe cannot risk being solely dependent on foreign nations to develop technological innovations needed to address the challenges of tomorrow; especially not in the very strategic sectors of energy and mobility.

Additionally, new generation consumers pay growing attention to health, environmental impacts, responsible sourcing and controlled quality when making consumption decisions. Growing social demand for shorter value chains, local production and local value creation is being observed. Balancing the framework for the global competitiveness of our industries is therefore essential to keep and create jobs at home. The abovementioned challenges represent threats, but also **huge innovation and business opportunities** for the European advanced materials industries. Opportunities should not be missed; it is urgent to boost the transitions. Innovation should not be delayed. Relevant priorities have to be addressed in the Strategic Plan for Horizon Europe. Identifying these priorities, setting ambitious, yet achievable objectives and suggesting relevant actions to address the priorities, is the purpose of the present EMIRI document.

2. Relevant EU policies

A large range of EU and national policies are needed for the transition to clean energy and sustainable mobility.

To strengthen a concerted global response in the framework of the Paris Agreement, the European Commission presented in November 2018 its vision[1] for achieving net-zero greenhouse gas emissions by 2050. The long-term strategy outlines a vision of the technological, economic and societal transformations required to achieve climate neutrality, and ensuring a socially fair transition that does not leave any EU citizens or regions behind.

In the medium term, the Energy Union Strategy provides the regulatory framework for achieving the EU's 2030 greenhouse gas emission reduction target – a decrease by 40% compared to 1990 levels – in a cost-efficient way. Sectorial EU legislation, such as the Clean Energy for All package and the Clean Mobility packages, imply major market transformation by 2030 in the energy and transport sectors.

Coordination of EU instruments with private sector engagements and funding programmes within Member States is essential to accelerate transformation and maximise impact. In the energy area, the Strategic Energy Technology Plan (SET-Plan) helps align research and innovation between the private sector, the Commission and Member States. Similar guidance to the transport sector is provided by the Strategic Transport R&I Agenda (STRIA).

All of these policies are directly related to one of the following high-level future policy priorities for the European Union announced by the European Commission at the Sibiu Summit on 9 May 2019 for the EU's next strategic agenda 2019-2024:

1. A Sustainable Europe, regarding sustainable development, climate change, circular economy and energy;
2. A Competitive Europe, which focusses on research and innovation, new technologies, digital capacities and industrial policy;

Together with the relevant UN Sustainable Development Goals[2] , these two priority areas can be seen as shaping future EU policy responses to support the energy and mobility transitions, with European research and innovation acting as an enabler and driver. In this context, Horizon Europe can make a major contribution to bringing more low- and zero-carbon technologies to market readiness and feed the innovation cycle with discoveries that may lead to disruptive solutions in the longer term.

3. EMIRI vision 2050 and key orientation pillars

Fully aligned with the vision adopted by the Commission for achieving a climate neutral economy by 2050, which recognises that a forward-looking research and innovation strategy should be guided by zero-carbon solutions that have the potential to be deployed by 2050, EMIRI`s long-term vision on advanced materials for clean energy and sustainable mobility sectors is the following:
A sustainable, competitive European industry holding a globally leading position in providing and using Advanced Materials for clean and sustainable energy and mobility, enabling a carbon-neutral and f ully circular future for our planet and society. EMIRI proposes four key orientation pillars that will drive all R&I actions to achieve the transformative long-term vision. The pillars are summarised in Figure 1.

"A SUSTAINABLE, COMPETITIVE EUROPEAN INDUSTRY HOLDING A GLOBALLY LEADING POSITION IN PROVIDING AND USING ADVANCED MATERIALS FOR CLEAN AND SUSTAINABLE ENERGY AND MOBILITY, ENABLING A CARBON-NEUTRAL AND FULLY CIRCULAR FUTURE FOR OUR PLANET AND SOCIETY"

[1] COM(2018) 773 final, A Clean Planet for all

[2] 7 – Affordable and Clean Energy; 8 – Decent Work and Economic Growth; 9 – Industry, Innovation and Infrastructure; 11 – Sustainable Cities and Communities; 12 – Responsible Consumption and Production; 13 – Climate Action

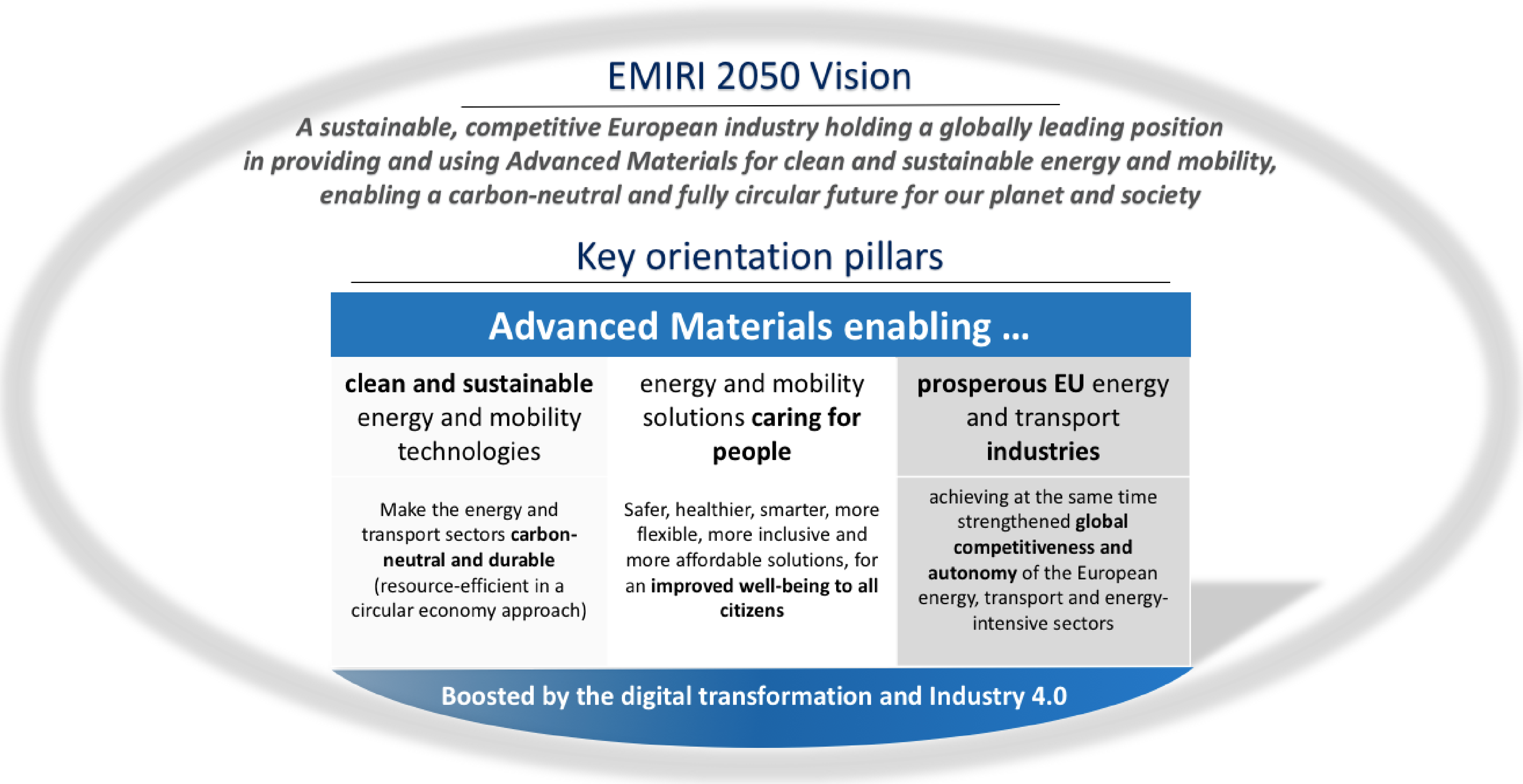


Figure 1: The 4 key orientation pillars driving R&I priorities in the field of advanced materials for clean and sustainable energy and mobility

Energy demand and climate change

Energy and climate change are closely linked: energy production and use account for more than 75 % of EU greenhouse gas emissions, with the heaviest share of emissions coming from energy supply and transport.

Tackling the climate change threat requires a fundamental shift from the current, fossil fuels-based energy system to a low-carbon, mainly renewables-based energy system and further drastic improvements in Energy Efficiency across all sectors.

Driven by the climate and energy targets, the share of renewable energy in the EU-28 countries has increased from 8.5% in 2005 to 17.5% in 2017 - with a share of 30.7% of electricity. Wind and solar PV are rapidly transforming power mixes worldwide, requiring more system flexibility in order to be integrated in a secure and cost-effective manner. Energy storage technologies provide a flexible response to the imbalances caused by the increased share of variable renewable energy sources. Batteries, and also hydrogen and synthetic fuels produced from renewable sources can help to cut emissions in the transport sector. Energy efficiency of end-use sectors improved by 30 % over the period 1990-2016.

"DRIVEN BY THE CLIMATE AND ENERGY TARGETS, THE SHARE OF RENEWABLE ENERGY IN THE EU-28 COUNTRIES HAS INCREASED FROM 8.5% IN 2005 TO 17.5% IN 2017 - WITH A SHARE OF 30.7% OF ELECTRICITY"

The further development and deployment of sustainable low-cost and highly efficient low carbon energy technologies are essential to ensure that the EU achieves its 2030 climate and energy targets and its long-term goal of a carbon-neutral society by 2050. Development in the EU and massive roll-out these low carbon energy technologies (renewable energy technologies, electro-mobility, energy storage, energy efficiency, technologies for decarbonisation of power and energy-intensive sectors) are also key to energy security and is crucial to promoting growth and jobs in the high-tech manufacturing sector. To ensure the adoption & deployment across the EU, the cost of low-carbon energy technologies must keep coming down.

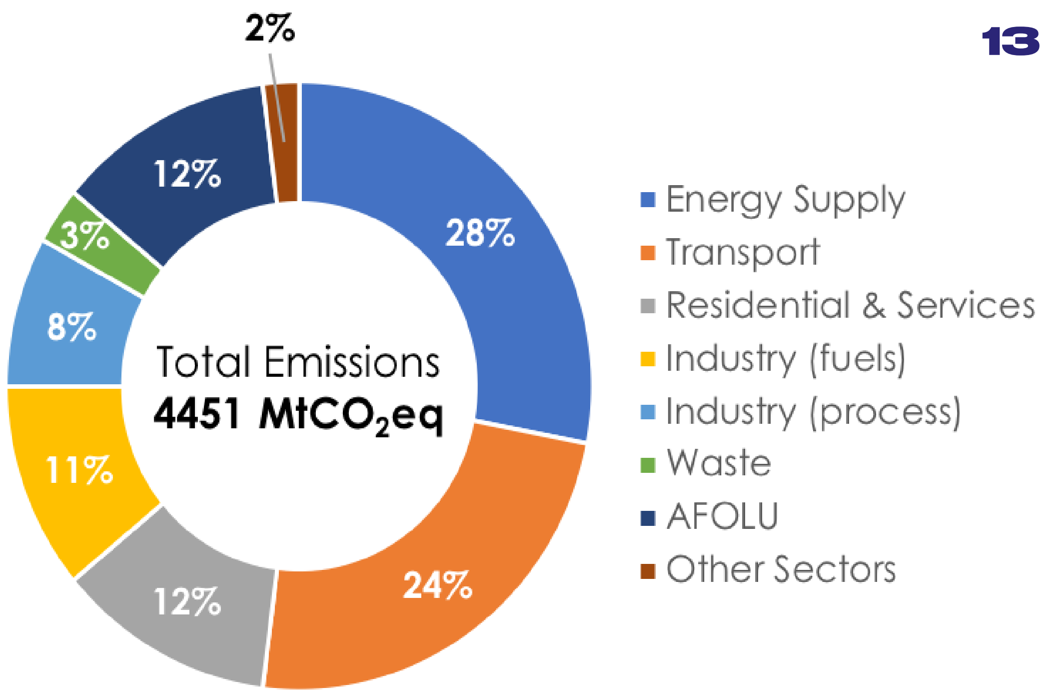


Figure 2: EU-28 greenhouse gas emissions by economic sector (European Commission [3])

Advanced Materials enabling clean and sustainable energy and mobility technologies...

Representing currently more than 50% of the cost structure of clean energy & clean mobility technologies, advanced materials are Key Enabling Technologies to accelerate the transformation of the European energy system. This is made possible by reduction in cost, increase in performance, and extension of lifetime of the advanced materials enabling these low carbon energy technologies.

Moreover, in near future, global trends like Industry 4.0 (automatisation, robotisation, machine learning, AI, IoT,...) and giga-factories will squeeze out labor, energy, equipment and maintenance costs. Social pressure for local production will impact transportation costs. These trends will possibly bring the share of advanced materials in the cost structure up to 80%. The global competition will then be on the usage and integration of the most innovative advanced materials into competitive technologies while at the same time (i) minimizing raw material consumption and facilitating their recycling into a closed-loop system and (ii) minimising carbon and environmental footprint over the whole life cycle of the products, including LCA-based design in line with a fully circular economy ambition.

Advanced Materials enabling energy and mobility solutions caring for people...

By advancing the state of the art of clean energy, clean mobility and energy efficiency technologies also in terms of cost, performance, safety and user convenience (such as speed charging for EVs batteries), innovative advanced materials will make technology more affordable and attractive for citizens, improving people well-being and at the same time generating a virtuous circle accelerating the energy and mobility transition.

Advanced Materials enabling prosperous EU energy and transport industries...

EU faces strong international competition in clean technologies at the expense of its industrial leadership:

- End-markets of low carbon energy applications are strongly developing outside of EU (e.g. Asia is rapidly developing its electricity generation capacity)

- Manufacturing of devices, of components and of advanced materials for these low carbon energy technologies is moving to end-markets and is established outside of EU (e.g. Asia is rapidly moving up the value chains, leading to emergence of new market winners, often at expense of historical players)

- Innovation in the field of advanced materials for low carbon energy & energy efficiency applications is steadily following manufacturing, but the EU is excelling on basic research, while the rest of the world

[3] Final Report of the High-Level Panel of the European Decarbonisation Pathways Initiative, European Commission, November 2018

also focuses on higher technology readiness level research to innovate, manufacture and commercialize.

This creates future dependency risks on imported low carbon energy technologies. To counterbalance for the current market trends, we need to build a strong European leadership with a global business reach. This requires the development and implementation of a supportive European Policy Framework, driving innovation, manufacturing and market development of low-carbon energy in the EU.

As the share of advanced materials could soon represent up to 80% in the cost structure of clean energy and clean mobility technologies, innovation on advanced materials will be a powerful lever for competitiveness. To reindustrialize the EU in clean energy & clean mobility techs, the EU can successfully leverage a strong advanced materials industry, further differentiating from other markets by building on EU leadership on sustainable development and circular economy. The development of these new materials will contribute to Europe‘s competitiveness in the context of increased sustainability standards.

There are more than two million jobs in the EU in renewables or energy efficiency. According to the Commission's "Clean Energy for All Europeans" package, there is a potential to create an additional 900,000 jobs by 2030 (provided that–public and private–investment is sufficiently mobilised). A successful energy transition could also lead to EU industry re-investing billions euro into R&D and CAPEX.
Being, more than any other region, focused on strengthening both competitiveness and sustainability, Europe has a unique opportunity to achieve sovereignty in these strategic technology areas.

Boosted by the digital transformation and Industry 4.0

Turning the global challenge of low carbon, secure, affordable energy and mobility into an opportunity for the European industry and European citizens can best be done by acting promptly at European level with a strong articulation between advanced materials and the other Key Enabling Technologies, in particular in the field of Digital and Manufacturing. As an example,

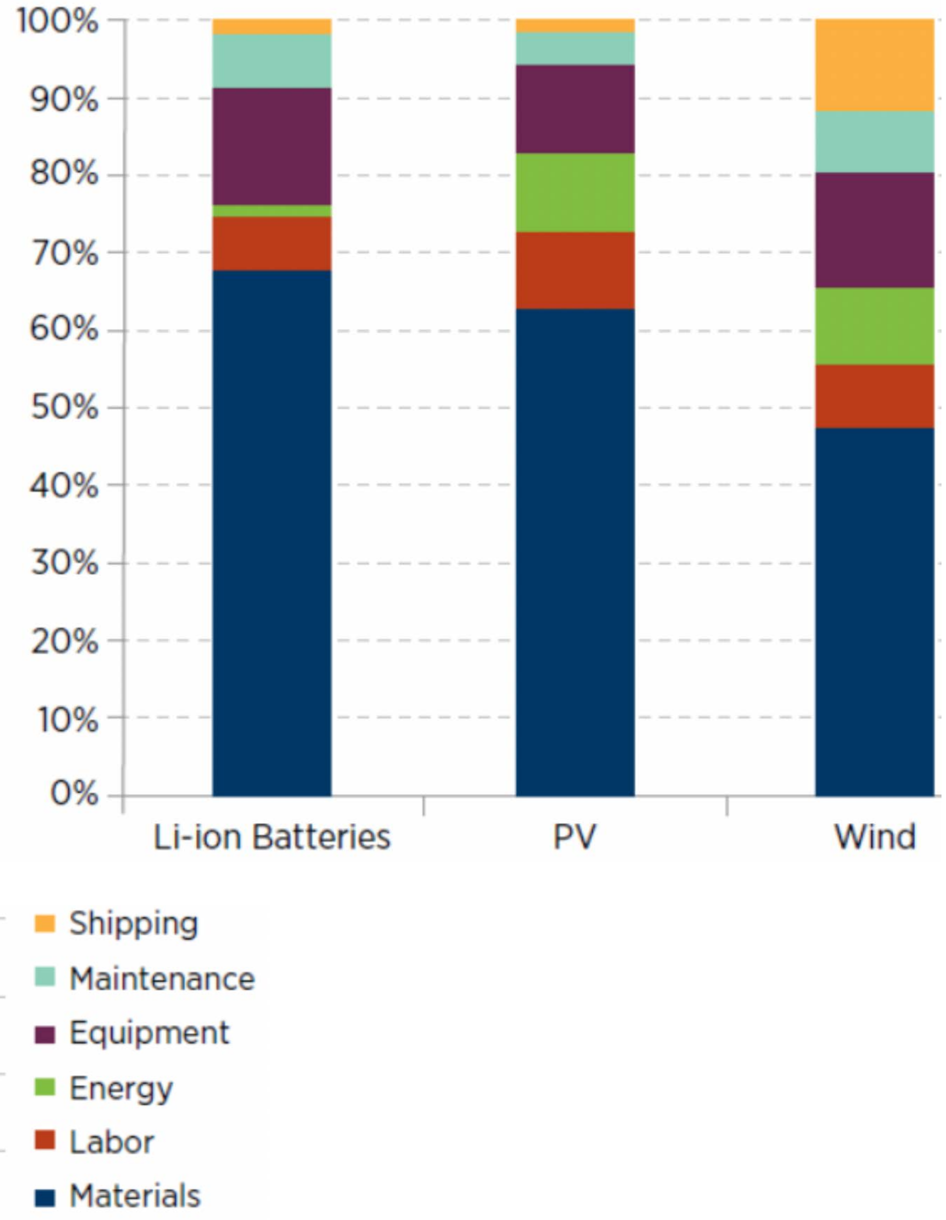


Figure 3: Current average relative cost structure of Li-Ion batteries, PV and Wind

smart materials embedding advanced monitoring and self-healing functionalities will dramatically increase the reliability and lifetime of technology applications.

Where to focus innovation?

Research & Innovation efforts must concentrate on technologies with the biggest potential to significantly contribute to total CO2 emission reductions in 2050 and where advanced materials make the difference in terms of sustainability along the whole life cycle of the products, well-being for the citizens and competitiveness for European Industry. These technologies are listed in Figure 4.

"AS THE SHARE OF ADVANCED MATERIALS COULD SOON REPRESENT UP TO 80% IN THE COST STRUCTURE OF CLEAN ENERGY AND CLEAN MOBILITY TECHNOLOGIES, INNOVATION ON ADVANCED MATERIALS WILL BE A POWERFUL LEVER FOR COMPETITIVENESS"

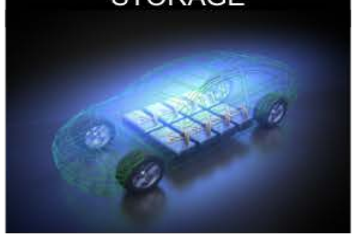
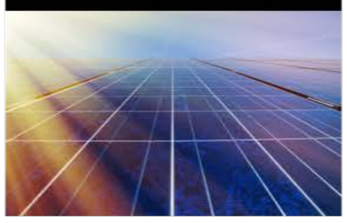
RENEWABLE ENERGY HARVESTING	BATTERY ENERGY STORAGE	HYDROGEN FOR MOBILITY	CHEMICAL ENERGY STORAGE AND CCU	ENERGY EFFICIENCY
				
Photovoltaics Building integrated photovoltaics Concentrated Solar Power Wind Power	Batteries for Electric Vehicles Batteries for stationary applications	Fuel Cells Low temp. PEM High temp. PEM Hydrogen storage tanks On-board H2 generation	Hydrogen generation by electrolysis (PEM; SO) Electricity generation from H2 Carbon Capture and purification Catalytic conversion of CO2 into fuels, chemicals, and e-fuels	Light weighting (transport) Insulation of buildings Thermal energy storage Lighting Glazing

Figure 4: EMIRI priority technology areas

End-user obsessed, coherent societal, industrial, financial and innovation policies will allow Europe to lead the global clean energy race, technology alone never being the solution. Technology is however a fundamental building block on the road to success. EMIRI supports and pursues a continued push from the European Commission on clean energy & clean mobility technologies. Advanced materials are key to these technologies and (due to industry 4.0) soon to be accounting for 80% of the technology manufacturing cost. We believe that a sizeable, stable, long term and multi-annual Innovation Pillar, relying upon a programmatic approach, and offering industry a clear outlook on where and how EU is aligning its innovation priorities, is central in succeeding in enabling a prosperous, sustainable and climate-neutral EU economy by 2050. The EMIRI strategic R&I priorities for the upcoming new European framework programme for Research and Innovation are presented in the following parts of the document. The industrial research and demonstration actions (TRL 4 to 7) proposed are exactly tailored to Horizon Europe's pillar II "Global Challenges and European Industrial Competitiveness", which translates the technology assets to market needs with high risks but also high gains. Further on, to maintain critical new advanced material development, we also support a strengthened focus on the development of advanced materials in the lower technology readiness level research programs in pillar I and pillar II.

"END-USER OBSESSED, COHERENT SOCIETAL, INDUSTRIAL, FINANCIAL AND INNOVATION POLICIES WILL ALLOW EUROPE TO LEAD THE GLOBAL CLEAN ENERGY RACE, TECHNOLOGY ALONE NEVER BEING THE SOLUTION. TECHNOLOGY IS HOWEVER A FUNDAMENTAL BUILDING BLOCK ON THE ROAD TO SUCCESS."

Methodology

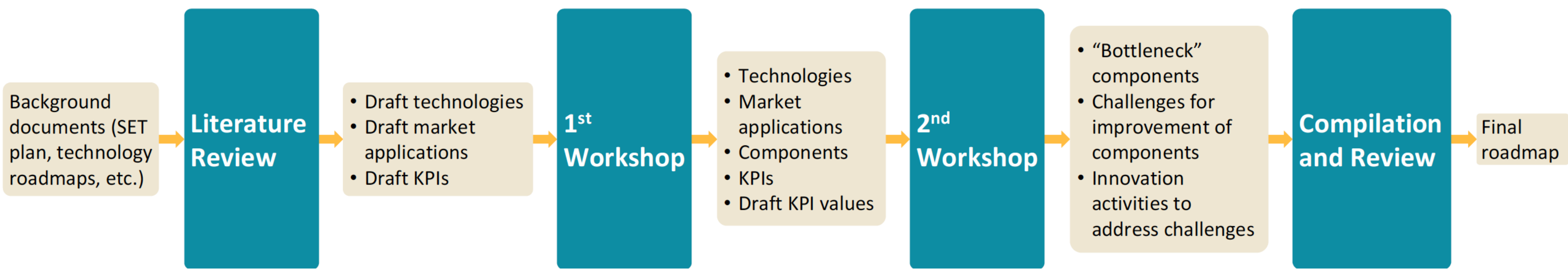
This roadmap was elaborated based on input from members of the EMIRI community, pan- European associations, and literature.

The process started with identifying the main sectors that could contribute to reducing the environmental impact of the energy and mobility sectors, by a small team from EMIRI, Bax & Company, and Sustesco.

For each of the sectors, a literature review was made, to identify the main technologies, their major applications, and Key Performance Indicators that can be used to evaluate the performance of each technology. The key points of the literature review were compiled into introduction papers for each sector.

In parallel, a call for expression of interest to contribute to the roadmap was circulated among EMIRI members, resulting to a list of more than fifty experts from thirty organisations. Subsequently, the first round of workshops was organised (one for each sector), where the relevant experts were invited. Prior to the workshops, the introductory documents were circulated to the experts as background reading, aiming to gain a common understanding on the main technologies and applications in each sector. The workshop was used to confirm – or update – the information shared in the introduction documents, as well as define the constituents of each technology, and KPIs for each.

The output of the first round of workshops was compiled and circulated for validation to the rest of the experts that were not able to participate to the workshops. The validated information was used as preparation to the second round of workshops, where experts came together to define "bottleneck" components that prevent the system from achieving higher performance as a whole, the particular challenges that need to be addressed, and innovation activities that need to be performed in order to address the aforementioned challenges. These innovation activities were subsequently clustered in "innovation calls", which were assigned to



"THE PROCESS SPAWNED FROM EARLY 2018 UNTIL LATE 2019, DURING WHICH SOME FIFTEEN PHYSICAL WORKSHOPS WERE ORGANISED, MANY MORE CALLS AND TELECONFERENCES, AND EVEN MORE FEEDBACK ROUNDS, INVOLVING WELL MORE THAN 100 PEOPLE FROM ACADEMIA, COMPANIES, AND EUROPEAN ASSOCIATIONS"

one or more experts for further elaboration. Finally, the calls were prioritised according to their expected impact, and urgency.

The output of this second round of workshops was once again shared with the experts for validation. Following the validation, experts assigned calls were tasked with further elaborating the calls. Another workshop was then organised to feedback all the calls.

The output from all the workshops was then compiled into the present document, which was undergone several feedback rounds, initially with smaller teams of experts, and gradually involving more people and European associations within or outside EMIRI.

The process spawned from early 2018 until late 2019, during which some fifteen physical workshops were organised, many more calls and teleconferences, and even more feedback rounds, involving well more than 100 people from academia, companies, and European associations.

R&I STRATEGY

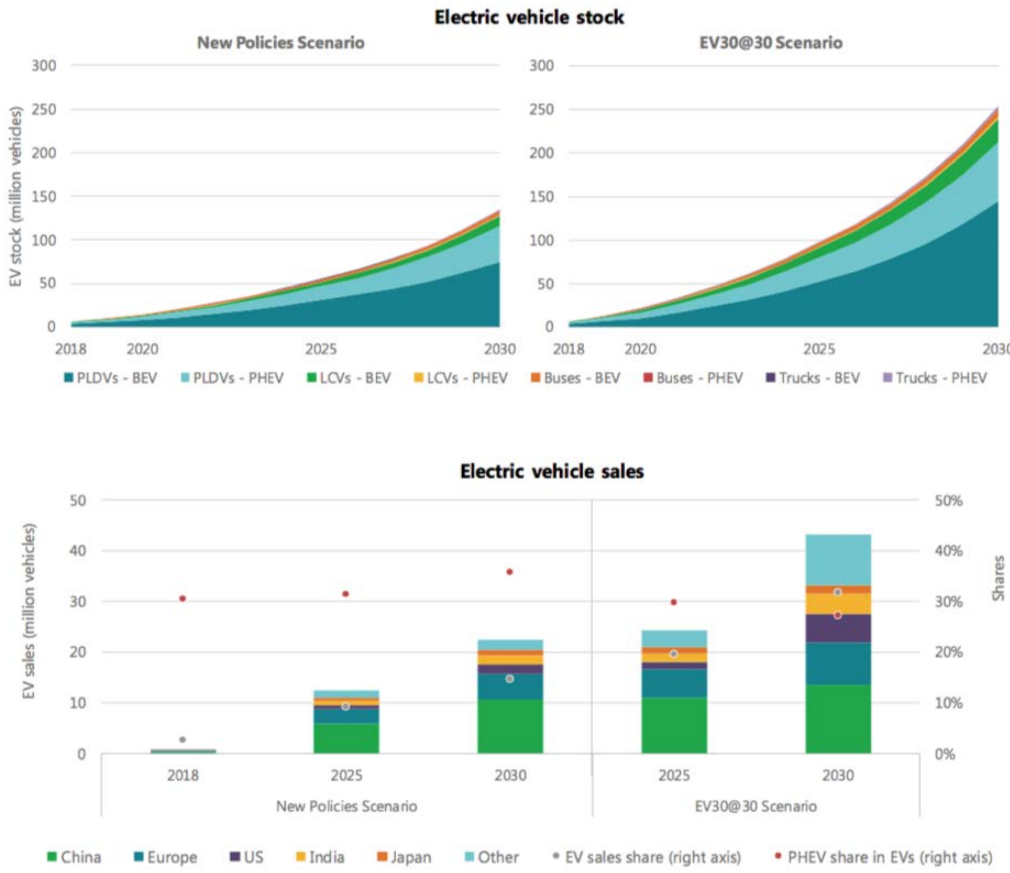
20 R&I Strategy

Overview

Driven by an ever-increasing world population as well as global economic growth, our energy needs – both for mobility as well as electricity production – have been increasing rapidly. The impact of this growth on the environment and well-being of society is becoming more apparent, raising the need for the decarbonisation of transportation and power generation sectors – the two highest polluting sectors in the EU[4] – as well as increasing the energy efficiency of our energy consuming applications – from buildings to vehicles.

Electromobility has become the prevalent solution for decarbonisation in the transportation sector. Sales of new electric cars globally have been increasing by 60% in the last two years while by 2030 total cumulative number of EVs is expected to surpass 120 million in the “new policies” scenario (considering existing and announced EV related policies). In the “EV30@30” scenario (considering policy ambitions continue rising to meet climate goals and other sustainability targets)[5] the cumulative number of EVs is expected to reach 250 million. To achieve mainstream adoption of EVs, new, advanced batteries to increase the range and power of vehicles are key."

Decarbonisation of the energy production sector will require further improvements of RES harvesting technologies, coupled with energy storage technologies, necessary when the energy supply is higher than the demand (the estimated current ES capacity of 4.7TWh is expected to increase to more than 12TWh by 2030, to accommodate to our needs for stationary and mobile energy storage[4]) and vice versa. Figure 6 illustrates the increase in our energy consumption over the last decades, as well as the penetration of RES in the electricity production mix."



PLDVs: Passenger Light Duty Vehicles
LCVs: Light Commercial Vehicles
BEV: Battery Electric Vehicle
PHEV: Plug in Hybrid Vehicle
Source: IEA Analysis developed with the IEA Mobility Model.

Figure 5: Evolution of global electric car stock (top), expected global EV stock (bottom) (source: IEA[2])

[4] Energy production and transportation accounted for more than 50% of GHG emissions in 2016 (source: European Environment Agency, Eurostat)

[5] International Energy Agency, Global EV outlook 2019, 2019

[6] IRENA, Energy storage and renewables: Costs and markets to 2030, October 2017

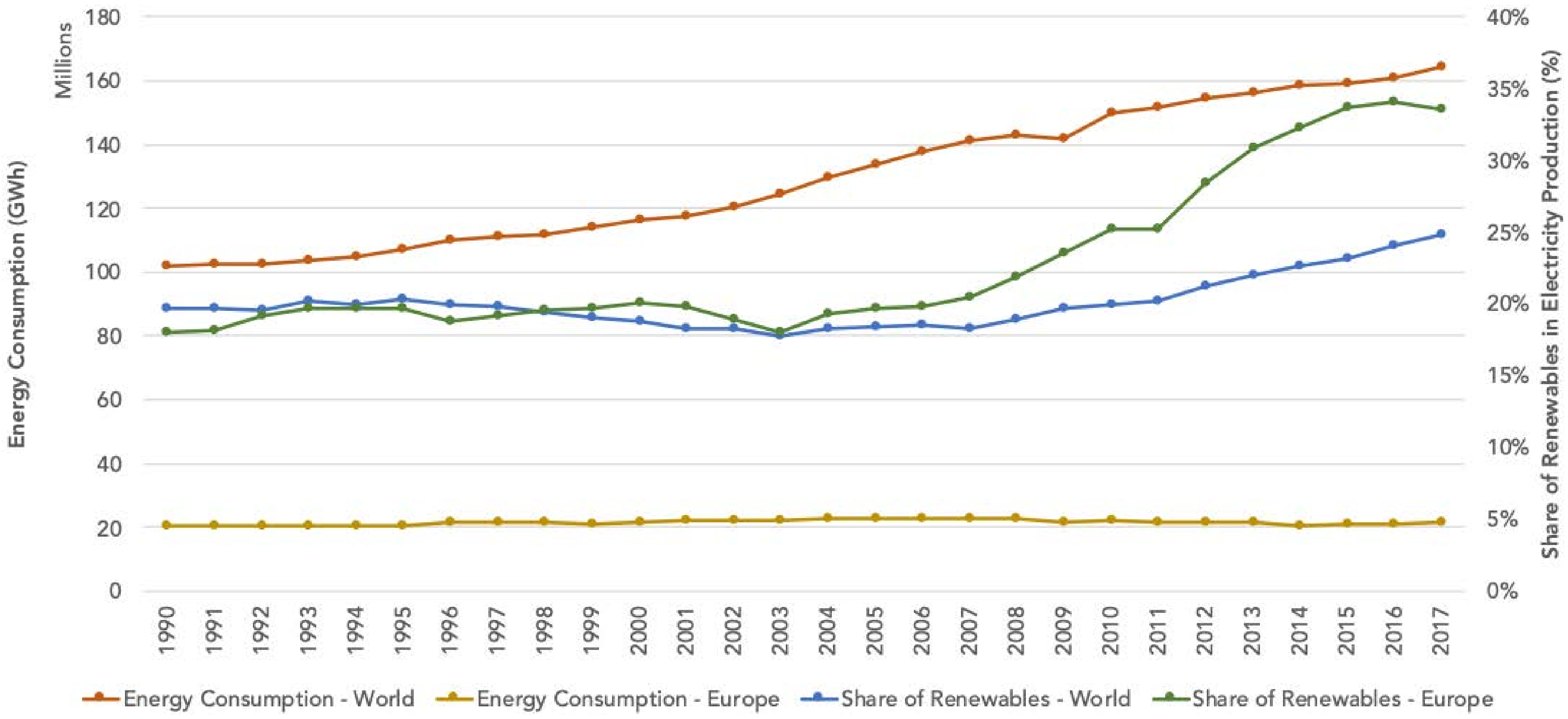


Figure 6: Energy Consumption and share of Renewables in Energy Production (source: Bax & Company based inEnerdata Yearbook; The World Bank)

At the same time, in order to further decrease our impact, we will need to ensure efficient use of energy, from building heating and cooling, to more efficient lighting systems.The objectives[5] are achieve a climate neutral Europe by 2050, as well as ensure a healthier life for its citizens, creation of more relevant jobs in the long term, and ensure a "first mover" advantage for the European technology ecosystem. Reaching the objectives will require further developments in advanced materials for energy and their applications. The following chapters elaborate on the main applications of advanced materials for energy in Europe, their market potential, the European industrial landscape, and finally concludes with suggestions to improve Europe's position globally."term, and ensure a "first mover" advantage for the European technology ecosystem. Reaching the objectives will require further developments in advanced materials for energy and their applications. The following chapters elaborate on the main applications of advanced materials for energy in Europe, their market potential, the European industrial landscape, and finally concludes with suggestions to improve Europe's position globally."

"ELECTROMOBILITY HAS BECOME THE PREVALENT SOLUTION FOR DECARBONISATION IN THE TRANSPORTATION SECTOR. SALES OF NEW ELECTRIC CARS GLOBALLY HAVE BEEN INCREASING BY 60% IN THE LAST TWO YEARS WHILE BY 2030 TOTAL CUMULATIVE NUMBER OF EVS"

1

BATTERY ENERGY STORAGE

1. Battery Energy Storage

Batteries are becoming increasingly ubiquitous as everyday products and devices become electrified and "smarter". Currently the main applications of batteries are mobility, portable electronics, and stationary energy storage. The share of the three applications are expected to represent 80%, 15% and 5% of the total global battery market in 2025 respectively6. Total rechargeable battery market (dominated by Li-ion) is forecasted to reach 250 billion euros per year by 2025[7]. Looking at battery production costs, the share of advanced materials is 60%, while the rest 40% represents amortization of manufacturing capacity, personnel, R&D, and other supporting activities. The growth of the batteries sector in the next 10-15 years will mainly be driven by the irreversible move towards decarbonisation of the transportation sector, enabled by the electrification of mobility.

Technology Overview

"Electric batteries serve a wide range of applications; therefore, a wide variety of technologies are available to satisfy the different requirements. Despite these differences, they all comprise of a combination of connected electrochemical cells which in turn consist of three main parts; the two terminals (anode, cathode) made of different active materials, and the electrolyte separating the two terminals. During discharge, the material of the negative terminal (anode) releases electrons which flow through the external circuit (on which an energy consuming device is connected, e.g. a lamp) to the positive terminal (cathode), generating electrical energy. During charging, the opposite occurs – electrons flow from the cathode to the anode.
Figure 7 above shows the structure of a battery cell, as well as the hierarchy considered within the roadmap.

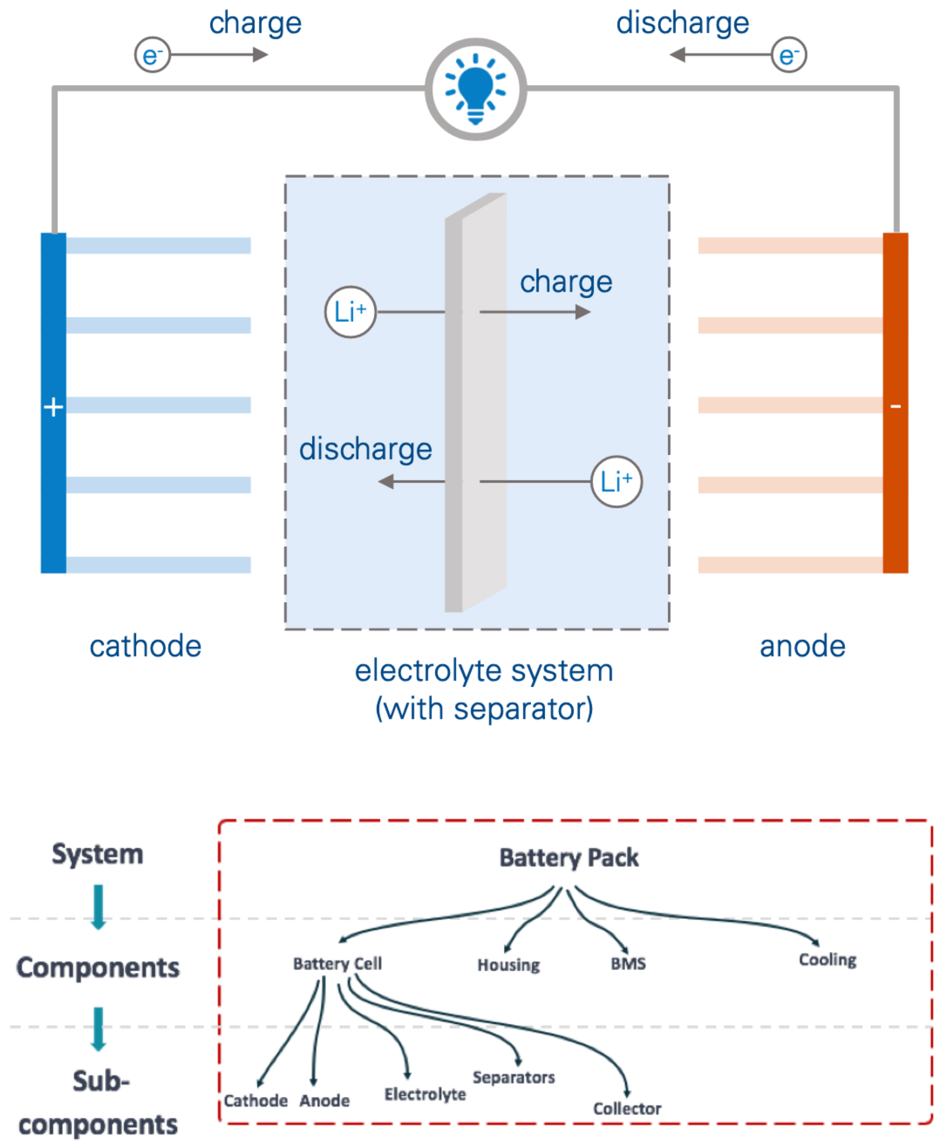


Figure 7: Main sub-components of a battery cell (top), component hierarchy (bottom)
(sources: Arthur D. Little[8],Bax & Company)

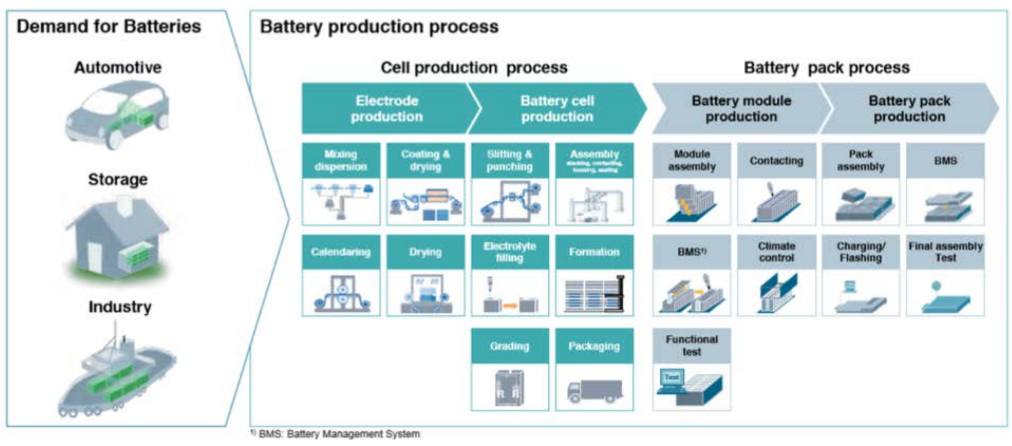


Figure 8: Battery manufacturing process (source: Siemens)

[7] As outlined in A Clean Planet for all - A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy.

Lithium-ion technologies

Li-ion batteries (LIB) are the most widely used technology at the moment. They are mature and robust systems, with adequate energy and power density for a multitude of applications, as well as a well-established supply chain.

Cathode composition is the main differentiating factor between Li-ion technologies. Currently, there are several LIB technologies competing to be the main choice for battery makers, each making use of a different blend of raw materials. All types of LIBs use lithium ions as the charge carriers between the anode and the cathode, with the majority having graphite as the anode. These anode chemistry archetypes are the basis for every producer's cathode "recipe". The main technologies along with their main attributes and applications are presented in Table 1.

"ESTIMATED CURRENT ES CAPACITY OF 4.7TWH IS EXPECTED TO INCREASE MORE THAN 12TWH BY 2030, TO ACCOMMODATE TO OUR NEEDS FOR STATIONARY AND MOBILE ENERGY STORAGE"

Type	Chemistry	Performance						Main Applications						
		Energy	Power	Calendar Life	Cycle Life	Safety/Stability	Cost	Consumer Electronics	Power Tools	Light Duty Vehicles	Cars	Trucks/ Commercial Vehicles	Buses	Grid
LFP (Lithium Iron Phosphate)	$LiFePO_4$	++	++	++	++	+++	+	•	•	•	•	•	•	•
NCA (Lithium Nickel Cobalt Aluminium Oxide)	$LiNiCoAlO_2$	+++	+++	++	++	+	+	•		•	•			•
LMO (Lithium Manganese Oxide)	$LiMn_2O_4$	+	+++	-	++	++	++	•	•	•	•			•
LCO (Lithium Cobalt Oxide)	$LiCoO_2$	++	++	+	+	+	+	•						
LTO (Lithium Titanate Oxide)	$Li_4Ti_5O_{12}$	-	+++	+	+++	+++	-				•		•	•
NMC (Lithium Nickel Manganese Cobalt Oxide)	$LiNi_xCo_xMn_xO_2$	+++	++	++	++	++	++	•	•	•	•	•	•	•
HE-NMC (High Energy Lithium Nickel Manganese Cobalt Oxide)	$LiNi_xCo_xMn_xO_2$	++++	++	+	+	-	++	•	•	•	•	•	•	•
HVS (High Voltage Spinel)*	$LiMn_{1.5}Ni_{0.5}O_4$	++++	++	+	+	-	+	•	•	•	•	•	•	•
Solid State**		++++	++	++	-	+++	++	•	•	•	•	•	•	•

* currently at TRL6-7
** currently at TRL4-5

Table 1: Li-ion technologies

Energy refers to the amount of energy that can be stored in the battery. It is commonly referred to as "energy density" and quantified by Wh/l (volumetric energy density) or Wh/kg (gravimetric energy density). It is crucial for mobile/mobility applications such as vehicles or consumer electronics where the amount of energy that can be stored within a specific volume or weight is important.

Power refers to the amount of power that the battery can deliver. It is commonly referred to as "power

Generation	1	2		3		4			5
		2a	2b	3a	3b	4a	4b	4c	
Type	Current	Current	State-of-the-Art	Advanced Li-ion HC	Advanced Li-ion HV	Solid State			Beyond Li-ion
Expected Commercialisation	Commercialised	Commercialised		2020	2025	>2025			
Cathode	• NMC/NCA • LFP • LMO	• NMC111	• NMC424 • NMC523	• NMC622 • NMC811 • NMC910	• HE NMC • Li-rich NMC • HVS	• NMC	• NMC	• HE NMC	• O_2 • S
Anode	• Modified Graphite • $Li_4Ti_5O_{12}$	Modified Graphite	Modified Graphite	Carbon (Graphite)+Si (5-10%)	Silicon/Carbon (C/Si)	Silicon/Carbon (C/Si)	Li metal		Li metal
Electrolyte	• Organic • $LiPF_6$ salts				• Organic+ Additives	• Solid electrolyte – Polymer (+Additives) – Inorganic – Hybrid			
Separator	Porous Polymer Membranes								

Table 2: Li-ion battery generations
(source: Nationale Plattform Elektromobilität[9], JRC[10], Meeus[11])

density" and quantified by W/l (volumetric power density) or W/kg (gravimetric power density). It is important in applications where high power is needed (typically for a relatively short amount of time) such as power tools, trucks and forklifts.

Calendar life refers to the amount of time the battery can maintain its health (expressed by its capacity) over time. Cycle life refers to the ability of the battery to maintain its health over charge and discharge cycles.

Significant work has already been done on defining the future of Li-ion technologies in Europe. European stakeholders have already defined current and future generations of Li-ion technologies, grouped according to the materials used in the main battery components. The different generations are presented in Table 2.

Figure 9 illustrates the main characteristics of the different generations. Higher gravimetric energy density is more crucial for weight-critical applications such as electric vehicles, while volumetric energy density is more important for volume-critical applications such as portable electronics.

"THE OBJECTIVES ARE TO ACHIEVE A CLIMATE NEUTRAL EUROPE BY 2050, AS WELL AS ENSURE A HEALTHIER LIFE FOR ITS CITIZENS, CREATION OF MORE RELEVANT JOBS IN THE LONG TERM, AND ENSURE A "FIRST MOVER" ADVANTAGE FOR THE EUROPEAN TECHNOLOGY ECOSYSTEM. REACHING THE OBJECTIVES WILL REQUIRE FURTHER DEVELOPMENTS IN ADVANCED MATERIALS FOR ENERGY AND THEIR APPLICATIONS. "

8 Umicore Capital Markets Day, June 2018
9 InnoEnergy, The EU Battery Alliance, February 2018.
10 Arthur D. Little, The future of batteries, May 2018.
11 Nationale Plattform Electromobilitat, Roadmap integrierte Zell-und Batterieproduktion Deutschland.
12 EC JRC, EU competitiveness in advanced li-ion batteries for e-mobility and stationary storage applications opportunities and actions.
13 Marcel Meeus, Overview of battery cell technologies, European battery cell R&I workshop, January 2018

Other Technologies

"Li-ion batteries are currently the most developed technology for many applications. LIBs excel at providing high power and long cycle life at a reasonable cost, but they are not the best solution for every purpose. LIBs are a fire hazard and consume raw materials that are not readily mined in Europe (e.g. Cobalt). As the demand for diverse energy storage solutions continues to grow, other battery technologies are needed to supplement Li-ion and pursue new performance and cost targets.
An overview of some of these promising technologies with their main attributes and applications are presented in Table 3.

The development of post-Li-ion batteries focuses on technologies based on abundant materials with very low cost and high energy density. This includes chemistries like Na-S or Li- S, long-life redox-flow batteries, or high-energy metal-air batteries. The main application of such batteries is grid-scale storage of renewable energy, but they could also find use as EV range extenders or in maritime transport electrification.

Type	Chemistry	Performance						Main Applications
		Energy	Power	Calendar Life	Cycle Life	Safety/Stability	Cost	Grid
Flow Batteries		+	+	+++	+++	++	++	•
Sodium Sulphur	NaS	++	+	++	++	+	++	•
Metal-Air*	In development	+++	+	+	+	++	++	•

* currently at TRL2-3; expected performance and applications (still early to define accurately)

Table 3: Promising non-Li-ion technologies

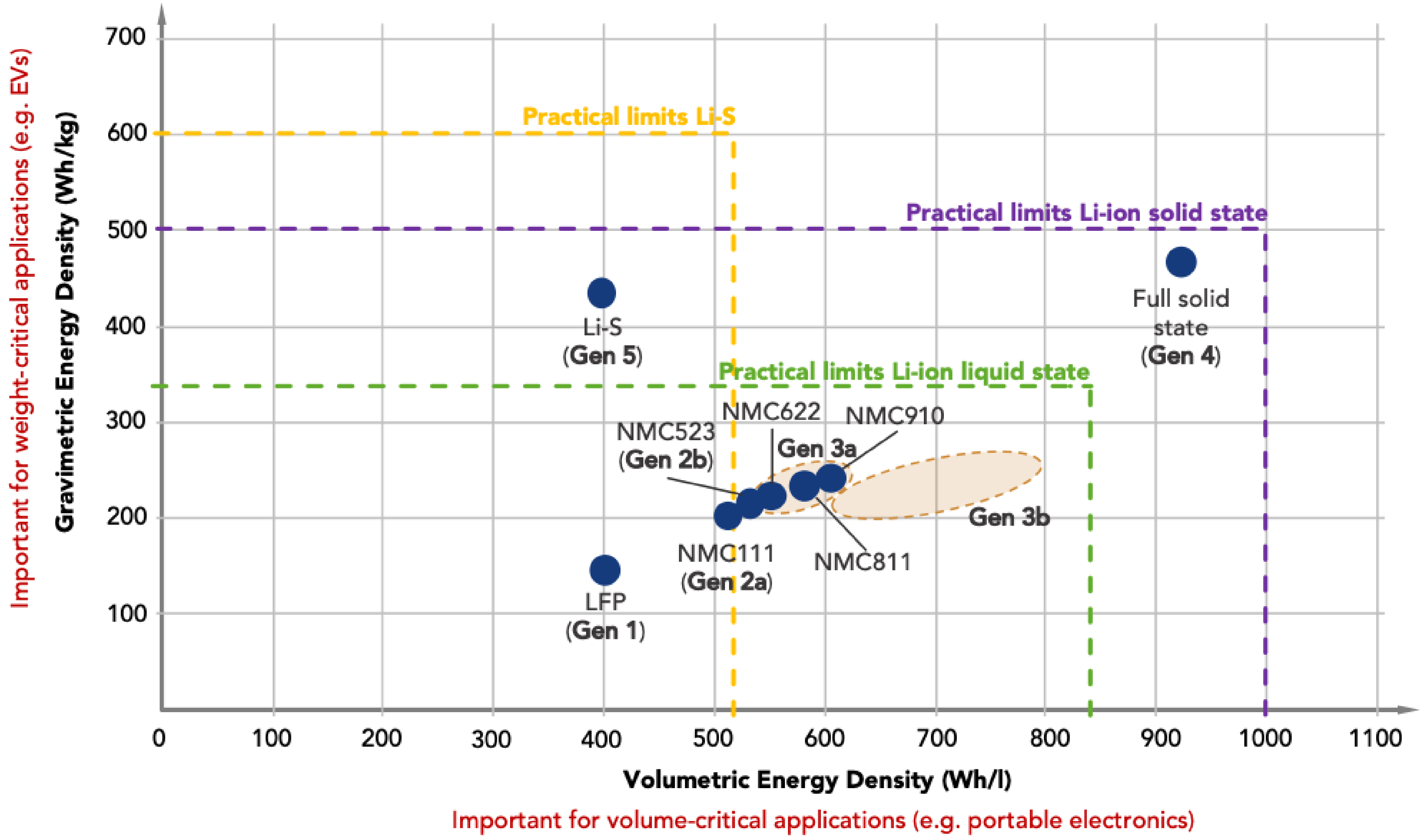


Figure 9: Characteristics and market potential of Li-ion technologies (adapted by Bax & Company, source:Umicore[8])

Each of the technologies listed in Table 3 brings its own advantages and disadvantages compared to Li-ion. Redox-flow batteries can store vast amounts of energy over long periods of time, but they are very large and require close monitoring and maintenance. Sodium and sulphur are two of the most abundant and easily accessible elements on earth and could dramatically reduce the cost of energy storage. However, sulphur-based chemistries have yet to achieve the lifetime required for industrial applications. As shown in Figure 10, metal-air batteries have the potential to achieve energy densities an order of magnitude greater than current Li-ion batteries, making them ideal for low-footprint energy storage systems. However, the rechargeability of these systems remains a significant challenge to commercialisation. Only rechargeable zinc-air batteries have achieved TRL8, with successful start-ups in the USA.

The shift towards a renewable electric grid and the electrification of the transport sector will only grow for the foreseeable future. To meet this demand, it is necessary to diversify battery technology. While Li-ion batteries will remain the industry standard, the development of post- Li-ion chemistries will enhance the security of energy storage and offer Europe an opportunity to lead the next generation of battery development.

Cost Structure

This section presents an overview of the cost breakdown and expected evolution within the next decade. Figures focus on Li-ion systems which is the one with the most comprehensive cost data among the prevalent technologies.

Figure 11 illustrates the cost evolution of LIB in recent years and an estimation for the future.

As one can see advanced materials account for 50% to 70% of total cell cost, while from the total cost of materials for the different cell components, materials for cathodes represent some 35% (Figure 12).

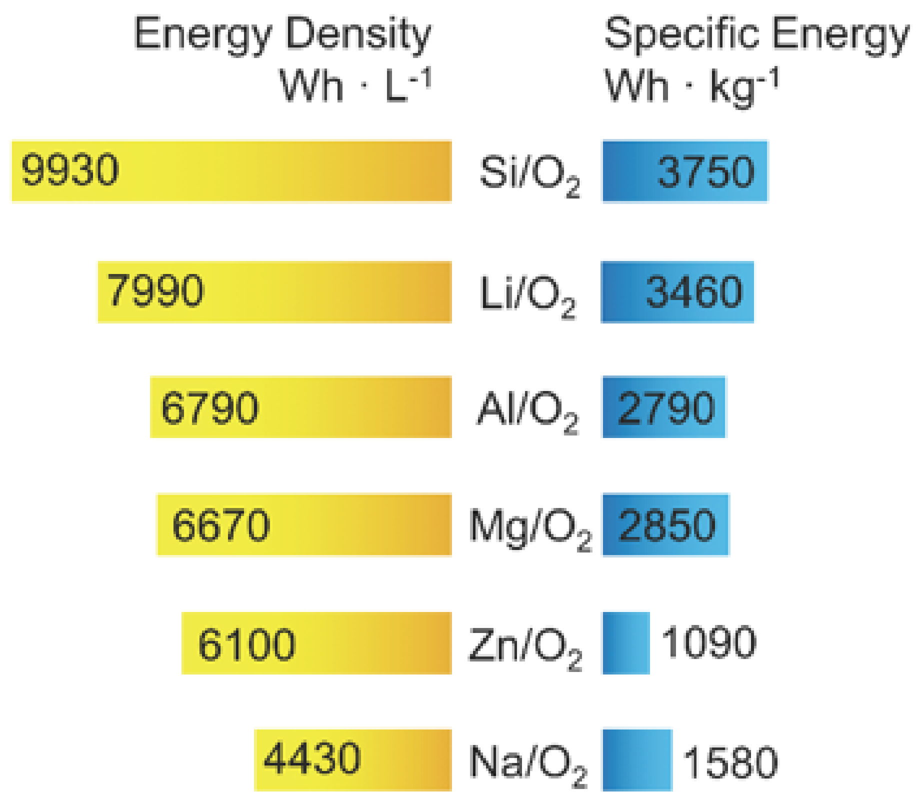


Figure 10: Theoretical energy density and specific energy values for selected metal-air batteries (source: Clark,[14])

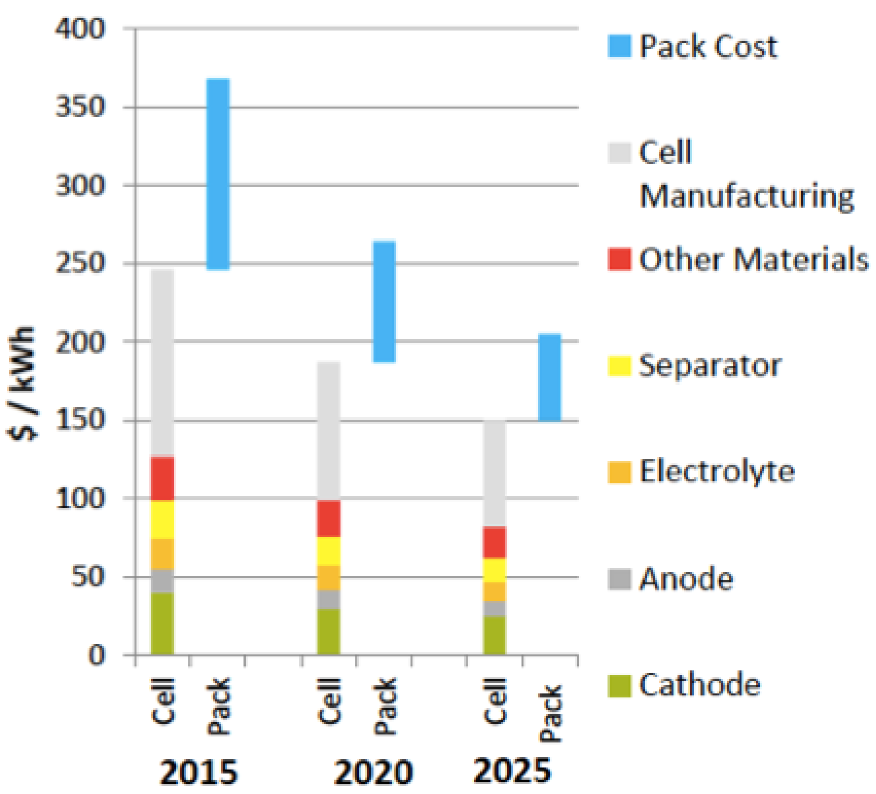


Figure 11: Breakdown of Li-ion battery costs for EVs (source: Avicenne Energy[15])

"TOTAL RECHARGEABLE BATTERY MARKET (DOMINATED BY LI-ION) IS FORECASTED TO REACH 250 BILLION EUROS PER YEAR BY 2025"

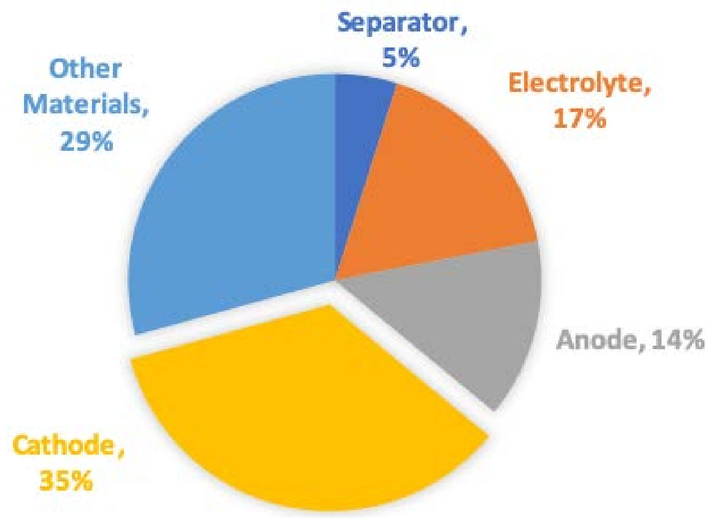


Figure 12: Breakdown of Li-ion battery component costs

Looking at the main application of batteries in the next decade – electromobility – the share of cost in a BEV was ~35% in 2017, expected to drop to below 25% by 2025.

Projections show a drastic decrease in the costs for LIB cells, allowing to meet the cost targets for packs in the Declaration of Intent (DoI) between EU industry, Member States and the Commission of 90 €/kWh in 2022 and 75 €/kWh in 2030 for EV and of 0.05 €/kWh/cycle for ESS by 2030[6,16]. Figure 14 below illustrates the historical and projected cost and volumetric energy density for Li-ion batteries.

The decrease in the cost of Li-ion batteries is mainly driven by the increase in manufacturing capacity which enable economies of scale (known as "gigafactories") but also due to the sustained efforts to improve performance – expressed by battery energy density.

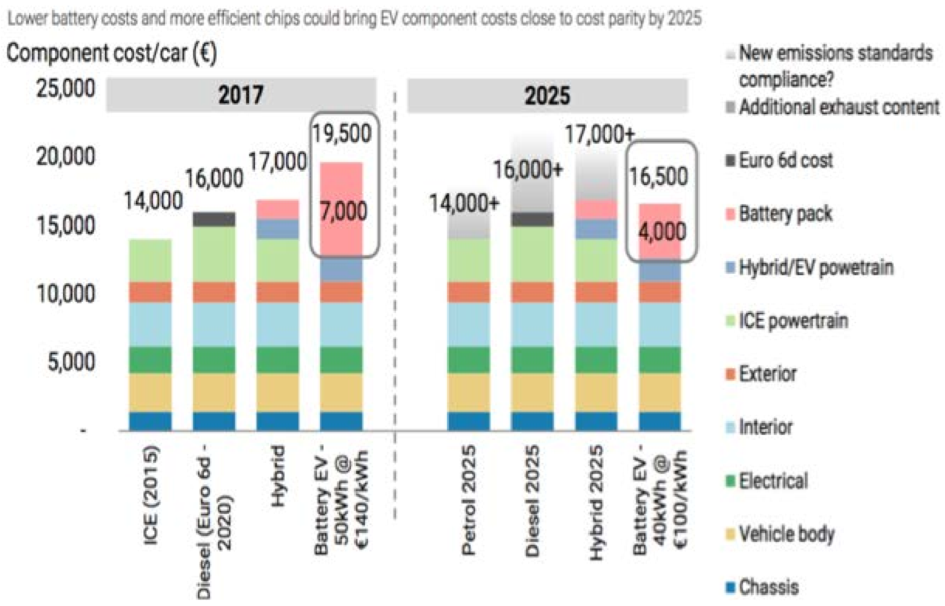


Figure 13: Breakdown of vehicle component costs (source: Technical University of Munich, ICCT, EPA, CARB, NHTSA, Morgan Stanley Research)

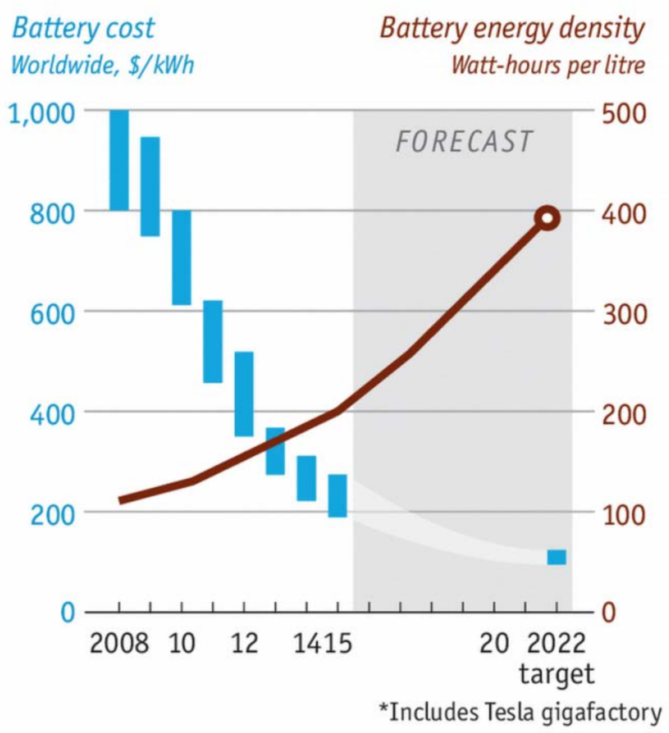


Figure 14: Historical and projected cost and energy density for Li-ion batteries (source: The Economist[17])

[14] Simon Clar, Armulf Latz and Birger Horstmann, A review of model-based design tools for metal-air batteries, 2018

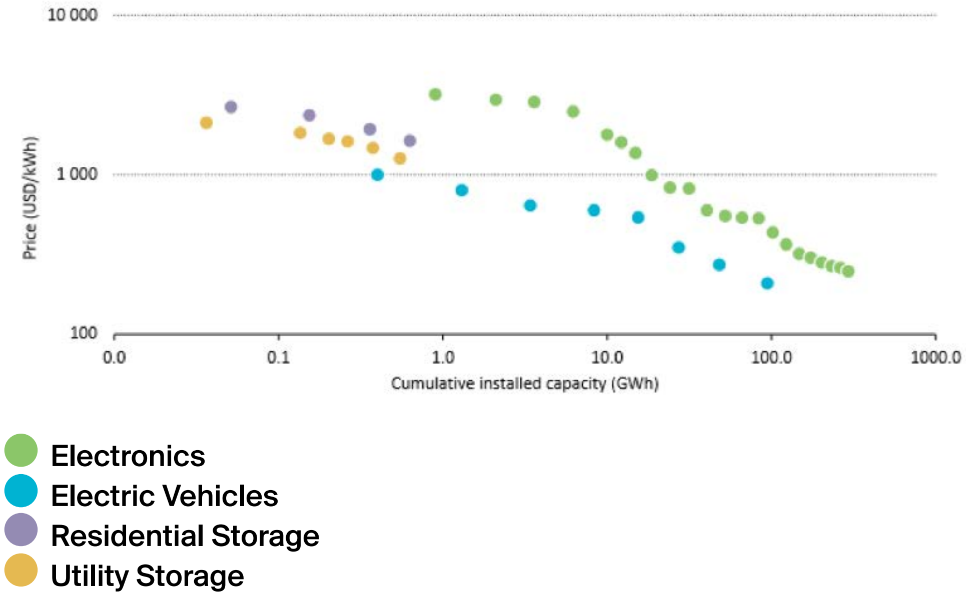
[15] Avicenne Energy, The rechargeable battery market 2016-2025, March 2017.

[16] European Commission, Integrated SET Plan, Action 7

[17] The Economist, The growth of lithium-ion battery power, August 2017

30 Figure 15 illustrates the expected evolution of battery cost as a function of the cumulative installed capacity for the main application sectors.

In the field of stationary energy storage, costs are expected to drop in a slower pace, as the main market share is expected to be related to electromobility applications.



Notes: Axes are on a logarithmic scale. Electonics refer to power electronic batteries (only cells); electric vehicles refer to battery packs for EVs; utility and residential storage refer to Li-ion battery packs plus power conversion system and includes costs for engineering, procurement and construction.
Source: Adapted and updated from Schmidt et al (2017).

Figure 15: Cost as a function of installed capacity for Li-ion (source: IEA[2])

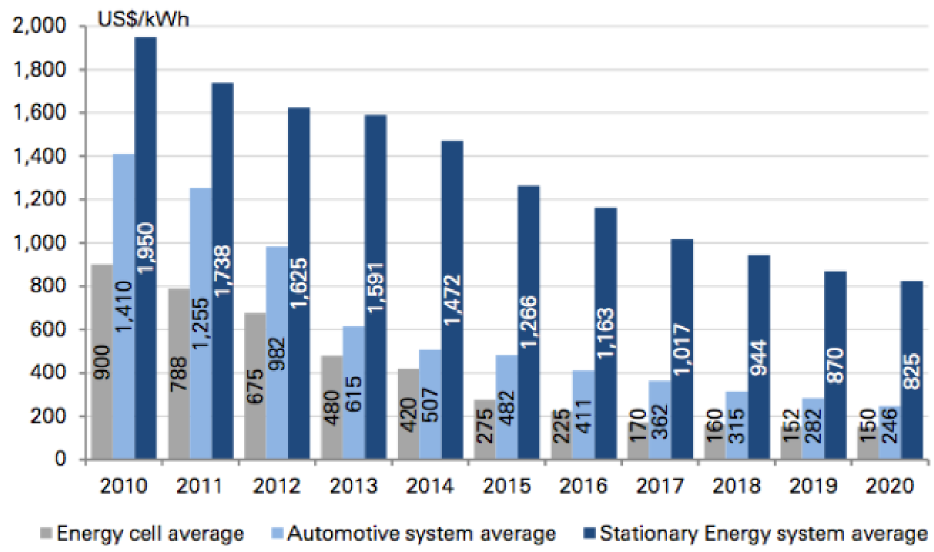


Figure 16: Projected cost for different applications (source: Deutsche Bank[18])

[18] Deutsche Bank Markets Research, EV battery makers, June 2016

European Landscape

Market and Applications

The market for energy storage technologies has been historically driven by battery demand for consumer electronics. In recent years, given the growing strategic interest in batteries for achieving EU policy goals, mobility as well as stationary storage applications are arising as the areas offering further opportunities. These are related to the development of hybrid energy storage systems to deliver power capacity, duration and cycle life in a single system, suitable for stationary and heavy-duty mobility applications. As one can see from the forecasted evolution of the different application areas in Figure 17, the mobility sector is expected to drive the growth in the next decade.

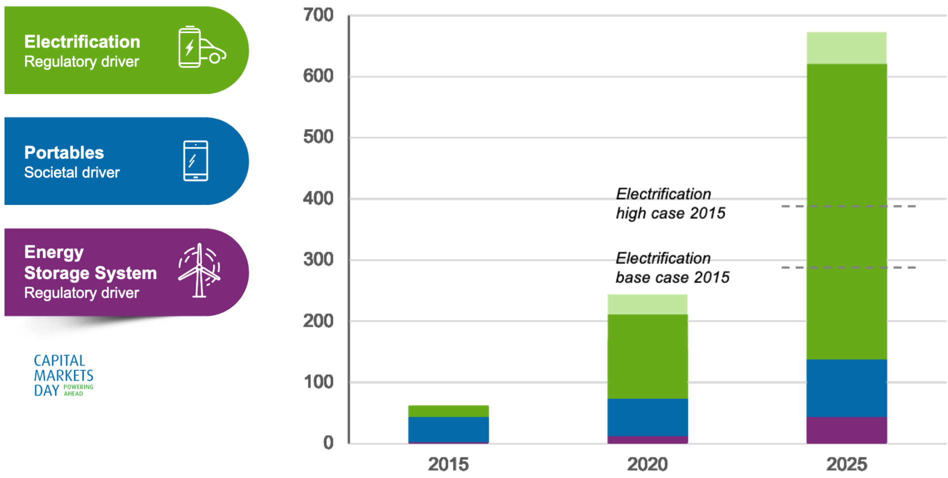
By 2030, ~83% of the demand is expected to come from mobility as one can see in Figure 18 below.

Applications can be divided between those requiring high power rating (HEVs, micro-hybrids) with a Price-to-Earnings (P/E) ratio typically higher than 15, and those requiring high energy rating (BEVs, PHEVs, grid batteries, back-up power, etc.) with P/E<3.

Focusing on the area of mobility, and particularly passenger cars, among the top-ten countries with most electric/hybrid cars, China has seen the highest increase as well as absolute volume in electric cars since 2013, followed by the United States. Norway is by far the world leader in EV market share. Forecasts for the next decade foresee that China will be the largest EV market with over 40% of global demand, while Europe is expected to be second with 30%[4].

"THE MOBILITY SECTOR IS EXPECTED TO DRIVE THE GROWTH IN THE NEXT DECADE"

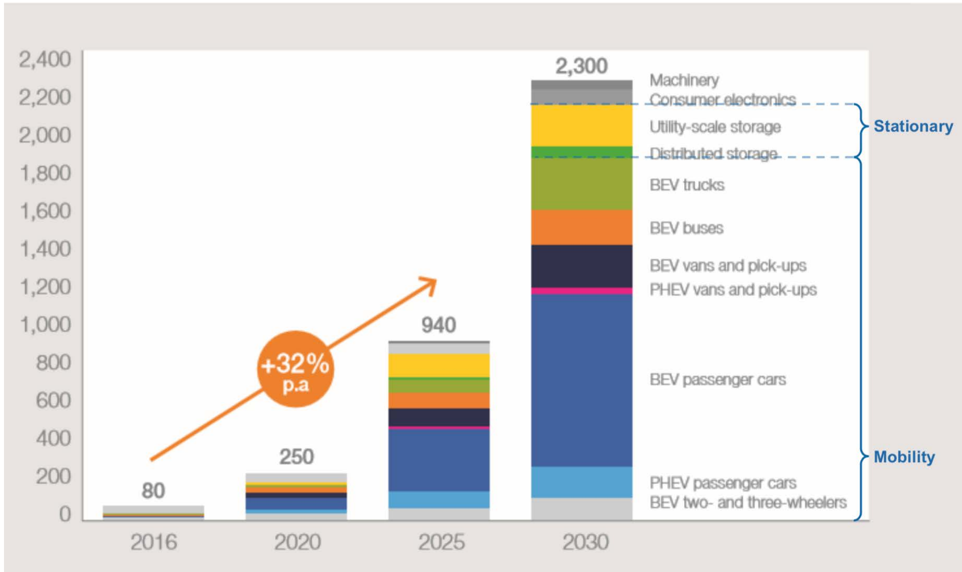
BY 2030, ~83% OF THE DEMAND IS EXPECTED TO COME FROM MOBILITY"



Rechargeable Battery Market (GWh)

- Heavy Duty Vehicles
- Electrification Current Scenario
- Portables
- ESS

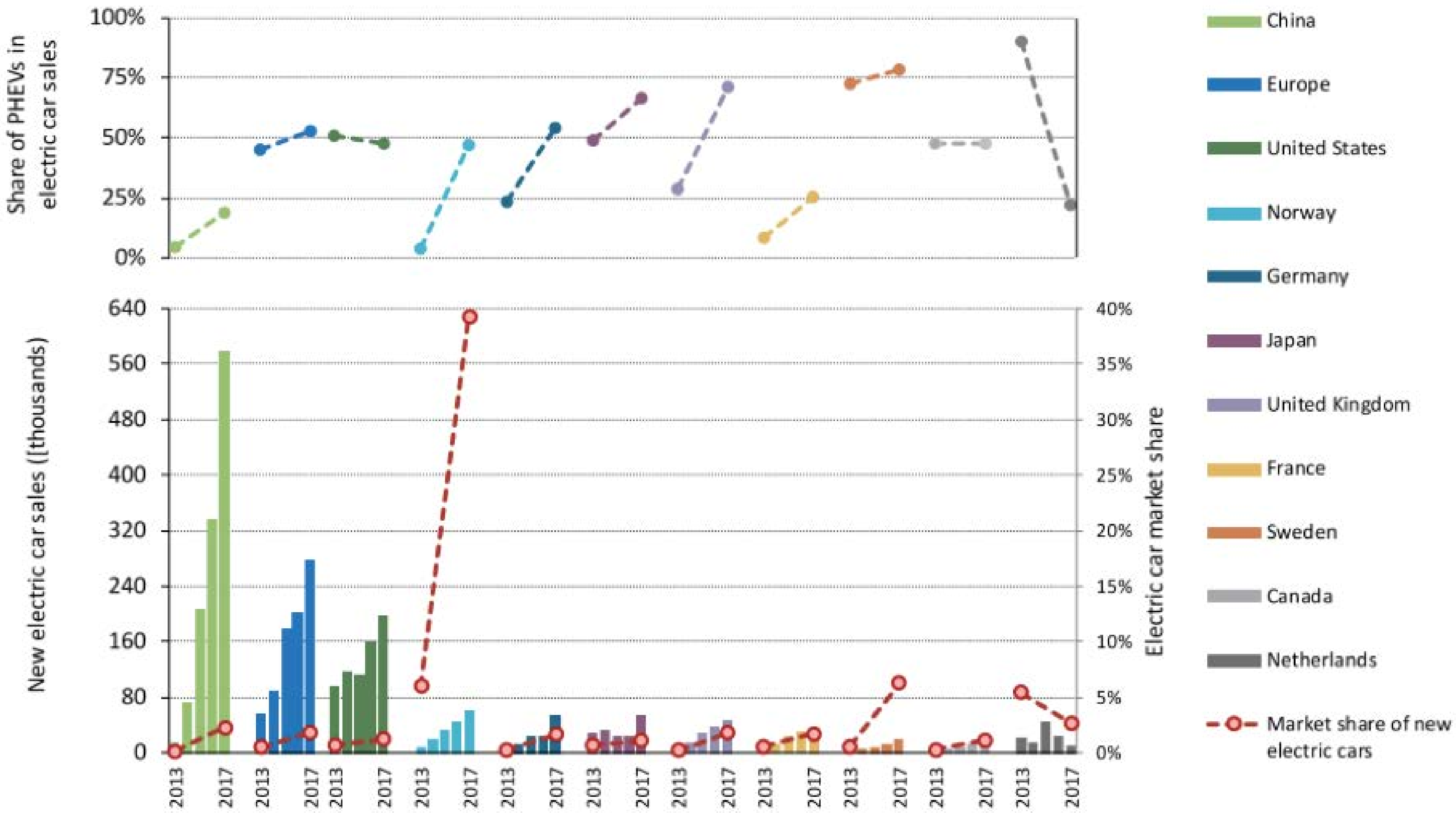
Figure 17: Rechargeable battery market projections (source: Umicore[6])



Annual battery demand:
Electric mobility segments, stationary battery storage, consumer electronics, and machinery (GWh/yr)

Figure 18: Battery energy storage projections (source: McKinsey[19])

[19] McKinsey & Co, Metal mining constraints on the electric mobility horizon, April 2018



Focusing on the area of mobility, and particularly passenger cars, among the top-ten countries with most electric/hybrid cars, China has seen the highest increase as well as absolute volume in electric cars since 2013, followed by the United States. Norway is by far the world leader in EV market share. Forecasts for the next decade foresee that China will be the largest EV market with over 40% of global demand, while Europe is expected to be second with 30%[4].

Notes: The countries in Figure 15 represent the ten leading EVI countries. This ranking closely resembles the ten leading countries worldwide in terms of sales - the only exception is Korea (not an EVI member), which is in the top-ten countries with 14 780 electric car sales in 2017.

Figure 19 Market evolution in the top ten leading EV countries (source: IEA[3])

Value Chain Step	Strengths	Weaknesses	Opportunities	Threats
Advanced Materials	• Established EU industrial leaders with strong know-how in certain key advanced materials • Excellent knowledge and competences in research, and well-organized R&D structures • Strong knowledge and infrastructure in recycling technologies	• No full coverage of the whole spectrum of advanced materials by EU companies • EU R&I initiatives up to now have not generated enough IP (which results in Europe lagging behind in emerging technologies)	• Gain competitive advantage on next generation (Gen 3-5 battery materials) • Become the dominant player in battery sustainability issues (incl. sourcing, recycling, carbon footprint) • Significant part of the value of the battery market lies in advanced materials • Battery 2030+ Flagship Initiative	• Manufacturing infrastructure of key players could be outside Europe • No competitive access to primary raw materials for European players • Development cycles for key battery market applications (e.g. EV) are very long
Battery Cell Making	• Modelling & simulation expertise • Strong educational and university network with more than 30 pilot plants • Europe – expertise and players – is strong in Industry 4.0 (making operations more efficient) • Strong Renewable energy implementation allowing to make "green batteries"	• Still no large-scale manufacturing capacity in Europe by European players although many initiatives ongoing • Delay in Solid State piloting and manufacturing • Non-homogeneous legislative work frame	• Momentum for implementation of manufacturing capacity for the upcoming technologies (e.g. solid state, Na-ion) before Asia and US dominates • Development of a strong equipment manufacturing industry • Development of battery design easy to dismantle and recycle	• Dependence on companies outside of Europe • High CAPEX needed to build cell manufacturing capacity could decelerate capacity building
Integration into Applications	• Strong Integrator and Automotive industry in Europe • Legislative framework that favours clean mobility and green energy production	• Limited partnerships inside European e-mobility value chain • Market confidence e-mobility still to be strengthened (model case Norway)	• Technology and legal base to create a "closed loop" battery industry (using second life applications for batteries and recycling) • Significant market anticipated in EU • Mobility industry in Europe under competitive stress to innovate	• Import applications (buses, ESS...) from China & Asia • Significant investment needs in infrastructure (charging stations, grid) could slow down market for batteries

Value Chain and Key Players

Table 4: SWOT analysis of Li-ion batteries for the European industry (sources: EMIRI community[20], Frost & Sullivan[21], RECHARGE[22], Meeus[9])

The battery value chain includes multiple steps, and presents opportunities for several stakeholders, from material suppliers, to manufacturers, to a multitude of sectors benefitting from electrification.

Table 4 above presents a SWOT analysis for the European Li-ion landscape.

[20] input from EMIRI workshops

[21] Frost & Sullivan, What are the opportunities and challenges for lithium-ion manufacturers in Europe, January 2010

[22] RECHARGE, E-mobility roadmap for the EU battery industry, July 2013

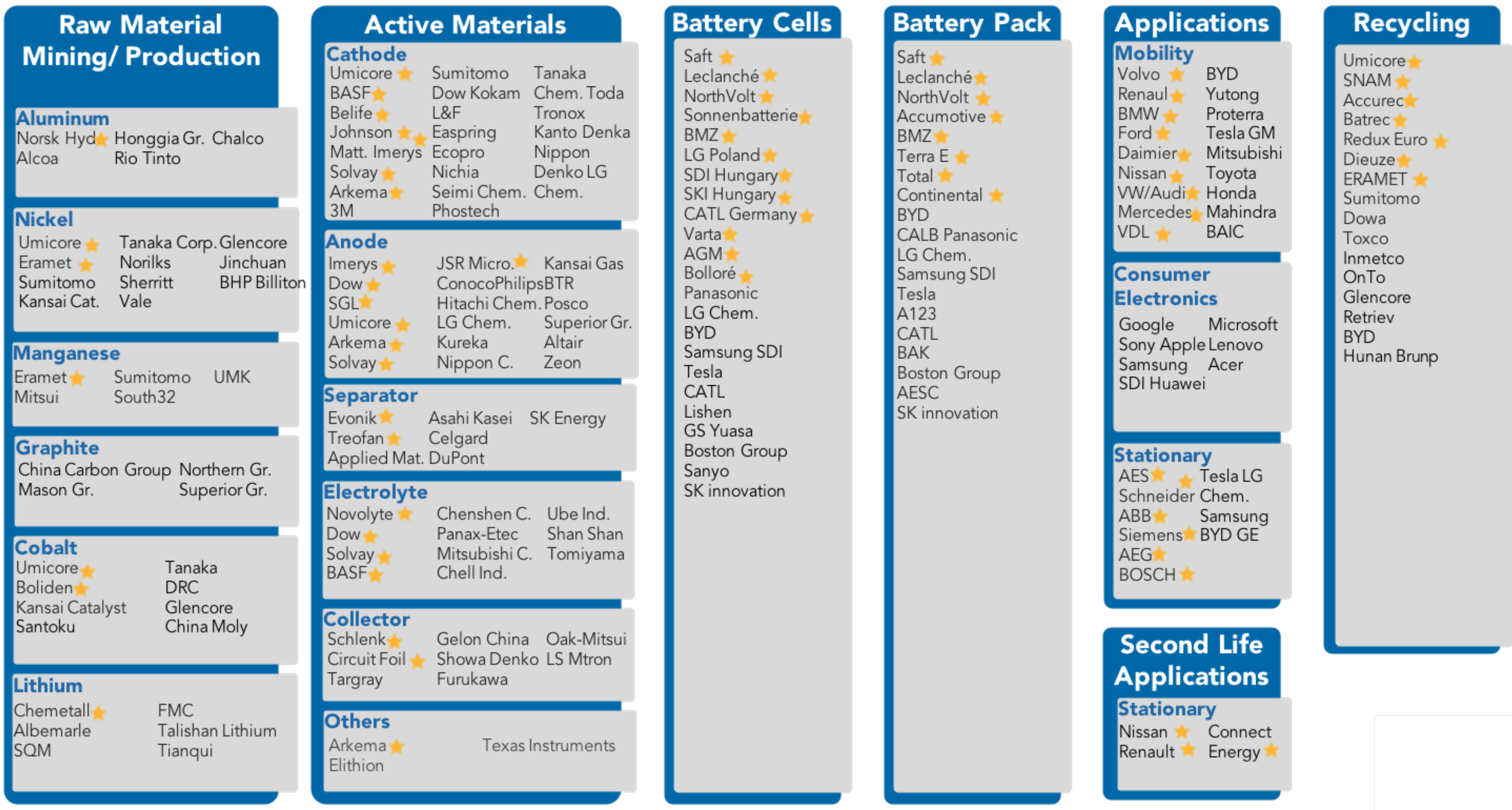


Figure 20 above illustrates the steps of the value chain, along with the main players. European organisations are marked with a star. As one can see, Europe is strong in research, manufacturing of active materials, applications and recycling, but is lacking capacity in cell Manufacturing Equipment Testing Equipment and pack manufacturing – although more European organisations are increasingly upscaling pack manufacturing capacity.Although Europe is preparing for the growing battery markets with "Giga" manufacturing plants utilising imported technologies and EU know-how (Figure 21), China has already taken the lead, as one can see in Figure 18.

In terms of shares in the different geographical locations (Figure 22), sourcing of raw materials comes mainly from Asia and the rest of the world. The majority of Li (>60%) sourced in Latin America and Asia (~25%), Cobalt from the Democratic Republic of Congo

Figure 20: Battery value chain and main players (non-exhaustive) (adapted by Bax & Company, sources: EC[10], InnoEnergy[5], GTM Research, Meeus, Sarkar et al[23])

"EUROPE IS STRONG IN RESEARCH, MANUFACTURING OF ACTIVE MATERIALS, APPLICATIONS AND RECYCLING, BUT IS LACKING CAPACITY IN CELL AND PACK MANUFACTURING ALTHOUGH MORE EUROPEAN ORGANISATIONS ARE INCREASINGLY UPSCALING PACK MANUFACTURING CAPACITY"

[23] Sarkar et al, Lithium-ion battery supply chain: enabling national electric vehicle and renewables targets, Current Science, Vol. 114, No. 12, 25 June 2018

(64%), and the majority of graphite (69%) from China. Although the majority of the active materials are manufactured in Asia, it is important to mention that a significant portion of the IP and know- how is owned by European companies. Asia is dominating most of the other value chain steps, with Chinese, Japanese and Korean players leading the race. Europe has a strong presence in the recycling field, as it has upscaled pyrometallurgical processes for the retrieval of active material. Nevertheless, it is lacking behind in the other steps, and particularly in battery cell production.

"EUROPE HAS A STRONG PRESENCE IN THE RECYCLING FIELD, AS IT HAS UPSCALED PYROMETALLURGICAL PROCESSES FOR THE RETRIEVAL OF ACTIVE MATERIAL."

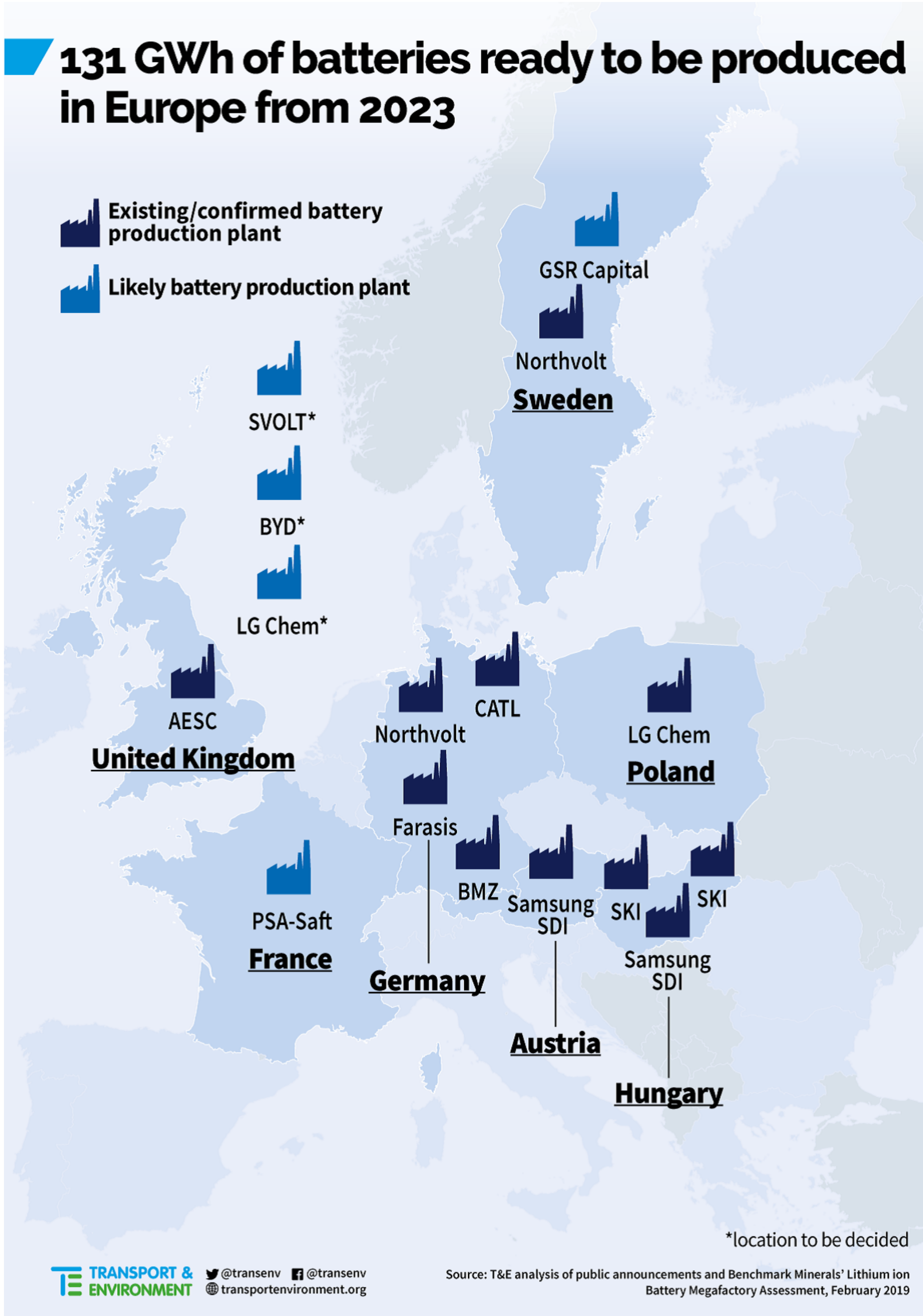


Figure 21: Planned “Gigafactory” projects in Europe (source: T&E)

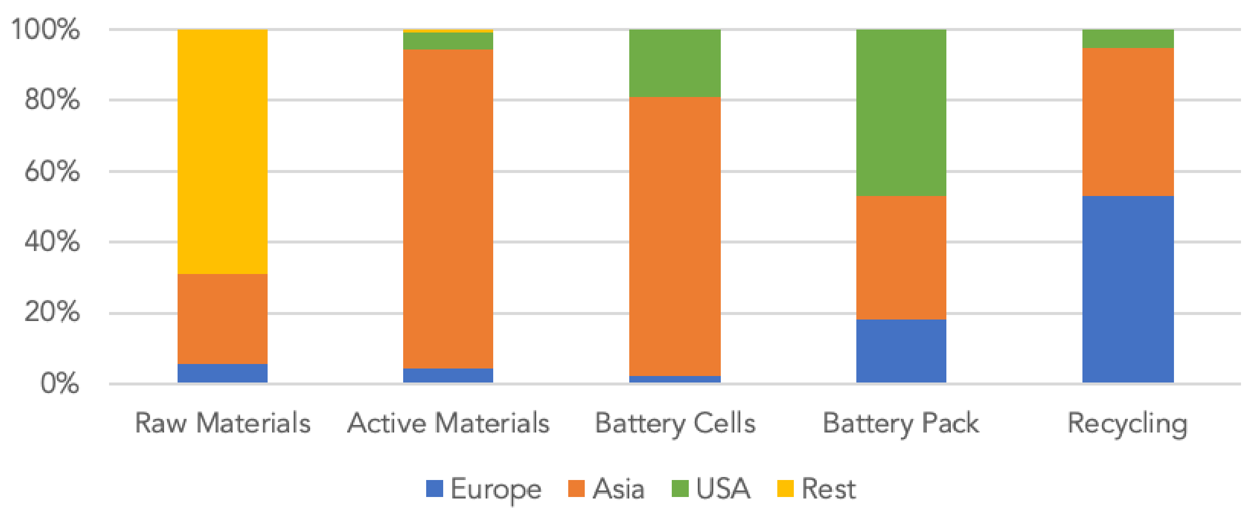


Figure 22: Share of supply per geographical location and value chain step (adapted by Bax & Company, source: EC[24], Marcel Meeus)

[24] EC JRC, Lithium ion battery value chain and related opportunities for Europe, 2016

Current Status/Market Overview

Main Trends

This section lists the main trends that drive the growth of the global battery market.

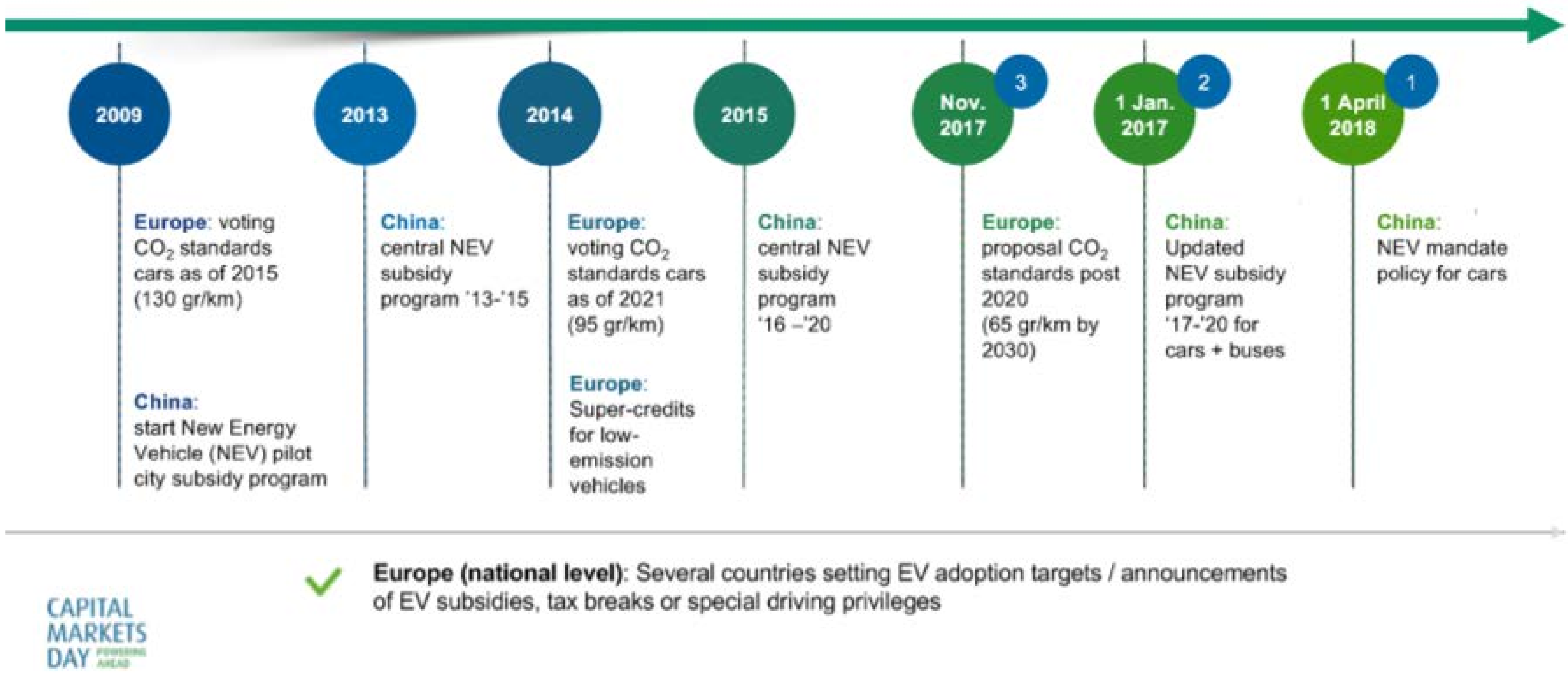


Figure 23: Legislative measures related to electrification of mobility (source: Umicore[8])

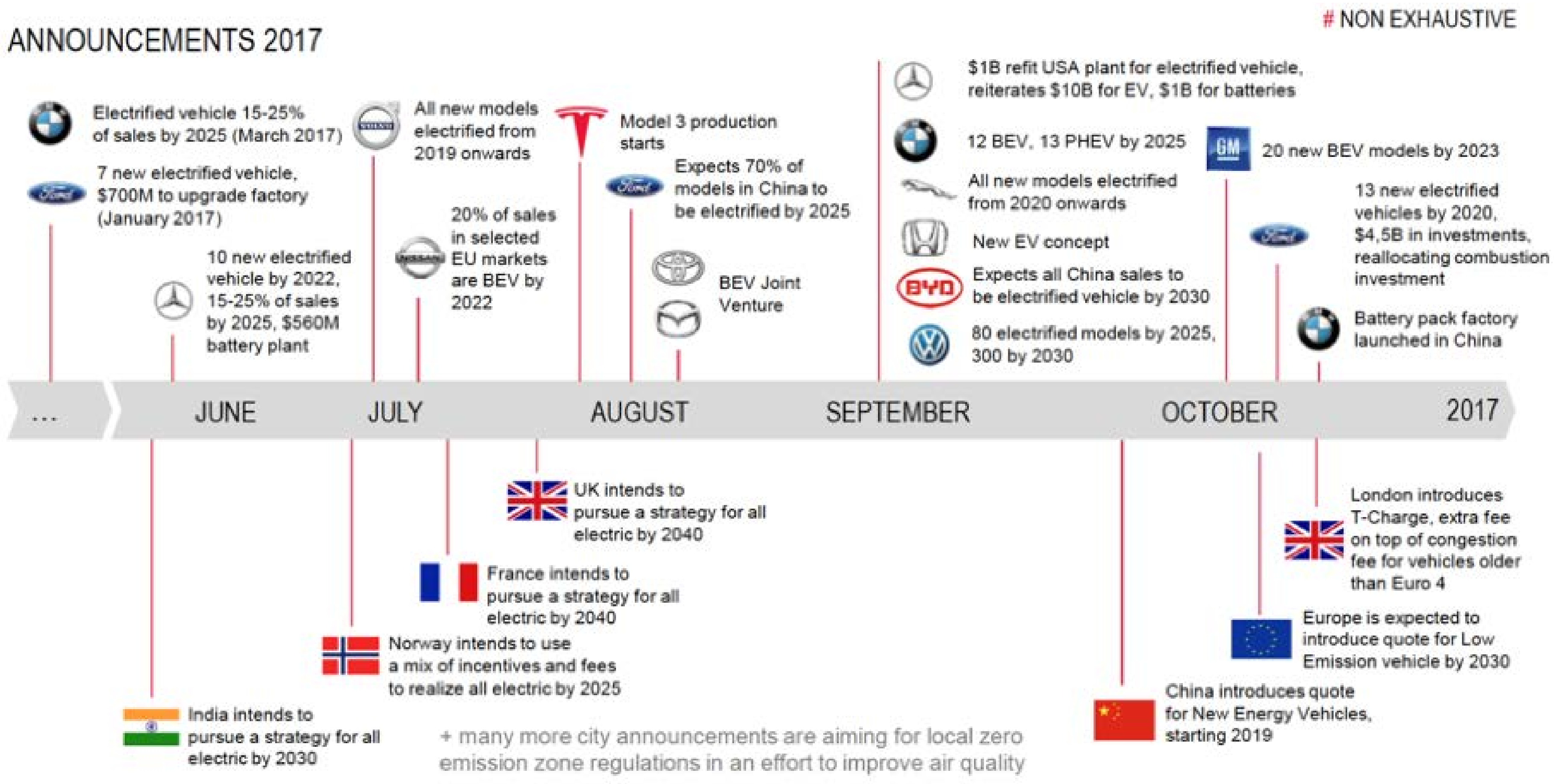


Figure 24: Electromobility-related OEM announcements (source: FEV)

<u>**Electrification of mobility**</u>

One of the core priorities of the Energy Union is to increase energy efficiency and decarbonisation of transport and energy sector. E-mobility facilitates the reduction of GHG emissions and at the same time, provides an opportunity for enhancing EU industrial competitiveness, a major enabler of future economic growth and job creation.

This is reflected in the EU's regulatory push, as well as several other regions, which are moving towards policy changes to set limits in CO2 emissions, as well as subsidising EV purchases.

The regulatory push as well as the market pull is also reflected in the OEMs plans for electrification of their fleets.

Energy production from RES

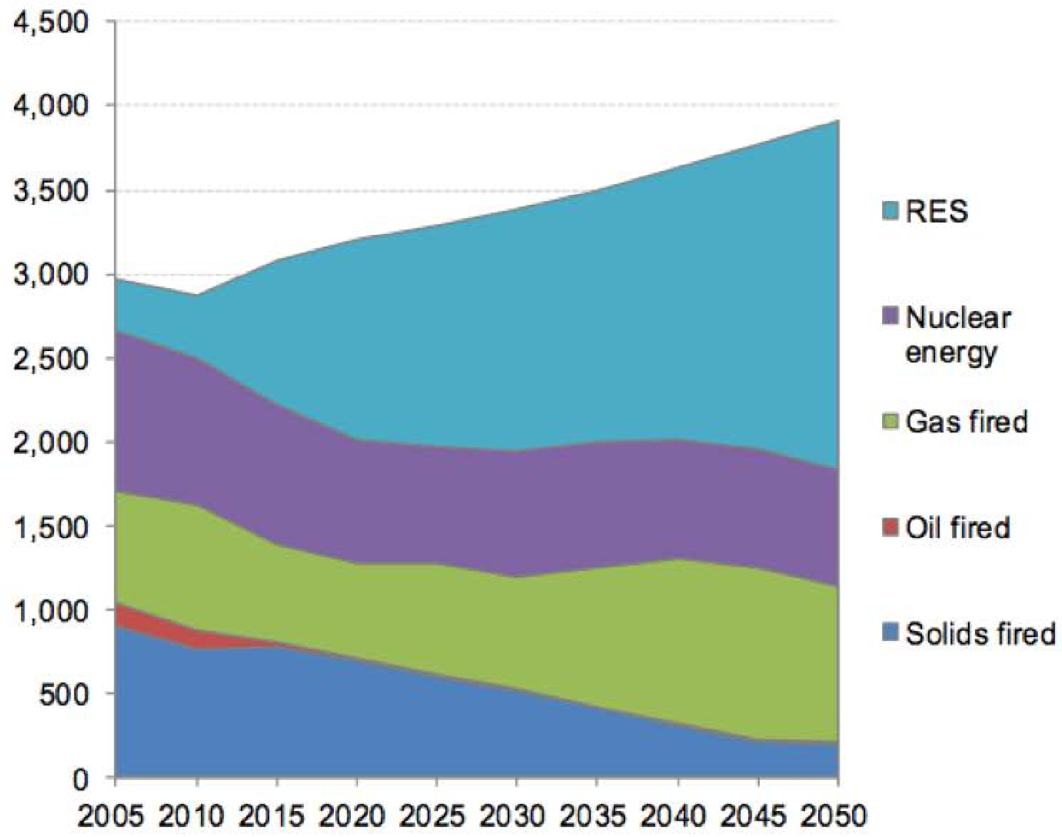
Increasingly, countries around the world are acknowledging the importance of decreasing their impact on the environment. In December 2015, the Paris Climate Agreement was adopted by consensus by all 195 UNFCCC participating member states and the EU to reduce emissions as part of the method for reducing greenhouse gas. The agreement aims at keeping the global increase of temperature "well below" 2°C from pre-industrial levels by creating the necessary policy and legislative changes and mobilizing $100 billion (by developed countries) in climate finance. It was put into effect on November 4th 2016 after enough parties had ratified it. Since then, several individual countries, regions or cities issued statements about setting even more ambitious targets for their reduction on the environment. Table 5 below mentions some of these announcements.

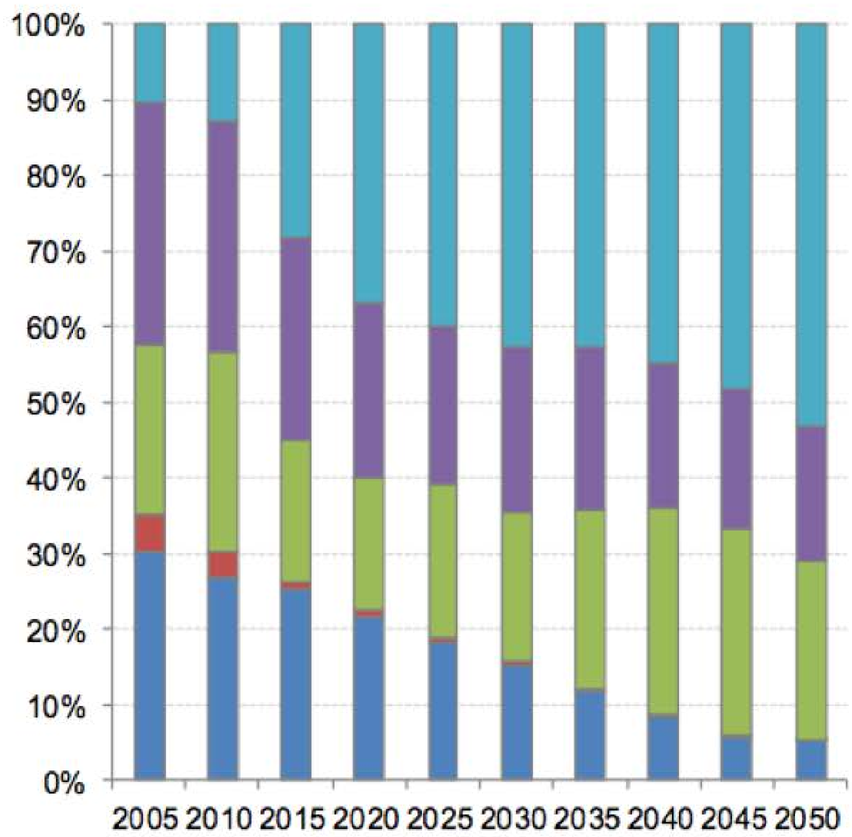
Country/City	Commitment	Date
Netherlands	• Reduce CO_2 emissions by 49% by 2030 compared to 1990 levels[25] • Reduce CO_2 emissions by 95% by 2030 compared to 1990 levels[26]	July 2018[27]
Norway	Become climate neutral by 2030[28]	June 2016
Rotterdam	Become CO_2 neutral by 2050[29]	December 2016
Sweden	Become carbon neutral by 2045[30]	June 2017
France	• Reduce CO_2 emissions by 40% by 2030 compared to 1990 levels • Reduce CO_2 emissions by 75% by 2050 compared to 1990 levels[31]	December 2016
Portugal	• Decrease CO2 emissions by 30-40% by 2030 compared to 2005 levels[32] • Reach 40% penetration of RES in final energy consumption[32]	April 2016
Luxemburg	Decrease CO_2 emissions by 40% by 2030 compared to 1990 levels[33]	January 2018
Denmark	• Reach 50% penetration of RES in final energy consumption[34]	April 2018

Table 5: Commitments by leading European countries in sustainability

Decarbonisation of the power generation cannot be achieved without the use of RES harvesting technologies. For the successful implementation of RES, the full integration of storage devices that will provide flexibility to the power system is crucial.

[25] NL Times, Netherlands climate agreement reached in broad terms; 48.7 megatons CO2 reduction by 2030, July 2018
[26] Climate Home News, Netherlands proposes 95% emissions cut by 2050 in draft climate law, June 2018
[27] Suggested to parliament
[28] Includes carbon trading, The Guardian, Norway pledges to become climate neutral by 2030, June 2016 27 Port Technology, Rotterdam: Carbon neutral by 2050, December 2016
[29] UNFCCC, Sweden plans to be carbon neutral by 2045, June 2017
[30] UNFCCC, France submits long-term national climate plan, December 2016





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FOR THE SUCCESSFUL IMPLEMENTATION OF RES, THE FULL INTEGRATION OF STORAGE DEVICES THAT WILL PROVIDE FLEXIBILITY TO THE POWER SYSTEM IS CRUCIAL.

Figure 25: EU power generation (net) by fuel (Mtoe – left,shares – right) (source: EC[35])

[31] UNFCCC, Multilateral assessment Portugal
[32] Luxemburg Times, Climate strategy to achieve 40% emission reduction target, January 2018
[33] Clean Technica, Danish government launches new energy initiative to support vision of low-emission society independent from fossil fuels by 2050, April 2018
[34] EC, EU reference scenario 2016, energy, transport and GHG emissions trends to 2015, July 2016

Main challenges

Table 6 below summarises the main materials related challenges that need to be addressed – per technology and application sector – within the next 10-15 years in order to increase Europe's competitiveness. The challenges were identified by the EMIRI community in workshops that took place throughout 2018.

Challenge	Application			
	High energy mobility	High power mobility	Stationary domestic	Stationary large scale
• Reduce investment and operating costs to achieve lower energy storage cost			••	•••
• Increase lifetime of batteries to achieve longer calendar life and cyclability	•••	••	••	•••
• Increase volumetric energy density of stationary batteries			••	•••
• Increase gravimetric and volumetric energy and power density of battery cells	•••	••		
• Reduce the ecological footprint and increase the recyclability of pack and cell components	•••	••	••	•••
• Gradual time scaling of capacity to cover longer ranges from kWh to GWh				•••
• Reduce self-discharge effects that reduce the capacity and operating life of batteries				•
• Reduce costs of battery packs	•••	••		
• Increase the temperature operating range of batteries	•••	••		
• Decrease charging time	••	••		

• Li ion • Na-ion • Redox flow • Metal-air • ZSM • Li-air, Li-S • Hybrid (supercapacitors)

Table 6: Main materials related challenges to be addressed

Identifier	Call Title	Type
B1S	Na-ion stationary batteries for domestic applications (5-10kW, 4>P/E>1/3)	RIA
B2S	Li-ion stationary batteries for domestic applications (5-10kW, 4>P/E>1/3)	RIA
B3S	Redox flow stationary batteries for utility scale applications (>100MW, P/E<1/3)	RIA
B4S	Metal-air stationary batteries for utility scale applications (>100MW, P/E<1/3)	RIA
B5S	Li-ion stationary batteries for commercial applications (<100MW, P/E>4)	RIA
B6S	Li-ion stationary batteries for utility scale applications (>100MW, P/E<1/3)	RIA
B1M	Li-ion generation 3b batteries for high voltage mobility applications	RIA
B2M	Li-ion generation 3b batteries for high capacity mobility applications	RIA
B3M	Li-ion generation 4a batteries (solid state with conventional materials) for mobility applications	RIA
B4M	Li-ion generation 4b batteries (solid state with Li metal-based anode) for mobility applications	RIA
B5M	Li-ion generation 4c batteries (Li-metal and high voltage systems) for mobility applications	RIA
B6M	Next generation 5 batteries for mobility applications (e.g. Li Air, Li S)	RIA
B7M	Zero Strain Material (ZSM) batteries (e.g. TiO_2) for high power mobility applications (trains, marine, buses)	RIA
B8M	Next generation Hybrid Supercapacitors for Power mobility applications	RIA
B9M	Advanced materials for the reduction of EV weight in battery packaging, drivetrain and car body	RIA
B10M	Advanced Material technology and system solutions enabling user friendly and reliable ultra-fast charging stations (350 kW) for EVs	RIA
B11M	Solid state technology 4b generation – Realization of processing and upscaling	IA

Table 7: Suggested materials related calls for battery technologies

Proposed R&D Topics

Table 7 above summarises the suggested calls to be included in the Horizon Europe framework program, based on the challenges identified above.

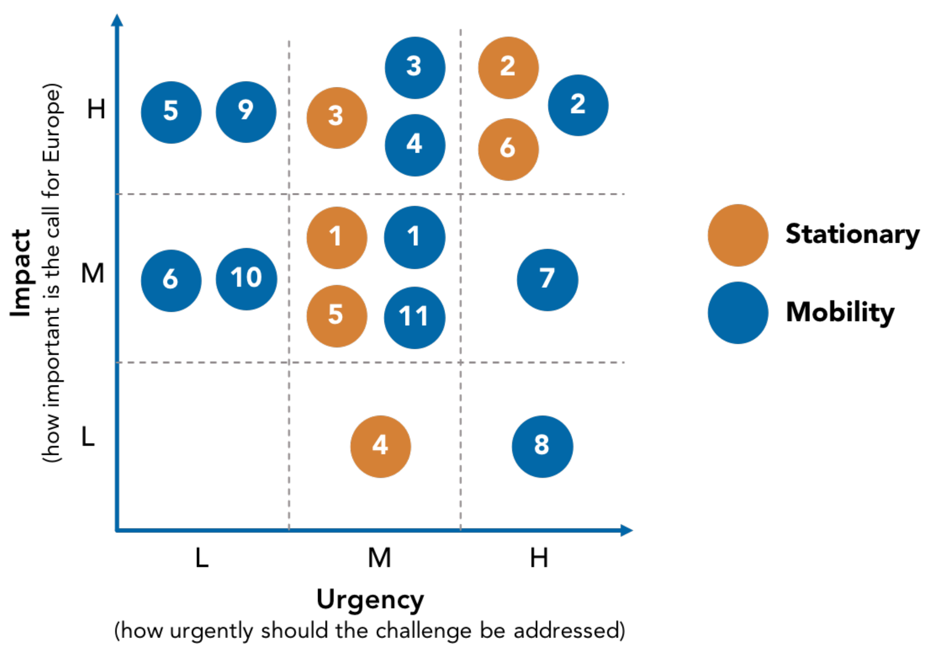

Figure 26: Prioritisation of battery calls

2

HYDROGEN FOR MOBILITY (FUEL CELLS)

2. Hydrogen for Mobility (fuel cells)

Similar to batteries, fuel cells convert chemical energy to electrical energy by means of an electrochemical reaction that takes place between an electrolyte and two electrodes. In a battery, the electrodes are fixed – therefore the battery can only hold a finite amount of energy (its charge). Fuel cells are different. As long as fuel and oxidant flow through the cell, FCs can continuously supply energy. A variety of fuels can be used, including hydrogen, natural gas, and biogas. Hydrogen-powered FCs are at least twice as efficient as traditional combustion technologies and only emit heat and water as waste.

Although FCs cannot yet fully compete with traditional energy technologies, ongoing research is being focused on identifying and developing new materials for reducing cost and increasing durability. Given their modular nature, FCs can be used for mobility and stationary purposes, in almost any application that typically uses batteries or an ICE. Future applications will include systems in which energy converters could be running on hydrogen (e.g. ICE, Stirling engines, and turbines) as well as other energy carriers (e.g. direct heat and electricity from renewable energy, and bio-fuels for transport)[36].

In 2018, global FC shipments for the mobility sector increased from 436 to 563 MWs (dominated by passenger cars), whilst the stationary sector increased from 222 MWs to 240 MWs[37]. Mainly driven by the pursuit of alternative clean energy sources, the fuel cell market at a global scale reached a value of USD 3.2 billion in 2016 (about €2.8 billion). For the 2018- 2025 period, it is projected to grow at an estimated CAGR of 21%[38].

In terms of the main players, the United States, Japan, Korea, Germany, and increasingly China are strongly supporting the implementation and deployment of hydrogen and FC technologies.

"IN 2018, GLOBAL FC SHIPMENTS FOR THE MOBILITY SECTOR INCREASED FROM 436 TO 563 MW (DOMINATED BY PASSENGER CARS), WHILST THE STATIONARY SECTOR INCREASED FROM 222 MWS TO 240 MW"

[36] European Commission, Hydrogen energy and fuel cells, A vision for our future, 2003

[37] E4tech, The Fuel Cell Industry Review 2018, December 2018

[38] Fuel cell market size, share & trends analysis report by product (PEMFC, PAFC, SOFC, MCFC), by application (stationary, transportation, portable), by region, and segment forecasts, 2018 – 2025.

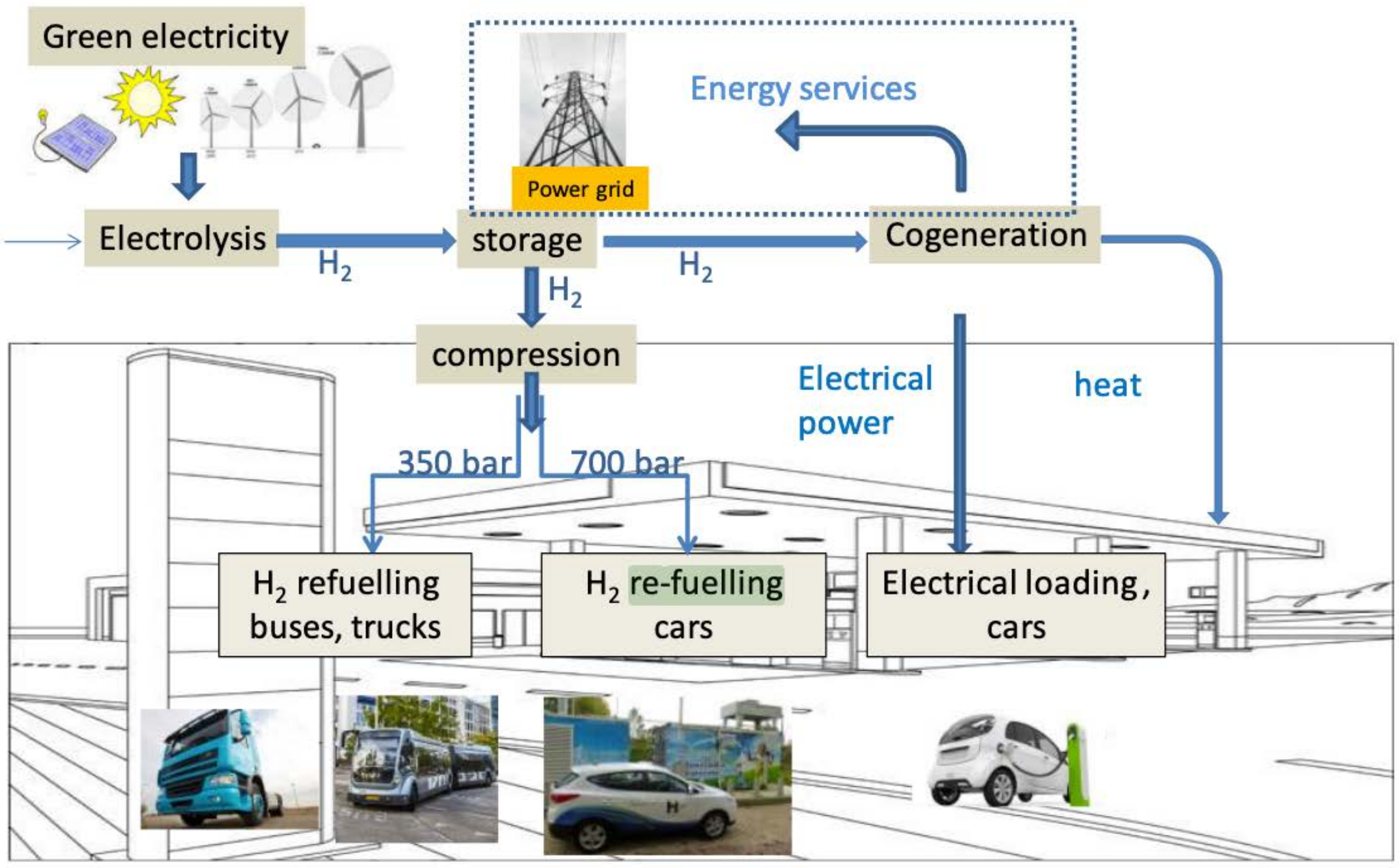

Figure 27: Production of hydrogen from electrolysis and use in mobility applications (source: Power to gas Roadmap for Flanders report[39])

Mobility Applications

Mobility represents the most promising application for hydrogen-powered FCs. Hydrogen from the electrolysis of water can be generated either locally (decentralised) using electricity from the grid or by means of renewable sources (Figure 27). The hydrogen is then buffered to match the varying refuelling schedule to customers. Fuel cell electric vehicles powered by hydrogen are commercially available now, while more models will become available in the next five years in medium-sized and large cars, buses, trucks, vans, and trains. Compared to BEVs, FCEVs will attain longer ranges and faster refuelling times, especially for heavily-used vehicles[38]. However, their energy efficiency is lower than that of BEVs (about 40% -50% from well-to-wheel if produced through electricity)[38].

Aiming at contributing to low carbon mobility, Hydrogen Europe aims at reaching 5 million FCEVs by 2030, while the Hydrogen Council has much more ambitious targets of reaching 10- 15 million FCEVs by the same year.

[39] Power to gas – Roadmap for Flanders report, 2016
[40] 4th Energy Wave, The fuel cell and hydrogen annual review, 2017
[41] Transport & Environment, 2017

Technology Overview

The basic configuration of a fuel cell is shown in Figure 29.

The reactions that produce electricity take place at the two electrodes, (positive cathode and negative anode), accelerated by a catalyst. While electrons flow through the externally connected circuit, the produced charged ions are transported from one electrode to the other through the electrolyte. In all types of FCs, individual cells are connected electrically in series (in an FC-stack) to achieve higher voltage and power.

The core elements of FCEVs are the FC configuration and the tank for storing hydrogen, as it is shown in Figure 29 for the hierarchy considered within the roadmap.
In vehicles, hydrogen can be stored directly as compressed gas, as cryogenic liquid or in solid state absorbed e.g. in metal hydrides. Alternative the storage can involve chemical bonding, e.g. liquid organic hydrogen carriers (LOHC), solid chemical hydrides or liquid fuels which are subjected to reforming.

There are different types of FCs, classified according to the electrolyte employed. Six main fuel cell types are currently available in the market:
- Polymer electrolyte membrane – also called proton exchange membrane (PEM)
- Alkaline fuel cells (AFCs)
- Phosphoric acid fuel cells (PAFCs)
- Molten carbonate fuel cells (MCFC)
- Solid oxide fuel cells (SOFCs)

PEM and SOFC are the most promising technologies, with the former being the preferred option for mobility while the latter is typically preferred for stationary applications.

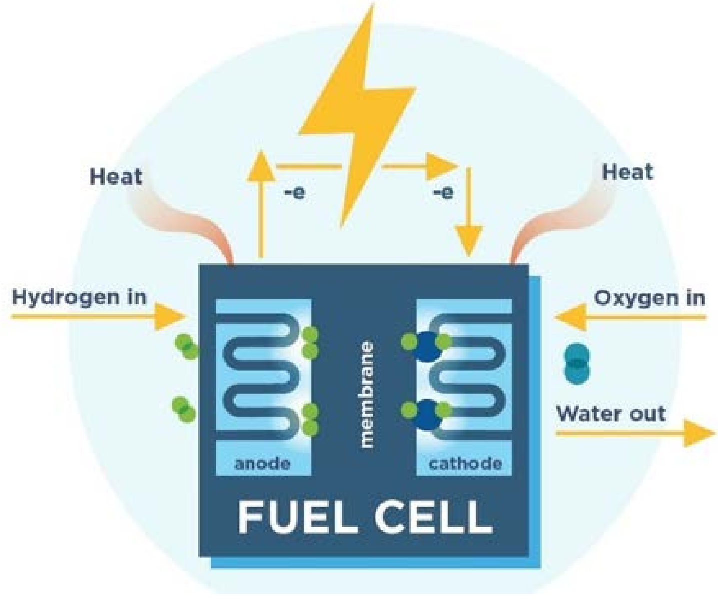

Figure 28: Basic configuration of a fuel cell (source: Fuel Cell & Hydrogen Energy Association[42])

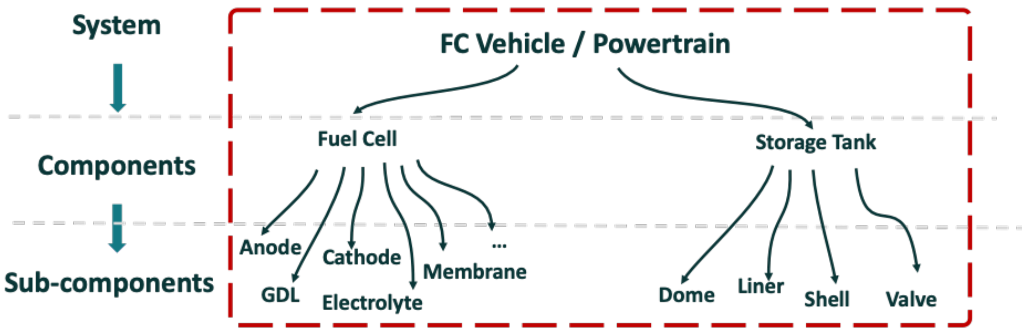

Figure 29: Component hierarchy of the electricity-generating system of FCEVs (source: Bax & Company)

[42] Fuel Cell & Hydrogen Energy Association (FCHEA), Fuel cell basics

Polymer Electrolyte Membrane (PEM)

The basic scheme of a PEM fuel cell is shown in Figure 30. The supplied hydrogen fuel enters the anode while ambient air containing oxygen is channelled through the cathode. At the anode, the platinum catalyst causes the hydrogen to split into protons (H+) and negatively charged electrons (e-). The protons pass through the (electrolyte) membrane into the cathode while electrons create an electrical current in an external circuit. At the cathode, oxygen is reduced and combined with the protons to produce water, which flows out of the cell.

A PEM fuel cell is characterized by a polymeric membrane acting as the electrolyte for proton conduction (notably sulfonated polymers such as the commercially available NafionÒ) and platinum-based materials (e.g. Pt-Co, Pt-Ni) as catalysts supporting the carbon electrodes.

Two types of PEM fuel cells exist[43] classified according to their operating temperature, in low and high. High temperature (HT) PEM (>120°C) technology has lower maturity than the more conventional low temperature (LT) PEM (60-95°C) range technology. A variety of PEM uses an anion exchange membrane (AEM) as electrolyte (AEMFC). These FCs strive to combine the advantages of classic alkaline fuel cells (e.g. possibility to use lower cost metals as the catalyst) with the advantages of PEMFC (e.g. high-power density and the all solid configuration avoiding electrolyte leakages). However, AEMFC technology is even less mature than HT- PEMFC. Although PEM-FCs are currently the preferred option of major OEMs, their commercialisation still faces several challenges, including cost reduction, improving performance and increasing durability[44].

Solid Oxide Fuel Cells (SOFC)

The basic functioning of this type of fuel cell is shown in Figure 31.

In this case, negatively charged oxygen ions (O2-) are the mobile species, which are produced when oxygen from the air gets reduced and ionized at the cathode by taking electrons from the circuit. In SOFCs, the two porous electrodes are separated by a dense, oxide ion conducting electrolyte, which gives the name for this type of FC. The solid electrolyte is typically a ceramic such as zirconium oxide stabilised with yttrium oxide (YSZ). Unlike PEM fuel cells, SOFCs require a high tem-

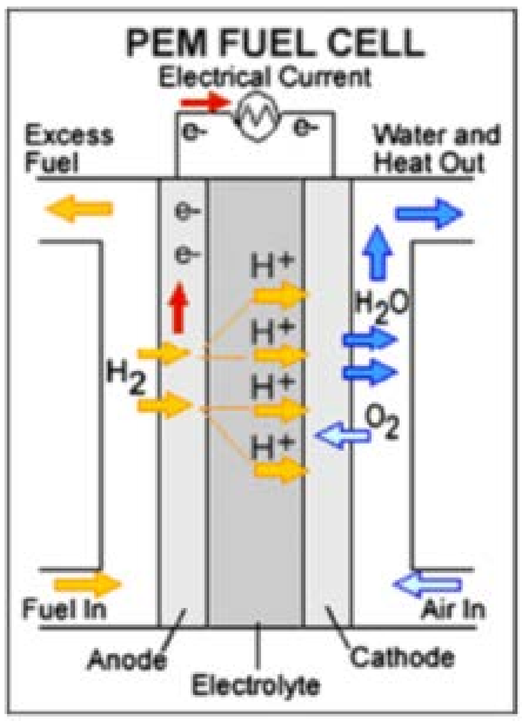

Figure 30: Schematic of a PEM fuel cell[44]

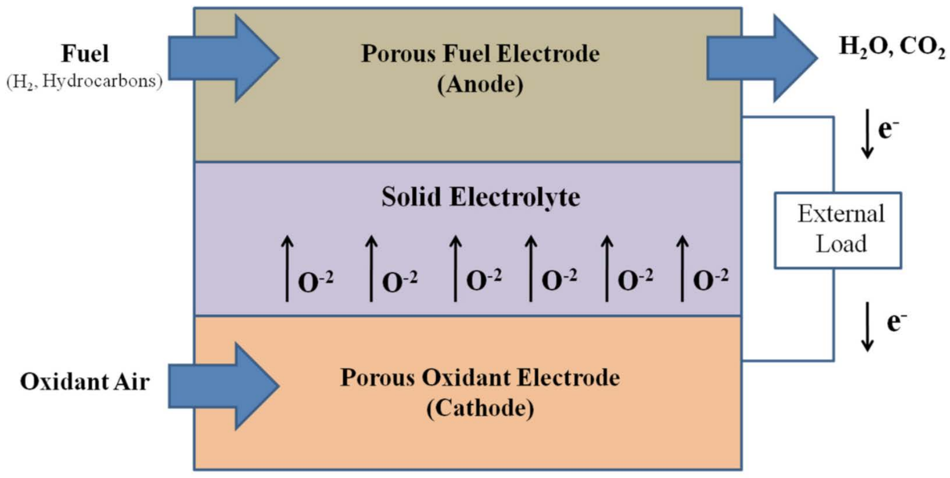

Figure 31: Schematic of a SOFC (source: Irshad et al., 2016[45])

[43] depending on the literature, one can find more definitions (medium, intermediate, very high temperature); in this roadmap we consider low temperature FCs that make use of either a PFSA or sulphonated hydrocarbon membrane that require water for being proton conductive, and high temperature FCs that make use of PBI/H3PO4 membrane, do not rely on water to maintain their conductivity, and are, in fact sensitive towards liquid water

[44] W.R.W. Daud; R.E.Rosli; E.H.Majlan; S.A.A.Hamid; R.Mohamed; T.Husaini. PEM fuel cell system control: A review, 2017

[45] Irshad, M. et al. A Brief Description of High Temperature Solid Oxide Fuel Cell's Operation, Materials, Design, Fabrication Technologies and Performance. Appl. Sci. 6, 75, 2016

perature range of operation in order to increase ionic conductivity in the solid media. This has a great impact on the materials which can be used with regards to the required lifetime. There are currently developments on Proton Conductive cells, allowing for operating temperatures of 500-600°C.

PEM vs SOFCs

The main features of PEM (low and high temperature range) and SOFC are presented in Table 8 while a comparative evaluation of their attributes is presented in Table 9.

Both PEM-FC and SOFC are the currently preferred technologies. Other technologies (i.e. AFC, PAFC, and MCFC) use corrosive materials and, in some cases, operate at high temperatures, a combination of factors that entails a significant risk during operation and handling.

The most important performance indicator for a fuel cell is its energy conversion efficiency; how much of the chemical energy contained in the fuel is transformed into electricity. Compared to traditional combustion processes, the energy conversion efficiency of all types of FCs is significantly higher. Among the different types of FCs considered, SOFCs might present the highest values, closely followed by LT-PEM. Although HT-PEM usually presents a lower efficiency range, harvesting energy from heat recovery results in a system with an efficiency similar to SOFC (Table 8). The working temperature range is the most important operational difference among both types of fuel cells, and it is directly related to efficiency. However, the cost and risks of degradation also increase with an increase in working temperature. Thus, there is a trade-off between temperature and performance, resulting in the grading assessment presented in Table 9. Furthermore, operating temperature significantly affects the heat exchange needs, i.e. the size of the radiators in the vehicles.

The materials used for the anode, cathode and electrolyte are key for the fuel cell performance. In both types of PEM-FCs, these elements are integrated into the membrane electrode assemblies (MEAs), which contains the catalyst layer. The amount of Pt contained in the catalyst is referred to as Pt-loading, which is usually expressed in mg per surface (mg/cm2), or g/kW. The MEA assemblies, electrodes, and in particular the catalyst can be affected by CO through what is known as

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COMPARED TO 47 TRADITIONAL COMBUSTION PROCESSES, THE ENERGY CONVERSION EFFICIENCY OF ALL TYPES OF FUEL CELLS IS SIGNIFICANTLY HIGHER"

[46] Haile, Sossina M. Materials for fuel cells. Materials Today, 2003
[47] XiaoJin Li, ChangChun Ke, ShuGuo Qu, Jin Li, ZhiGang Shao and BaoLian Yi, High Temperature PEM Fuel Cells Based on Nafion®/SiO2 Composite Membrane, September 2011
[48] Wang, Y., Chen, K. S., Mishler, J., Cho, S. C. & Adroher, X. C., A review of polymer electrolyte membrane fuel cells: Technology, applications, and needs on fundamental research, April 2011
[49] Neelima Mahato, Amitava Banerjee, Alka Gupta, S. O. K. B. Progress in material selection for solid oxide fuel cell technology: A review, January 2015

Type	Materials			Key Features			
	Anode	Electrolyte	Cathode	Temperature range (°C)	Efficiency (%)	Mobile ion	Type of fuel
Low temperature PEM	Pt supported on carbon	Sulfonated polymer	Pt supported on carbon	60-95	40-50	H^+	High purity H_2, methanol
High temperature PEM	Pt supported on carbon	Inorganic/organic composites; mineral acid	Pt supported on carbon	>120	35-40	H^+	H_2, some hydrocarbons
SOFC	Ceramic oxides (e.g. Ni, Cu, La)	YSZ (and others Zr, Ce, La oxides)	Ceramic oxides (e.g. La, Gd, Sr)	700-1000	45-60	O^{2-}	H_2, CO, CH_4

* small and medium scale (e.g. 50-250 kW for decentralized use or <10 kW for households)
** large scale (e.g. from 250 kW up to 20MW)

Table 8: PEM vs. SOFC performance (source: Haile, 2003[46]; Li et al, 2011[47]; Wang et al., 2011[48]; Mahato et al., 2015[49])

Type	Performance								Main Applications				
	Efficiency	Cost	Durability	Operability	Safety	Fuel versatility	Heat recovery	Stability	Passenger vehicles	Portable devices	Heavy duty vehicles	Back-up power	Power generation
LT-PEM	++	+++	+++	+++	+++	+	-	++*	•	•	•	•	
HT-PEM	+++**	++	++	++	++	++	++	+++	•	•	•	•	
SOFC	+++	++	+	+	+	+++	+++	+			•	•	•

* provided a water management system to keep the polymer electrolyte hydrated
** provided a heat recovery system

Table 9: Evaluation performance of PEM and SOFC.

"CO poisoning". Other elements such as gas diffusion layers (GDL), micro-porous layers, gas flow channels, cooling channels, bipolar plates, and interface are also important, although they might not be directly related to the electrochemical process.

In SOFCs, no precious metals are used as catalysts resulting in a lower cost. Since their weight, material characteristics (brittleness or ceramic materials) and operation at high temperatures impose constraints related to safety and handling, their use is practically limited to stationary applications of medium and large-scale power generation and distribution (e.g. from 250 kW up to 20 MW), some heavy off-highway vehicles and back-up generators (Table 9).

"THE MATERIALS USED FOR THE ANODE, CATHODE AND ELECTROLYTE ARE KEY FOR THE FUEL CELL PERFORMANCE"

A comparison of both types of technologies in terms of power output and temperature of operation is shown in Figure 32. Several commercially available products are presented and grouped per application, with the name of the manufacturer indicated as well. In some cases, the reading of the temperature scale should be taken with caution, as most of these products operate within a temperature range.

As can be seen, LT-PEM fuel cells are the main technology for mobility (and to extend portable) applications, being available for several products that are already in the market. This is not the case for HT-PEM, which is in very limited commercial use. Some commercial products for PEM can be also found for stationary applications (> 100 kW for power output), although this is the domain in which SOFCs finds the greatest applicability. Hence, having achieved a commercial status during the last years, both types of PEMs are the most promising technologies for FCEVs.

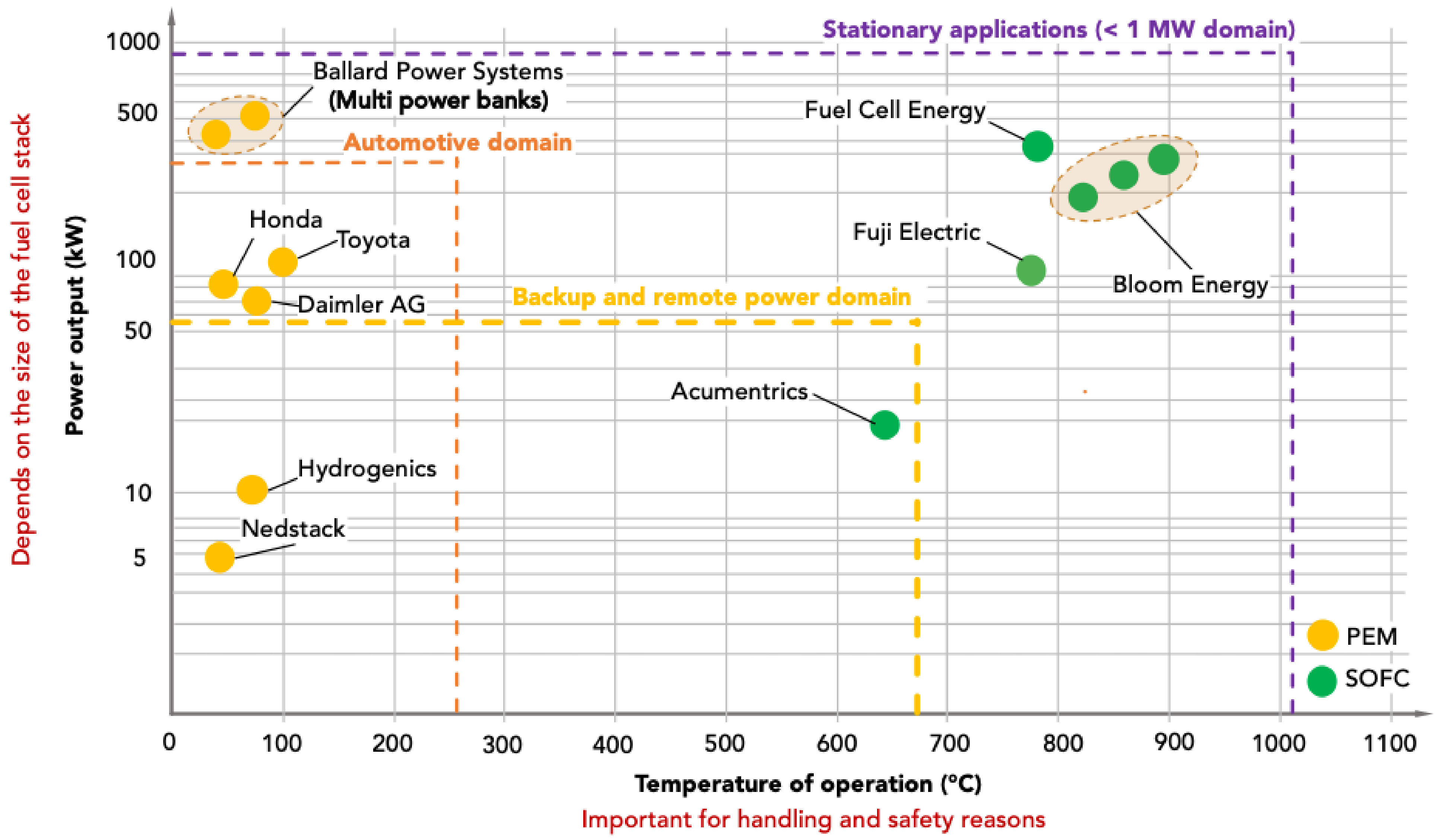


Figure 32: Power output vs. temperature of operation for several commercial PEM and SOFC (not exhaustive) (source: U.S. Department of Energy; Elcogen[50],[51])

[50] U.S. Dep. Energy, Curtin, S. & Gangi, J., Fuel Cell Technologies Market Report 2014, 2014 49 Elcogen, Solid Oxide Fuel Cells Opportunities for a clean energy future, 2017

[51] Elcogen, Solid Oxide Fuel Cells Opportunities for a clean energy future, 2017

Hydrogen storage

The main methods for hydrogen storage are reviewed in Figure 33.

Out of the methods available, the most common storage systems are high-pressure gas cylinders with a maximum pressure of about 700 bar for passenger vehicles and 350 bar for buses and heavy duty vehicles. The most used materials for storage tanks are made of high-strength composites, typically carbon fibre reinforced.

In order to evaluate storage efficiency, volumetric and gravimetric densities are used, which express the energy stored per volume and weight, respectively. Figure 34 shows the current status using both parameters for comparisons, as well as cost (USD/kg H_2).

To achieve the ultimate target, hydrogen storage technologies should be developed with the performance that could enable fuel cell products to be competitive with conventional technologies.

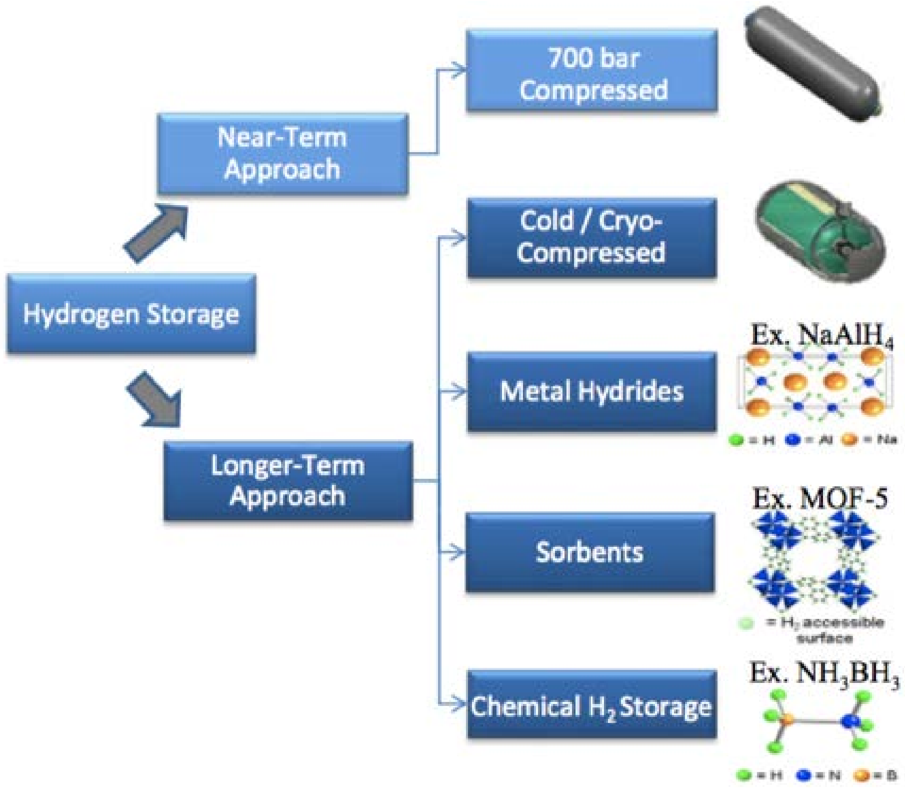


Figure 33: Hydrogen storage methods (source: U.S. Department of Energy[50])

Storage Targets	Gravimetric kWh/kg (kg H_2/kg system)	Volumetric kWh/L (kg H_2/L system)	Costs [1] \$/kWh (\$/kg H_2)
2020	1.5 (0.045)	1.0 (0.030)	\$10 (\$333)
2025	1.8 (0.055)	1.3 (0.040)	\$9 (\$300)
Ultimate	2.2 (0.065)	1.7 (0.050)	\$8 (\$266)
Current Status [2]			
700 bar compressed (5.6 kg H_2, Type IV, Single Tank)	1.4 (0.042)	0.8 (0.024)	\$15 (\$500)

Figure 34: Current status of hydrogen storage and targets for 2020, 2025, and beyond. (source: U.S. Department of Energy[52])

[52] Fuel Cell Technologies Office, Ned T. Stetson, Hydrogen Storage Program Area, June 2017

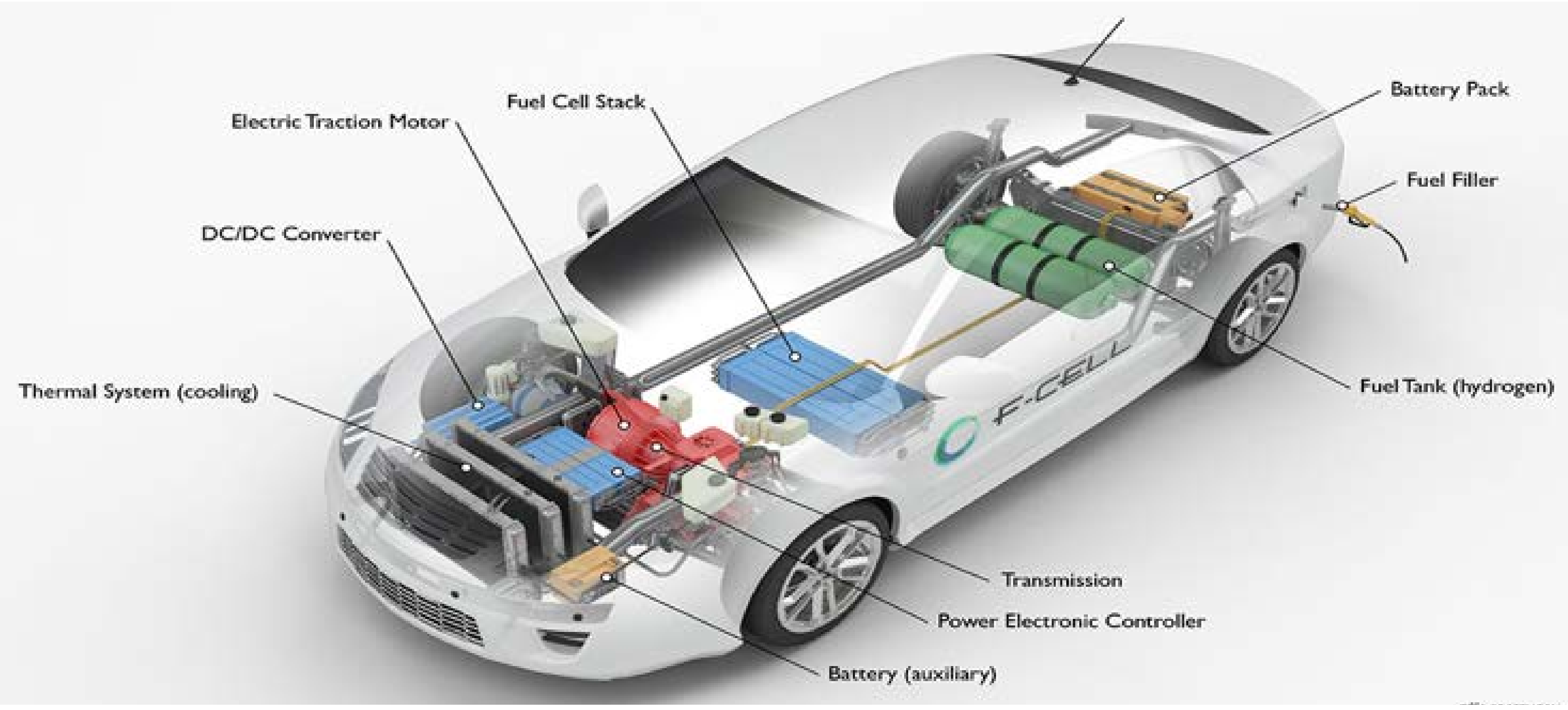


Figure 35: The elements of a FCEV (source: U.S. Department of Energy[54])

Fuel Cell Electric Vehicles (FCEVs)

A FCEV integrates several components, out of which the fuel cell stack accounts for about 45% (2015) of the total cost (Figure 31). The power capacity of a FC in a FCEV ranges from 80 to 120 kW, with a tank-to-wheel efficiency of 43-60%[53].

Figure 35: The elements of a FCEV (source: U.S. Department of Energy[54])

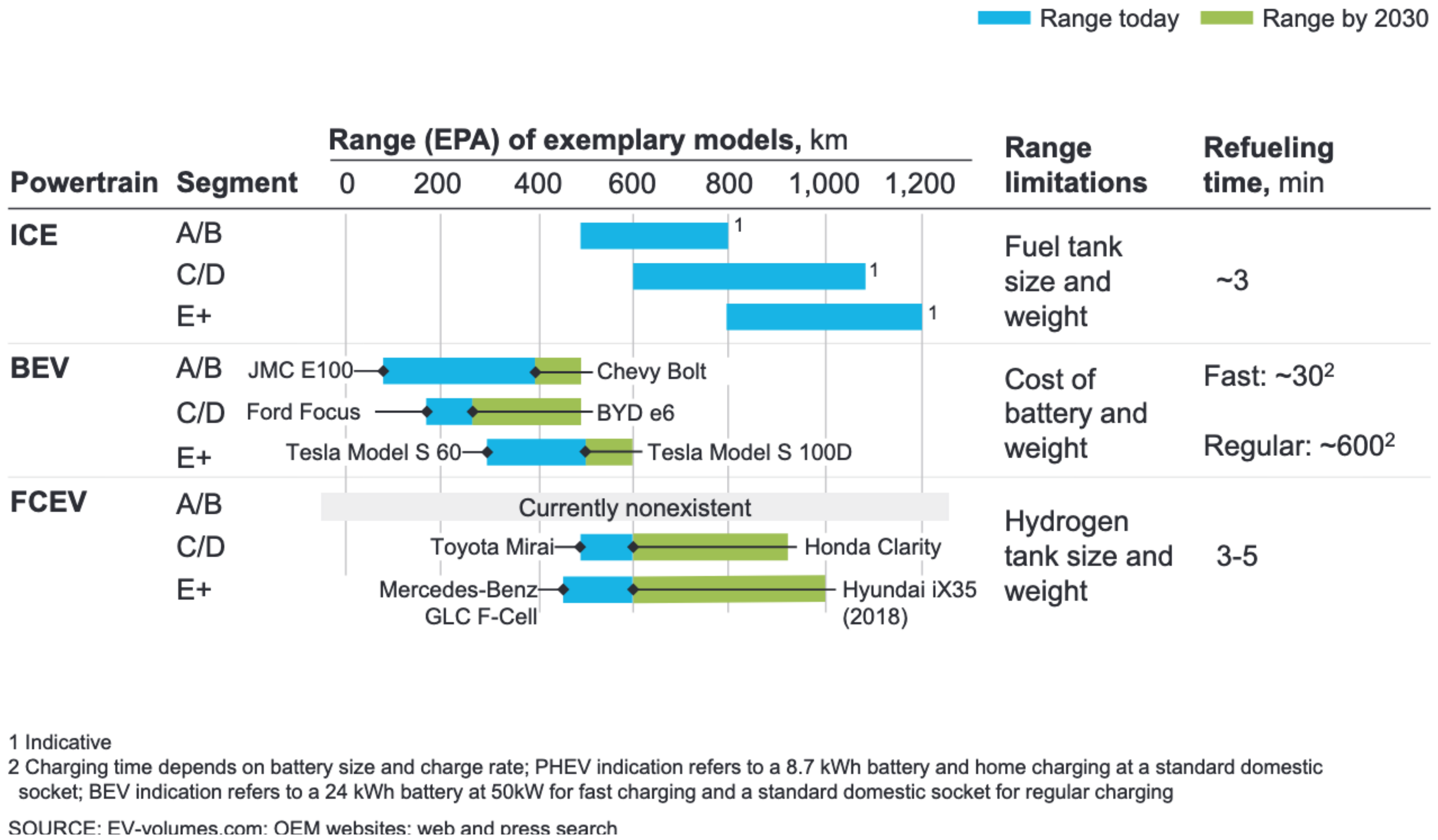
At first glance, the natural competitor of the FCEV is BEV. In reality, it is more likely that both technologies will complement each other in the future and will share the market[40]. Both types are typically compared in terms of driving range and refuelling times, as it is presented in Figure 36 for today and by 2030, where an ICE powertrain is included as well.

As one can see, FCEVs present superior driving range and faster refuelling times for medium to large size vehicles (C/D and E+ segments). However, FCEVs are currently more expensive, mainly due to low

> **"AT FIRST GLANCE, THE NATURAL COMPETITOR OF THE FCEV IS BEV. IN REALITY, IT IS MORE LIKELY THAT BOTH TECHNOLOGIES WILL COMPLEMENT EACH OTHER IN THE FUTURE AND WILL SHARE THE MARKET"**

[53] International Energy Agency, Technology Roadmap-Hydrogen and Fuel Cells

[54] Alternative fuels data center, How Do Fuel Cell Electric Vehicles Work Using Hydrogen?



production levels (100 – 1,000 units/year). Plans from Hyundai and Toyota to reach 30,000 units/year by 2020 and 100,000 units/year by 2025 respectively are expected to drive costs down significantly, although they would have to be coupled with the corresponding R&D investments to ensure performance and further cost reduction.

Cost structure

In order to be competitive with ICE vehicles, the cost of fuel cell systems per kW delivered should reach an ultimate target of $30/kW by 2030 (around €26/kW), shown in Figure 37. As one can see, FC projected cost has decreased by 52% from 2006 to 2010.

Figure 36: A comparison performance of FCEV, BEV and ICE (source: Hydrogen Council[55])

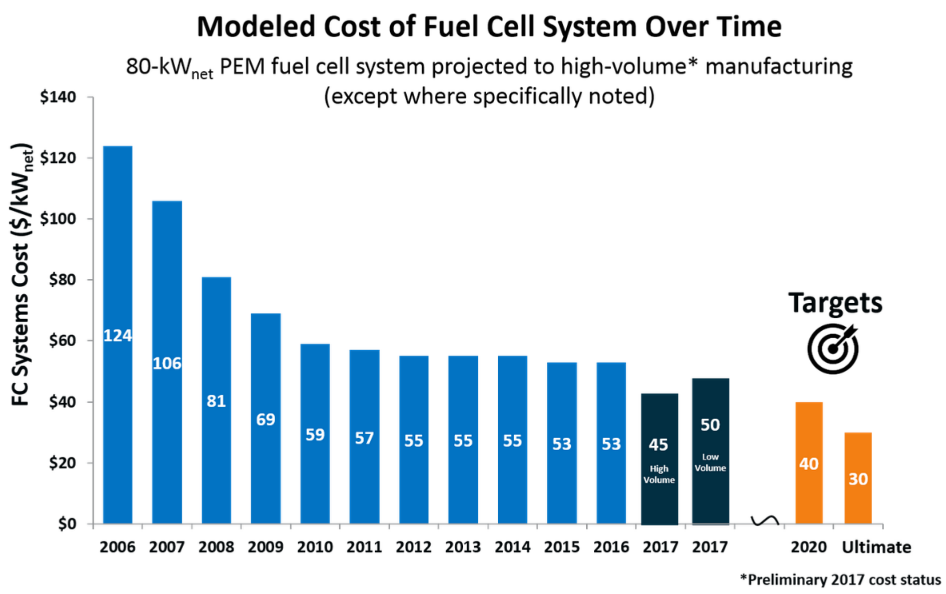


Figure 37: Modelled cost of fuel cell system over time for mobility applications by 2020 and 2030 (at high- volume production rates of 500,000 units per year) (source: U.S. Department of Energy)[56].

[55] Hydrogen Council, Hydrogen scaling up: A sustainable pathway for the global energy transition, November 2017

[56] Department of Energy, US, Fact of the Month April 2018: Fuel Cell Cost Decreased by 60% since 2006

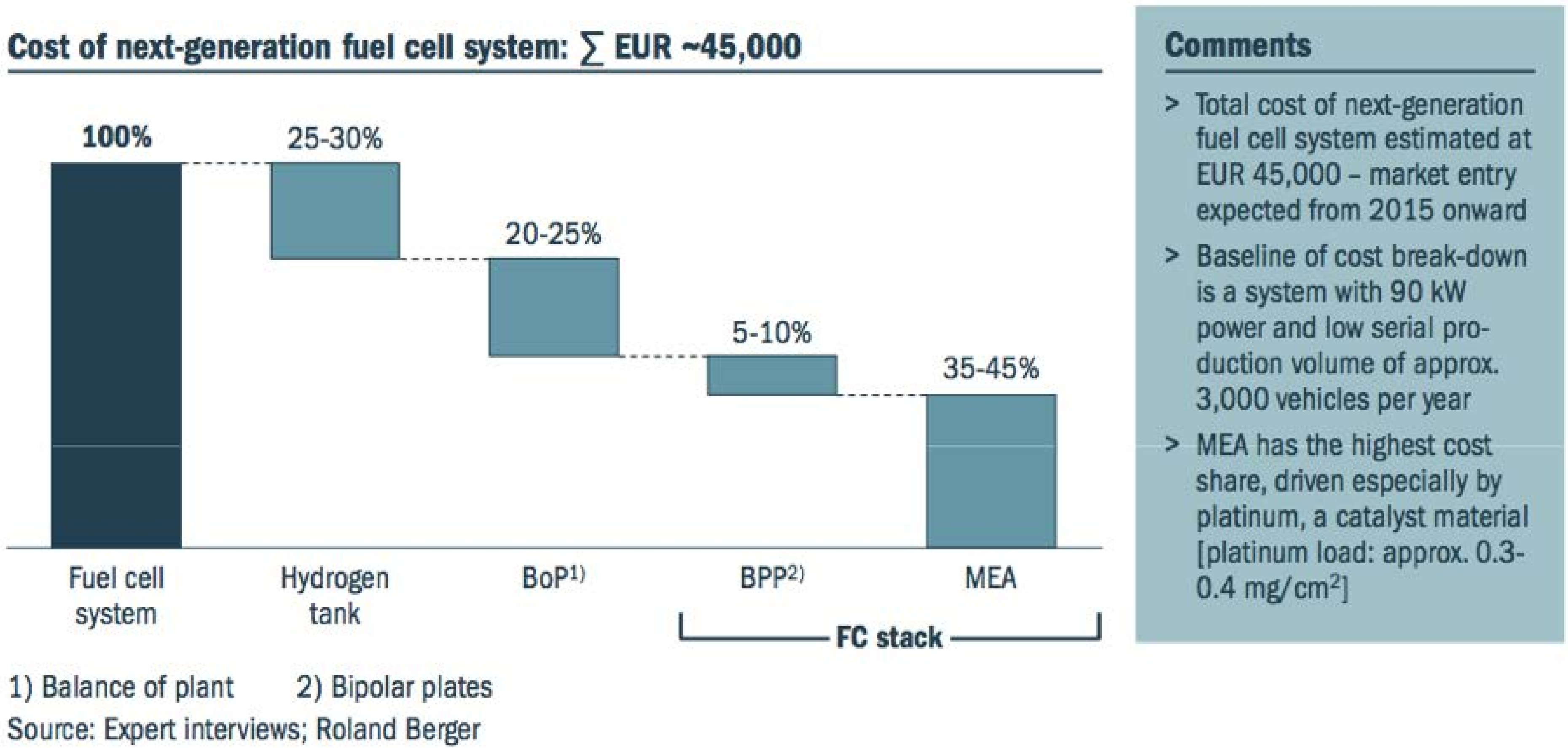


Figure 38: Breakdown of PEM fuel cell costs (source: Roland Berger[57])

Within the fuel cell system, the breakdown cost per component for PEM technology (e.g. for a system with an estimated cost of €45,000) used in FCEVs is shown in Figure 38. The fuel cell stack, especially the membrane electrode assembly (MEA), accounts for the highest share of the cost.

Materials are the dominant cost factor in MEAs, accounting for roughly 90% of overall costs (Figure 39). The most expensive element in the MEA is the catalyst layer, namely platinum.

A combination of improvements in stack operations, design and production technology may reduce MEA costs by 60%, down to roughly €3 per unit or €1,000 per vehicle[22]. In the case of SOFCs, the electrode-electrolyte assembly (EEA) is the most expensive element, accounting for about 50% of total cost[56]. Within EEAs, anode materials account for about 75-82% of the whole material cost because of their thickness. Their costs depend on the annual production volume, which is regarded to become constant at production levels higher than 325,000 EEA cells per year[57].

For hydrogen storage tanks at 700 bar and 500,000 units per year, the cost breakdown is dominated by composite materials and processing, as it is shown in Figure 40.

"IN THE CASE OF SOFCS, THE ELECTRODE-ELECTROLYTE ASSEMBLY (EEA) IS THE MOST EXPENSIVE ELEMENT, ACCOUNTING FOR ABOUT 50% OF TOTAL COST . WITHIN EEAS, ANODE MATERIALS ACCOUNT FOR ABOUT 75-82% OF THE WHOLE MATERIAL COST BECAUSE OF THEIR THICKNESS.

[57] Roland Berger, Fuel cells: a realistic alternative to zero emission, 2014

[58] Department of Energy, US, Fuel Cell System Cost -2016, September 2016

[59] Environmental Energy Technologies Division, A Total Cost of Ownership Model for Solid Oxide Fuel Cells in Combined Heat and Power and Power-Only Applications, December 2015

[60] Ned T. Stetson, Fuel Cell Technologies Office, Hydrogen Storage Program Area, June 2017

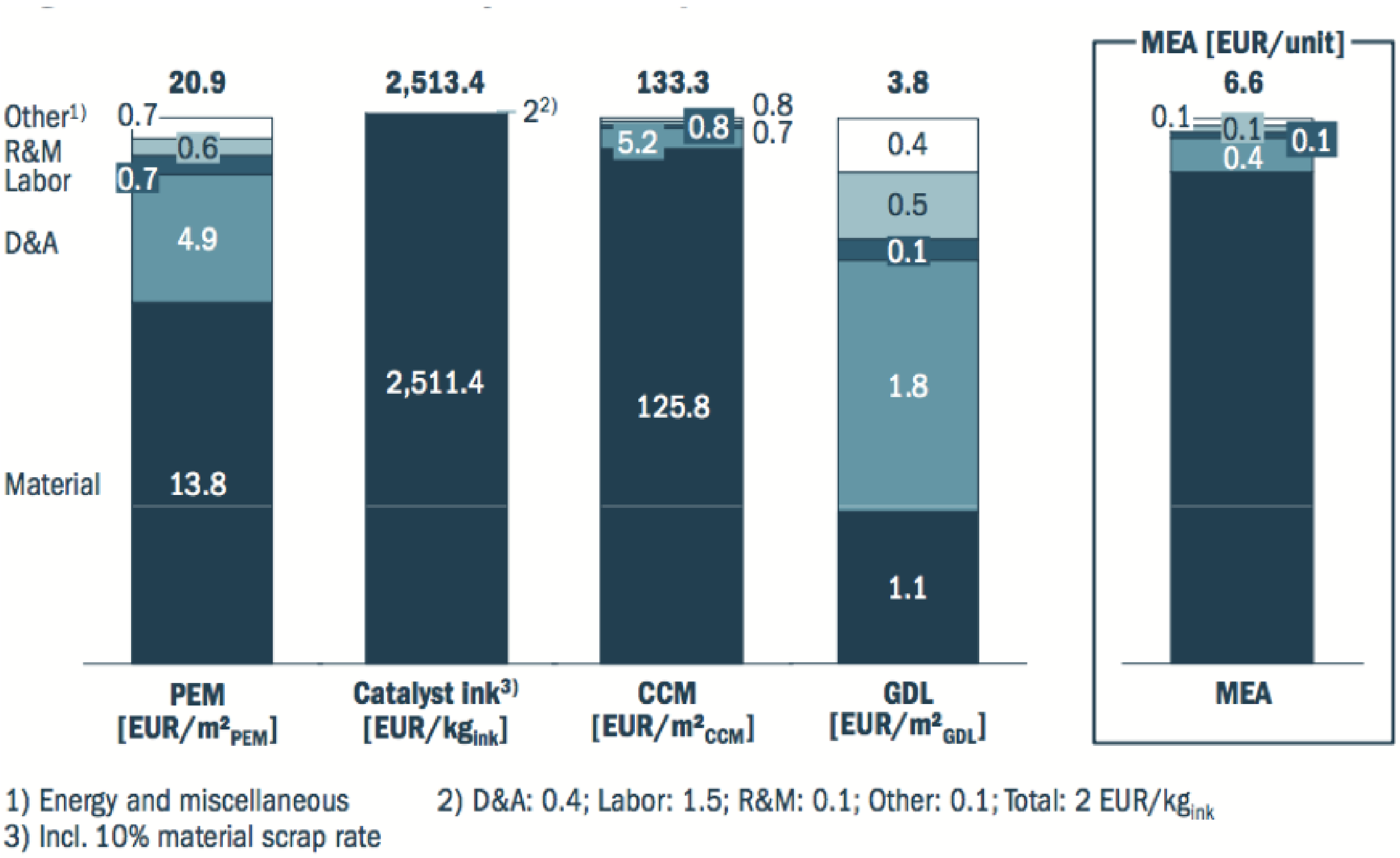


Figure 39:Cost structure by MEA component (source: Roland Berger[55])

Balance of Plant (BoP) costs and assembly (which includes all supporting components and auxiliary systems needed to deliver energy) are also major cost contributors, although their effect is reduced at economies of scale.

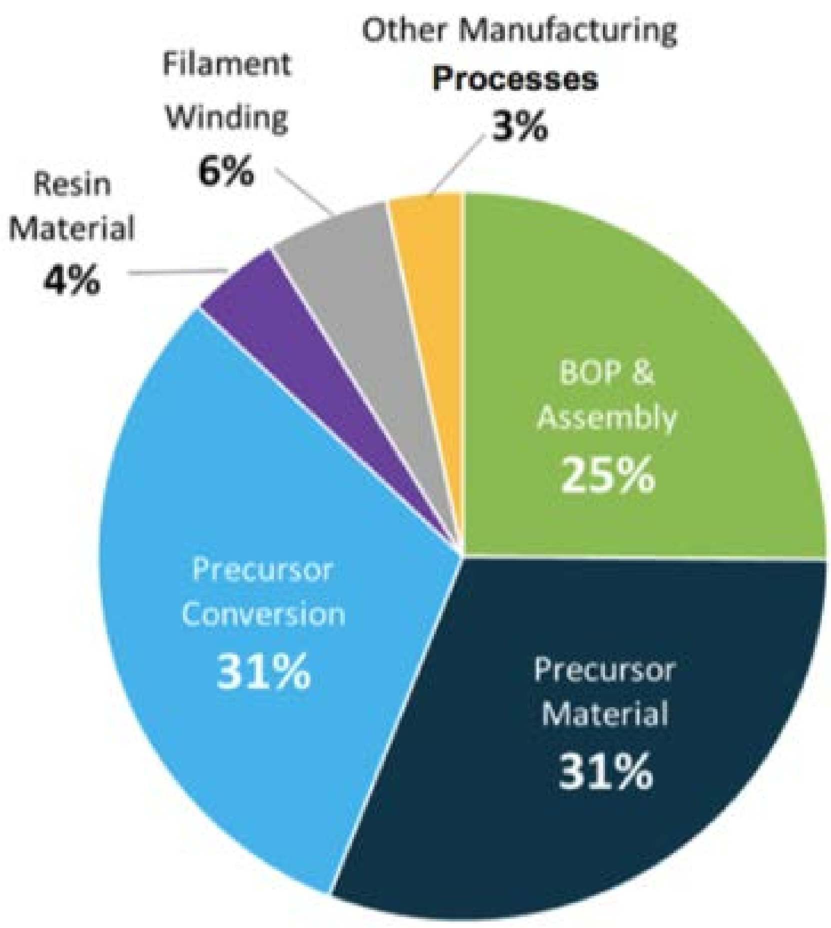


Figure 40: Cost breakdown for a hydrogen storage system at 700 bar (source: U.S. Department of Energy[60])

Market and Applications

At a global level, about 74,000 fuel cells, totalling over 800 MW, were shipped worldwide in 2018 for the three main types of applications: portable, transportation, and stationary (Figure 41)[37].

The use of FCs for transport applications has the highest share of units shipped, followed by stationary and portable systems respectively. The number of fuel cell systems increased slightly with respect to 2017, although the total MW grew significantly (Figure 42). This large increase occurred in the transportation sector, which can be attributed to the introduction and expansion of FC light-duty vehicles such as the inclusion of Honda's FCEV to the marketplace and other transportation applications such as buses and material handling.

For the number of fuel cell systems shipped during the last years, PEM fuel cell technologies have dominated the market, although SOFC has experienced a significant increase after 2015, as it can be seen in Figure 39. In 2018, more than 90% of the PEM megawatts went into transport.

Other FC technologies have negligible market share with low growth: PEM and SOFC are the two dominant technologies.

In Europe, the FC market was valued at $821 million in 2017[61]. It is expected to increase with 16% CAGR over the period of 2018-2026. The leading country in the European FC market is Germany, followed by the UK.

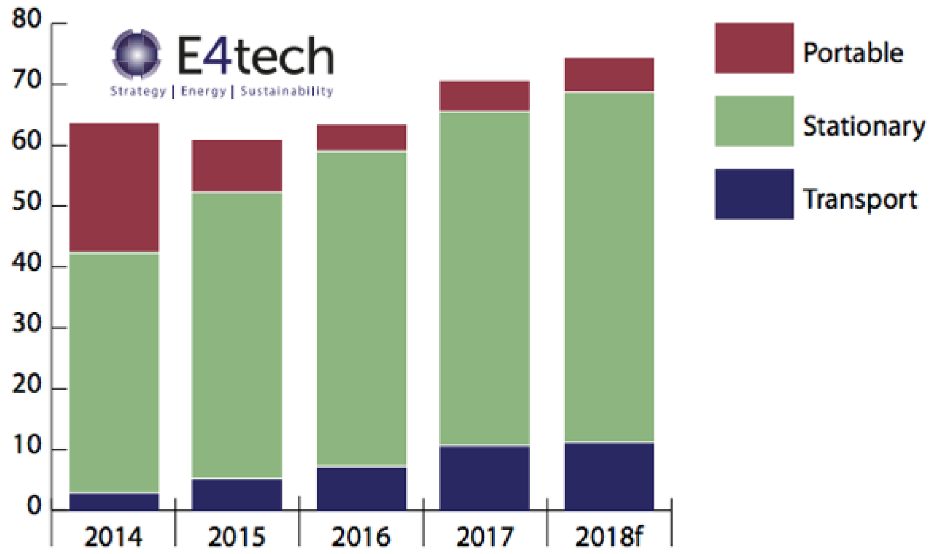


Figure 41: Fuel cell systems shipped worldwide (x 1,000 units) per type of application (source: E4Tech[37])

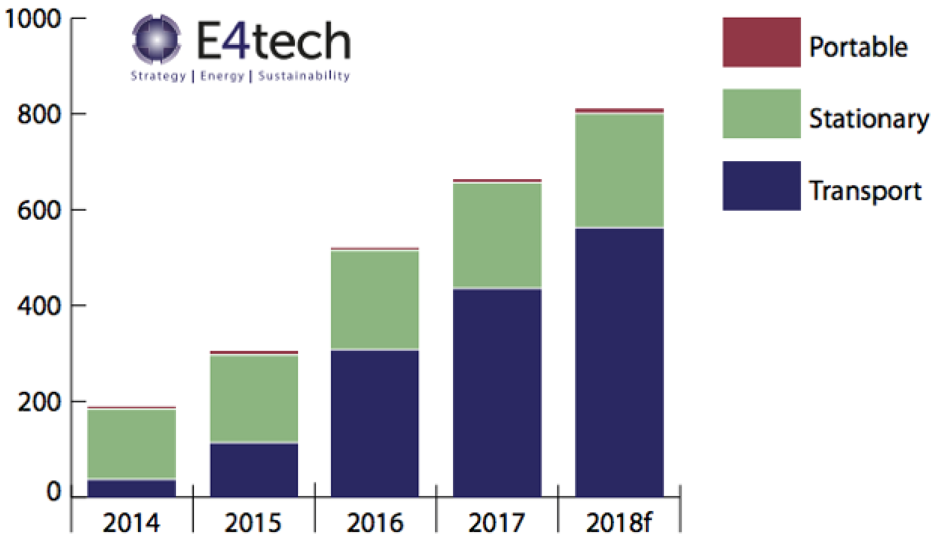


Figure 42: Megawatts of fuel cells shipped worldwide by application area (source: E4Tech[37])

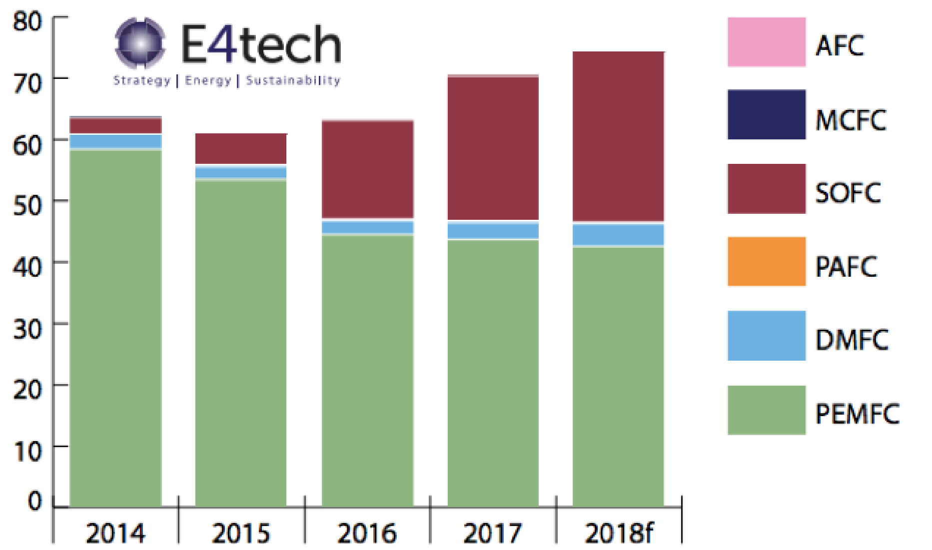


Figure 43: Shipments of fuel cell stacks per type of technology (source: E4Tech[59])

[61] INK Wood Research, Europe Fuel cell market forecast 2018-2026

Value chain and key players

Value chain and key players Regardless the applications, FCs can be considered conversion systems that are integrated within the entire hydrogen energy value chain (Figure 44).

Focusing on FC systems, the value chain is integrated by different actors, including knowledge-based entities (universities and research institutions), upstream supply chain actors (from advanced materials manufacturers to single FC and stack producers), product integration (FC systems) and FC vehicle integration (final users, such as OEMs, including testing and quality)[63]. A strong cross-cutting interaction among all actors usually takes place, and companies derive revenue from the sale of FCs and related equipment (such as hydrogen generators), support and maintenance contracts, and contract research and development with knowledge providers.

The manufacturers of FCs rely on material supply and fabrication of the components integrating a single FC and the stack as well. A FC stack that includes the BoP is assembled and further integrated before being shipped to final users (OEMs).

"IN EUROPE, THE FC MARKET WAS VALUED AT $821 MILLION IN 2017 . IT IS EXPECTED TO INCREASE WITH 16% CAGR OVER THE PERIOD OF 2018-2026"

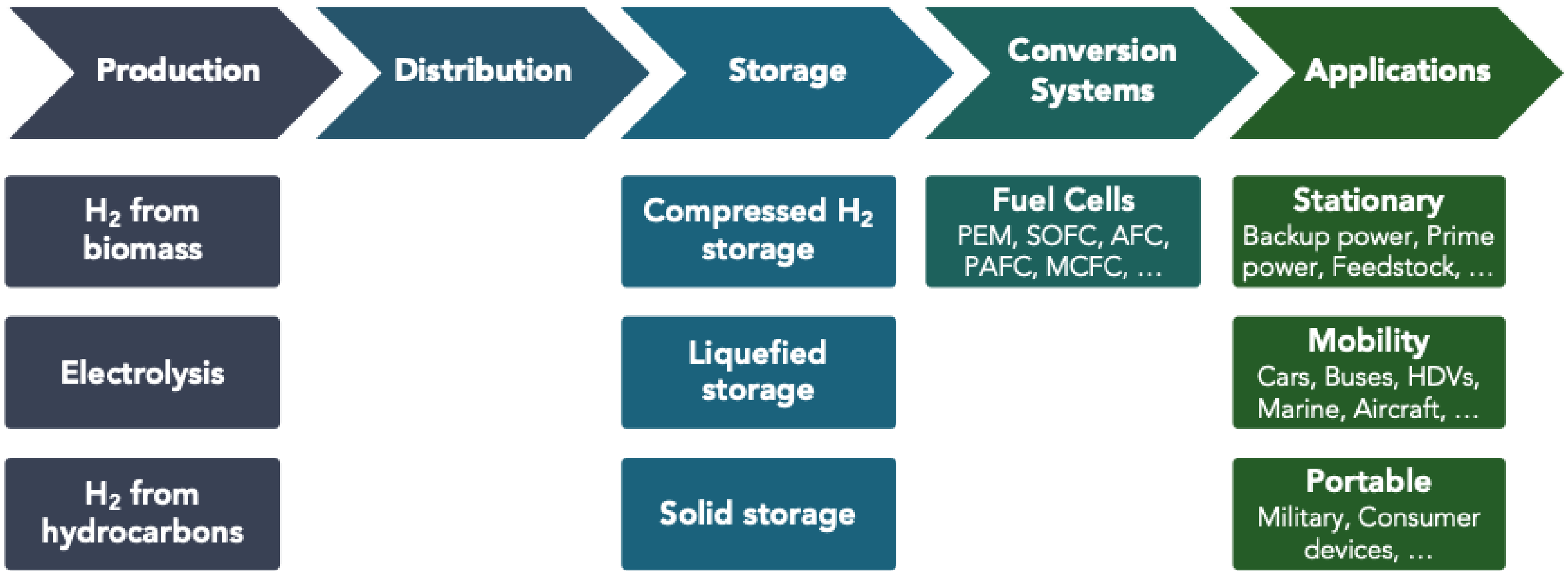


Figure 44: Entire value chain for hydrogen energy (source: Inferia Consulting[62], adapted by Bax & Company)

[62] Inferia Consulting, Hydrogen Energy and Fuel cells market research

[63] Fuel Cells and Hydrogen Joint Undertaking, Fuel Cell and Hydrogen Technology: Europe's Journey to A Greener World

Table 10 below presents a SWOT analysis for the European FC landscape.

Value Chain Step	Strengths	Weaknesses	Opportunities	Threats
Advanced Materials	• Europe has very highly educated researchers, especially in the fields of chemistry, materials science and energy systems, which has led to strong know-how and IP through a sound infrastructure network. • Effective cooperation between research and industry on catalysts. • Many companies are active in the field of advanced materials for FCs.	• There is a need for a more coordinated effort among material suppliers, Tier-1 suppliers and end users (OEMs).	• Support to SMEs and start-ups working on FC might be a very important driver of innovation. • Development of testing capabilities and quality control for the materials and components developed for the automotive sector. • Potential to radically decrease cost of FC through materials development and better understanding of material behaviour (that would lead to increase of performance and reliability and decrease of cost) • Increase recycling capacity to close the loop and decrease dependence of raw materials	• Catalyst material (platinum, ruthenium, iridium, Cobalt) dependence if no new catalyst formulations are developed without CRM and/or precious metals
Fuel Cell Manufacturing	• Europe has committed to supporting research, technological development and demonstration activities in FC and hydrogen energy technologies. • To date the European Union has committed more than € 1 billion to public–private partnership, and there have been matching contributions from industry and research • Successful model of cooperation and interconnection between European industrial companies, research organisations and public authorities. • The European public private partnership (PPP) structure is able to nurture a network of partners among SMEs.	• For many years, Europe had lagged behind the other regions in developing hydrogen fuel cells for mobility. • Lack of coordination between European and national or regional programmes. • Lack of a sound and green hydrogen infrastructure and comprehensive government policies. • Non-homogeneous legislative framework for hydrogen safety and applications.	• Large-scale storage of intermittent RES energy in the form of hydrogen facilitating automotive FC deployment • Less dependence on imported fossil fuels • Strategic technical alliance with North America or Japan for exchanging expertise and knowledge, especially for PEM.	• The market outside Europe, especially in Asia, is growing faster, which could overshadow European competitiveness and drive European companies out of business.
System integration and applications	• Strong know-how in electric drive systems, with a good sense of public awareness in EV's impact on the environment. • Tax exemptions on sustainable propulsion technologies in several European countries • Existing experience in heavy duty and commercial vehicles, trains and marine vessels • Refuelling infrastructure programmes (Scandinavia, UK, Germany, France, Belgium and the Netherlands) • Strong Hydrogen Refilling Stations (HRS) industry • Global Technical Regulation (UNECE R134) existing for FC vehicles	• Few European OEM commercialising FC passenger cars • Lack of sufficient hydrogen infrastructure	• Opportunity to decarbonise heavy duty mobility applications (trucks, buses, trains, …) • Strong European automotive OEMs and Tier 1 suppliers with large market shares worldwide	• Fast charging of BEVs and/or higher energy density batteries would decrease the need for FC passenger cars • Price of green decarbonised hydrogen staying too high to make TCO competitive with alternative powertrain technologies • Lack of regulation for compact hydrogen refuelling stations.

Table 10: SWOT analysis of fuel cells technologies for the European landscape (sources: Greater Rocher Enterprise[64],RTD info[65], E4Tech [66], TKI Nieuw Gas[67])

[64] Greater Rochester Enterprise, SWOT Analysis – Fuel Cells
[65] European Commission, SWOT in Energy Research
[66] E4tech and Element Energy, Hydrogen and Fuel Cells: Opportunities for Growth, November 2016 66 TKI New Gas, Outlines of a Hydrogen Roadmap
[67] TKI New Gas, Outlines of a Hydrogen Roadmap

Figure 45 below illustrates the steps of the value chain, along with the main players. European organisations are marked with a star Europe is strong in manufacturing of catalyst materials, single and fuel cell stacks, and final users (OEMs) and recycling. There is lacking capacity in several elements of the single fuel cell as well as the integration into systems.

The price of FCEVs is heavily influenced by the raw materials used as catalysts, namely platinum, cobalt, and nickel. Platinum is regarded as the best catalyst for PEM not only for its performance but also due to its stability over time. South African mines provide more than 70% of the worldwide supply[40]. As for cobalt, this is mainly produced as a by-product from copper and nickel mining, with the reserves being heavily centred in Democratic Republic of Congo and the refining capacity mostly located in China.

> **EUROPE IS STRONG IN MANUFACTURING OF CATALYST MATERIALS, SINGLE AND FUEL CELL STACKS, AND FINAL USERS (OEMS) AND RECYCLING.**

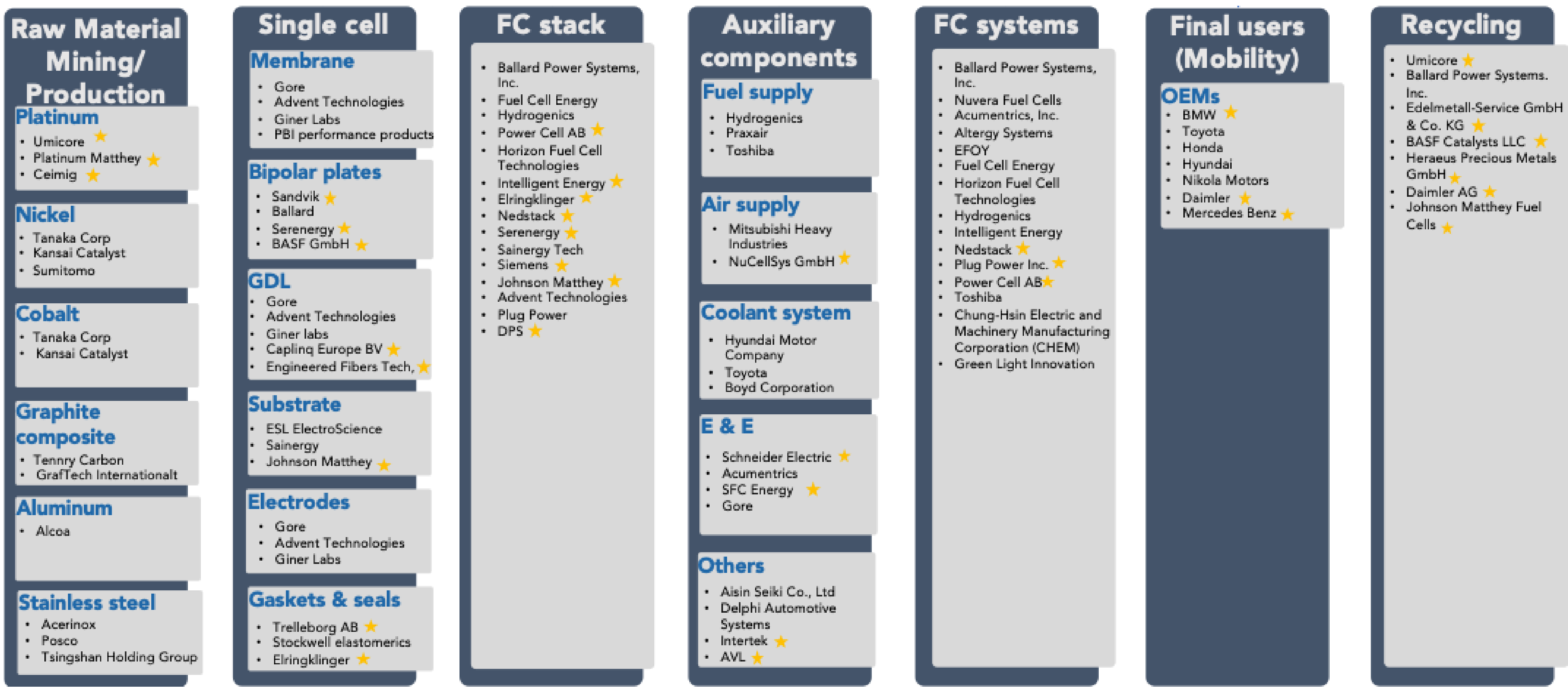


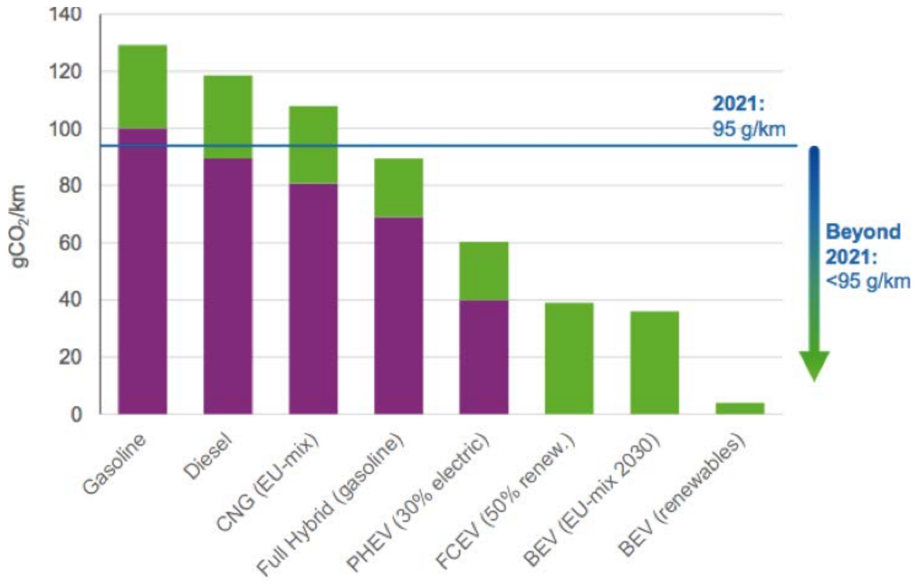
Figure 45: Fuel cell value chain and main players (non-exhaustive) (adapted by Bax & Company, sources: online web search, E4Tech, Wittstock et al. 2016, U.S. Department of Energy[50])

Main Trends

Due to their reduced GHG emissions, there is an increasing demand of FCs for mobility applications. FCEVs only emit water vapour. However, the source of hydrogen must be taken into account when estimating the well-to-wheel GHG emissions (Figure 46). Similar to BEVs, the energy mix used can significantly influence the emissions levels.

As one can see, BEVs have the lowest GHG emission levels, followed by hydrogen-powered FCEVs. FCEVs are a necessary complement to BEVs to achieve deep decarbonisation of the transportation sector. Both technologies enable the reduction of GHG emissions and at the same time, provides an opportunity for enhancing EU industrial competitiveness, create jobs and stimulate economic growth. However, until now, the number of BEV models in the pipe line for release between now and beyond 2020 far surpasses the number of FCEVs[40].

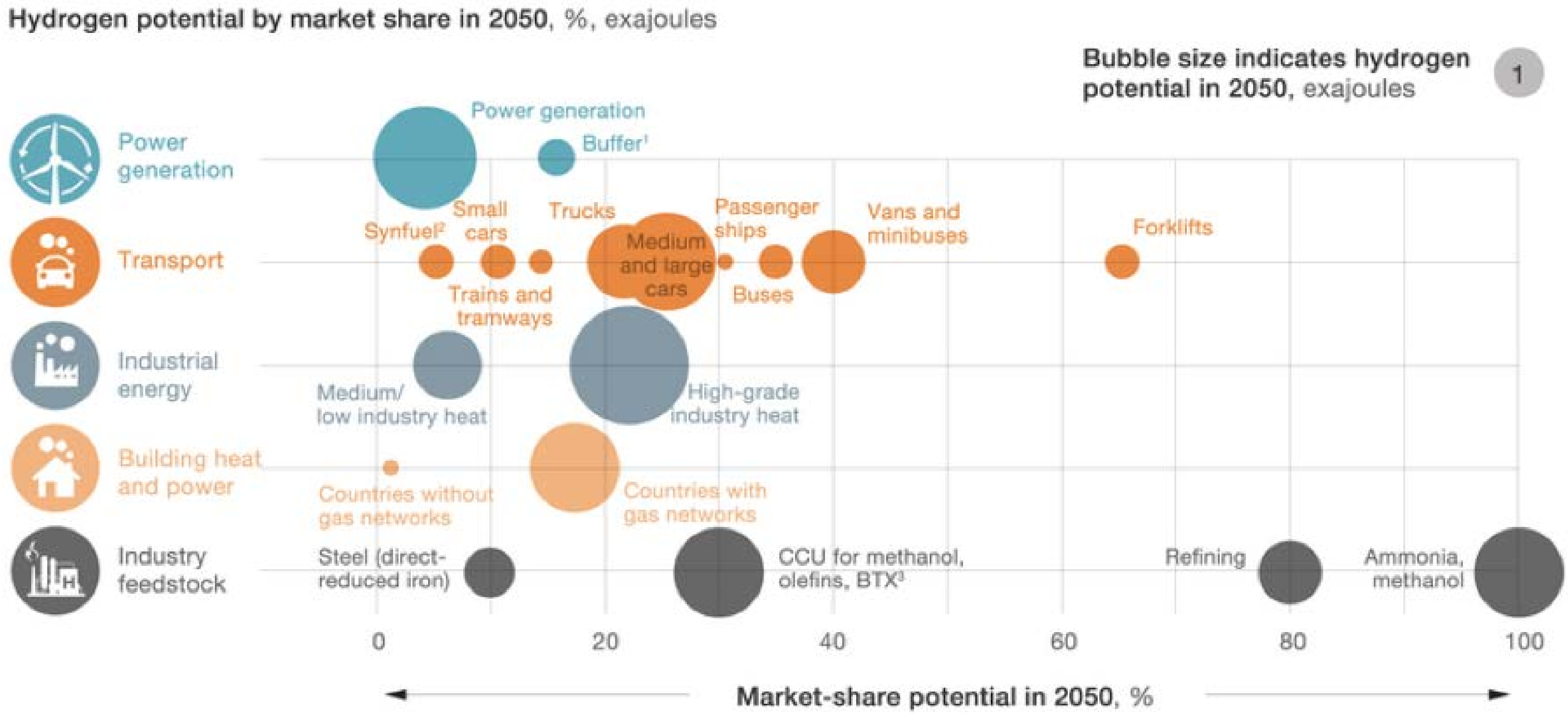
BEVs are, however, not suitable for the transportation segment of large vehicles with long range, mileage, and heavy payloads. Decarbonizing of all segments in transportation can only be possible through a scheme in which FCs are used for medium and large vehicles with long range, mileage, and heavy payloads (as it can be seen in Figure 47). By this scheme, in 2050, FCEVs could account for up to 20% of the total vehicle fleet.



Notes: Typical C-segment car
Sources: JEC Consortium, Roland Berger studt
and Umicore estimates

Figure 46: Well-to-wheel analysis GHG emissions for different technologies (source: Umicore)

"DECARBONIZING OF ALL SEGMENTS IN TRANSPORTATION CAN ONLY BE POSSIBLE THROUGH A SCHEME IN WHICH FCS ARE USED FOR MEDIUM AND LARGE VEHICLES WITH LONG RANGE, MILEAGE, AND HEAVY PAYLOADS"



For both BEVs and FCEVs, infrastructure aspects for supply and distribution remains one of the major challenges. In this aspect, a number of countries have developed hydrogen infrastructure plans, including Japan, Korea, the United States, and China. Major trends around the globe have been recognized for including FC modularization and serialisation, electrification of hydrogen FCEV powertrain (in contrast to a hybrid system), on-board hydrogen storage for multiple sources and FCEV's industry alliances and collaborations[68].

Notes:
[1] % of total annual growth in hydrogen and variable renewable-power demand.
[2] For aviation and freight ships.
[3] Carbon capture and utilization; % of total methanol, olefin, and benzene, toluene, and xylene (BTX) production using olefins and captured carbon.

Figure 47: Hydrogen potential by market share in 2050 (source: McKinsey & Company[68])

[68] McKinsey & Company, Hydrogen: The next wave for electric vehicles, November 2017
[69] Strategy Advisory Committee of the Technology Roadmap for Energy Saving and New Energy Vehicles, Hydrogen Fuel Cell Vehicle Technology Roadmap

Main challenges

Table 11 below summarises the main materials related challenges that need to be addressed for mobility applications within the next 10-15 years in order to increase Europe's competitiveness. The challenges were identified by the EMIRI community in workshops that took place throughout 2018 and 2019.

Challenge	Application: Mobility
• Reduce the purchasing and operating costs of H_2 systems by optimizing components' materials and manufacturing	●●●
• Improve performance and efficiency while decreasing weight of components	●●●
• Increase lifetime, cyclability and corrosion resistance to improve durability of systems	●●
• Enhance recyclability and circular design of components to improve sustainability	●●●

• Low temperature PEM • High temperature PEM • Storage and on-board tanks

Table 11: Main materials related challenges to be addressed.

Proposed R&D topics

Table 12 below summarises the suggested calls to be included in the Horizon Europe framework program, based on the challenges identified above.

Identifier	Call Title	Type
H1M	Improve durability, efficiency and cost through new materials for low temperature PEM FC (60-95°C)	RIA
H2M	New advanced materials for high temperature PEM FC (>120 °C)	RIA
H3M	Combination of advanced materials and industrialisation aspects for low TCO PEM FC system	IA
H4M	Advanced materials for on-board hydrogen storage tanks (including tanks for vehicles and for tanks for transportation of hydrogen)	RIA
H5M	Advanced materials for on-board H_2 generation	RIA

Table 12: Suggested materials related calls for hydrogen for mobility.

Figure 48 below illustrates the importance and urgency of each call.

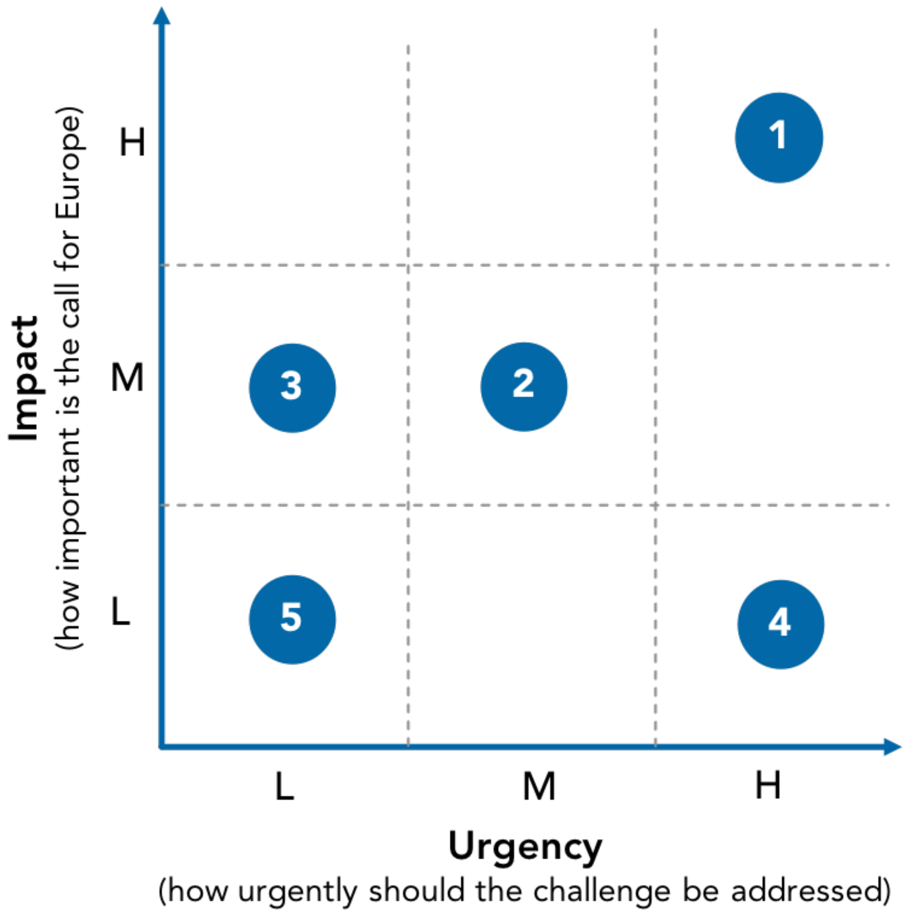
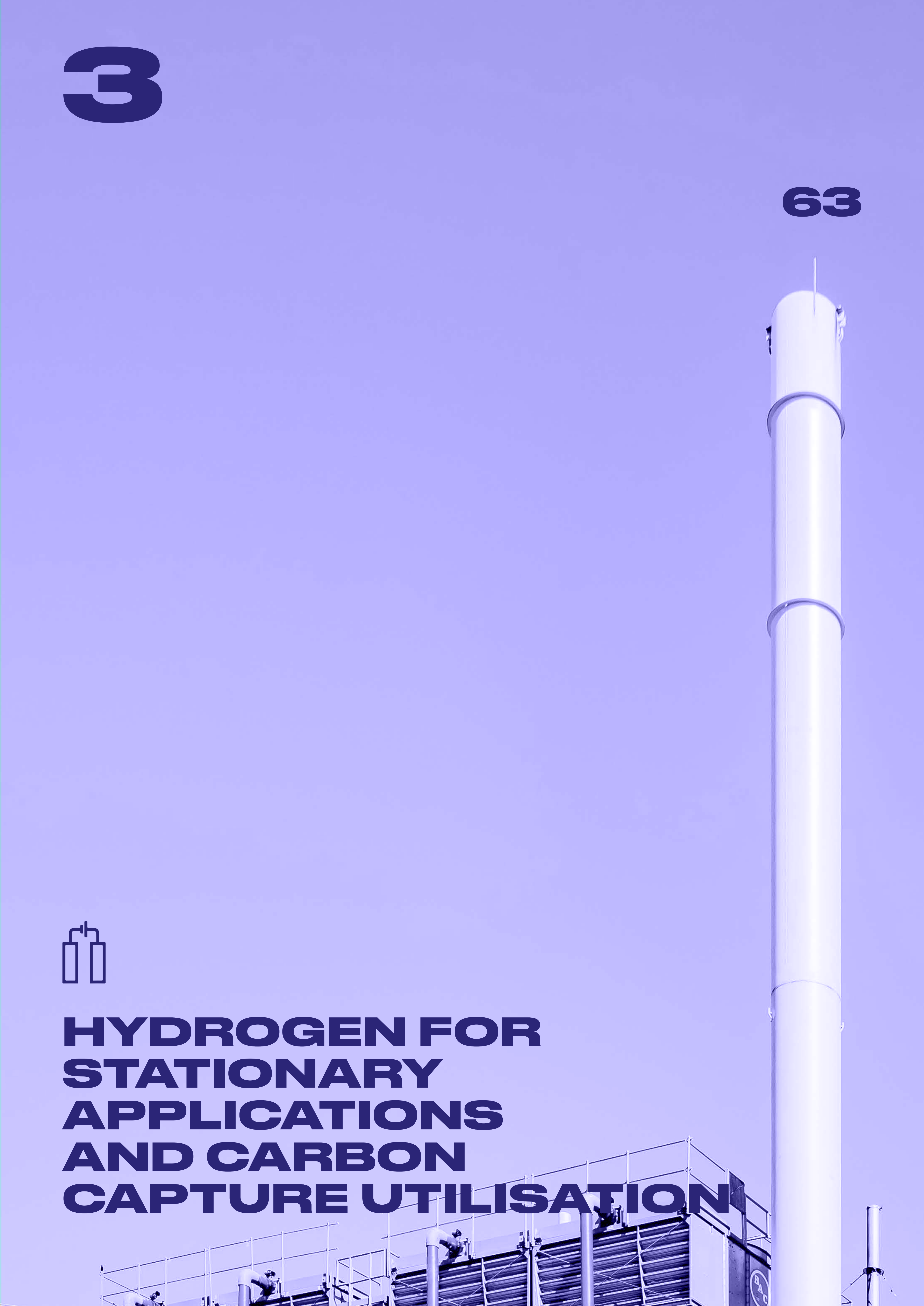


Figure 48: Prioritisation of hydrogen for mobility.



3

HYDROGEN FOR STATIONARY APPLICATIONS AND CARBON CAPTURE UTILISATION

3. Hydrogen for stationary applications and carbon capture utilisation

Nowadays, more than 55 Mt of hydrogen is produced every year by steam-methane reforming of natural gas (SMR). It is mostly used as a reactant for several processes in the chemical sector, namely ammonia production and hydrocracking and desulphurisation of fuels[70]. These applications account for 80% of global demand[71].

Since more than 95% of hydrogen sources are fossil fuels, significant amounts of CO_2 result from its production[71]. However, hydrogen can be produced from renewable electricity by means of an electrolyser and used as the energy carrier in a large range of applications.

After being produced, the chemical energy of hydrogen can be converted into other forms of energy by means of different routes, giving rise to the concept of power-to-X routes of valorisation. Hydrogen can be converted into electricity (power-to-power), transformed into methane and/or injected into the natural gas grid (power-to-gas), served as feedstock for the chemical sector (power-to-industry), converted to fuels – e.g. methanol (power-to-fuels) – or for mobility purposes (power-to-mobility), as mentioned in the chapter of hydrogen for mobility applications. Through these different approaches, hydrogen can enable the integration of large-scale renewables and into power generation, act as a buffer to increase system flexibility and help decarbonise all major sectors in the economy.

In industry and building sectors, hydrogen can be used together with captured carbon to replace fossil fuels as feedstock for several processes. This has opened a bright future for hydrogen and carbon capture and utilisation (CCU) in the renewable energy domain. The hydrogen generation market is expected to grow

"HYDROGEN CAN ENABLE THE INTEGRATION OF LARGE-SCALE RENEWABLES AND INTO POWER GENERATION, ACT AS A BUFFER TO INCREASE SYSTEM FLEXIBILITY AND HELP DECARBONISE ALL MAJOR SECTORS IN THE ECONOMY.

[70] Global Trends and Outlook for Hydrogen. IEA Hydrogen, December 2017.

[71] Hydrogen from Renewable Power, Technology outlook for the energy transition, IRENA, September 2018.

[72] "Global Carbon Capture, Utilisation, & Storage Technologies Market Analysis & Trends – Industry Forecast to 2025". Research & Markets, September 217.

to $155 billion in 2022[70], while that of CCU will do at a CAGR of 25% over the next decade, expected to reach more than $16 billion by 2025[72].
In the renewable energy domain, hydrogen can be used through FCs or directly for the generation of electricity through gas turbines. For stationary applications, it includes the use of fuel cells for primary power, backup power, or combined heat and power (CHP) in small/medium size plants. By this manner, the versatility of hydrogen as the energy carrier is compatible with production using RES (or other decarbonised electricity) through electrolysers while providing energy to sectors for decarbonisation[71].

Hydrogen Generation

As mentioned before, hydrogen is mostly produced from steam methane's reforming, a chemical process in which steam and methane react at high temperature and pressure for producing hydrogen and other hydrocarbons (e.g. syngas, carbon monoxide). Significant amounts of hydrogen are also produced by reforming of heavier hydrocarbons and coal gasification. To a much lesser extent, hydrogen is also produced via electrolysis of water using electrolysers. When renewable sources (wind, solar, biomass, hydro and geothermal) are used for providing the energy for electrolysis, the so-called green or renewable hydrogen is obtained. This allows for storing and recovering the excess of energy avoiding curtailment, enabling increasing amounts of intermittent renewable energy connected to electricity grids by balancing while also capturing renewable energy which is difficult to connect to the grid.
Electrolysers hold considerable potential for material innovation for reducing costs and improving efficiency, which would increase their use over conventional and less environmentally friendly methods.
Once generated, hydrogen can be used for heat and power stationary applications and as feedstock for several chemical processes. It can be converted into methane and other fuels through reactions with carbon dioxide captured from different sources (separation from combustion flue gases, biogas upgrading, etc).

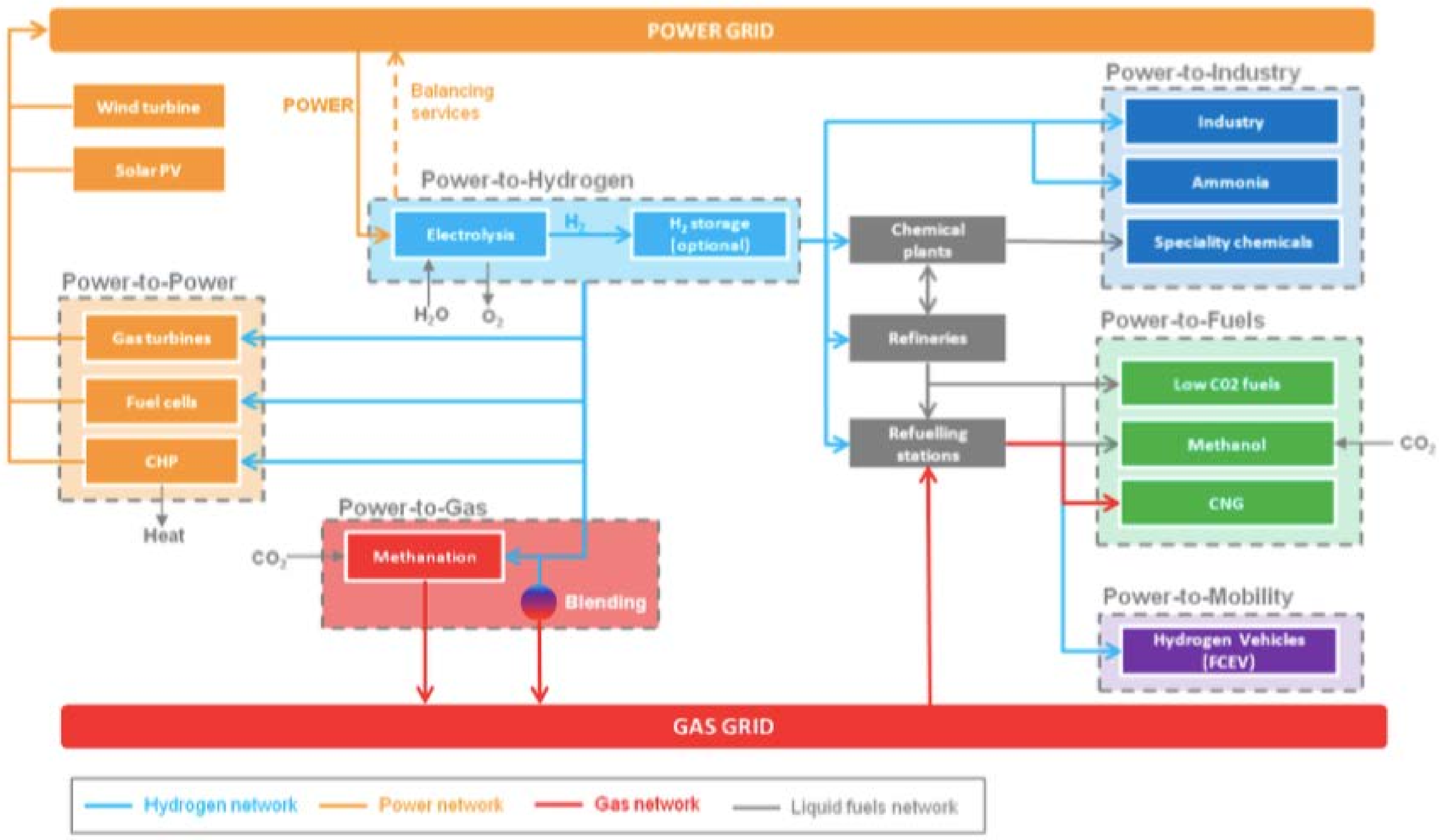


Figure 49: Different routes for hydrogen valorisation (source: Power to gas Roadmap for Flanders)[39].

Stationary Applications

Once it has been produced, hydrogen can be used in different applications (Figure 49).

In the renewable energy domain, the stationary applications for hydrogen include the following routes:

- Power-to-power (P2P): hydrogen produced by electrolysis is used for balancing intermittent renewable energy connected to electricity grids; hydrogen is used to produce back electricity in a fuel cell or in a conventional gas turbine. In this process heat is also produced, resulting in combined heat and power (CHP) applications.
- Power-to-hydrogen (P2H) and Power-to-Gas (P2G): hydrogen produced by electrolysis is used for balancing intermittent renewable energy connected to electricity grids, injected into the natural grid or as feedstock to other processes (chemical plants, refineries, and refuelling stations for mobility).

- Power-to-industry (P2I) and power-to-fuels (P2F): hydrogen can be used as feedstock to several chemical processes, including the production of alternative fuels by reaction with carbon captured from different sources.

Stationary P2P includes any application in which the fuel cells or thermodynamic conversion plants are operated at a fixed location for primary power, backup power, or combined heat and power (CHP). The development of new advanced materials and improving the existing ones have the potential to improve performance and enhance durability.

"INDUSTRIALLY EMITTED OR AIRBORNE CO_2, COMBINED WITH HYDROGEN, CAN BE CONVERTED INTO CHEMICALS, FUELS, AND MATERIALS"

Carbon Capture and Utilisation

Industrially emitted or airborne CO_2, combined with hydrogen, can be converted into chemicals, fuels, and materials, by chemical reactions assisted by catalysts or in biochemical reactors. The technologies encompass CO_2 capture and conversion as well as hydrogen production. It significantly differs from carbon capture and storage (CCS), which aims at permanently storing CO_2 underground. In fact, CCU can be implemented in parallel to CCS, serving additional purposes[73].
CCU technologies allow producing added-value products by means of renewable energy sources, reducing hence the carbon footprint. Several CO_2 capture technologies are available commercially but are costly in general and contribute to around 70–80% of the total system cost[73]. Once captured, CO_2 should be refined through separation process before being used. Advanced materials have the potential to improve all the process integrated in CCU: capturing, separation and utilisation.

[73] Styring, P., Jansen, D. Carbon Capture and Utilization in the Green Economy Using CO2 to manufacture fuel, chemicals and materials. Centre for Low Carbon Futures, 2011

[74] Leung, D.Y.C., Caramanna, G., Maroto-Valer, M.M. An overview ocurrent status of carbon dioxide capture and storage technologies. Renewable and Sustainable Energy Reviews, 2014

Electrolysers (H_2 production)

Electrolysers use electricity to break the water molecule into hydrogen and oxygen. The basic elements of a hydrogen production facility are shown in Figure 50 for the hierarchy considered within the roadmap. As can be seen, the subcomponents of an electrolyser are the same as in fuel cells (FCs). In fact, an electrolyser can be seen as a FC running in reverse. Like FCs, electrolysers are scalable, so they can be combined to make larger systems. The technology of the main type of FCs is covered in the chapter of hydrogen for mobility applications.

The main technologies of electrolysers are shown in Figure 51, together with the most important feature parameters.

In an alkaline electrolyser (AKE), a diaphragm membrane hinders the mixing of gasses produced at the two electrodes and allows OH- to pass through the liquid electrolyte that is made of a solution of potassium hydroxide. AKEs have been used by industry for nearly a century and are commercially available together with proton exchange membrane electrolysers (PEME).

The main parameter of an electrolyser is efficiency, which is defined as the energy required (kWh) per kg of hydrogen, with theoretical values of 33.33kWh/kg (LHV) and 39.4 kWh/kg (HHV)[76]. In this sense, solid oxide electrolysers (SOE) hold the potential of achieving high values of energy efficiency, although there are still in the development phase. Like solid oxide fuel cells (SOFC), SOE work at high temperatures (typically 500-850°C)[7]. Another advantage is their potential use for co-electrolysis, in which both steam and CO_2 can be used to produce syngas, from which hydrocarbons such as liquid fuels can be further produced.

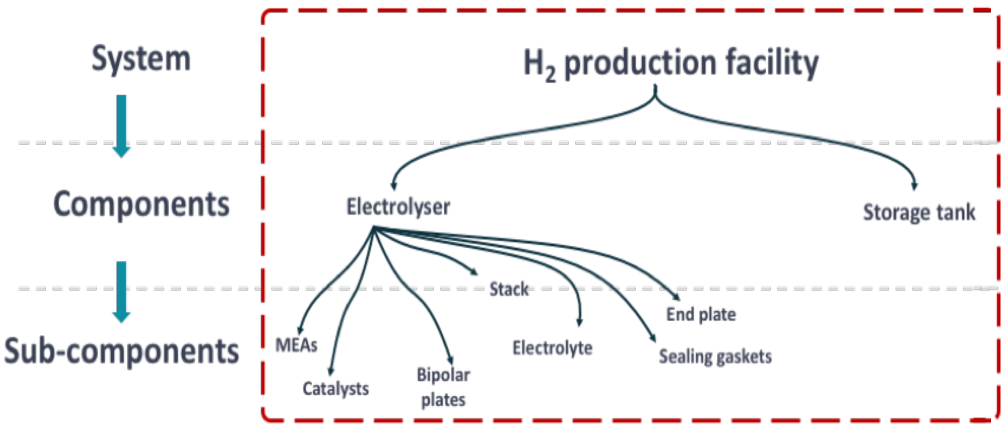


Figure 50: Component hierarchy of the H_2 production facility through electrolysis (source: Bax & Company).

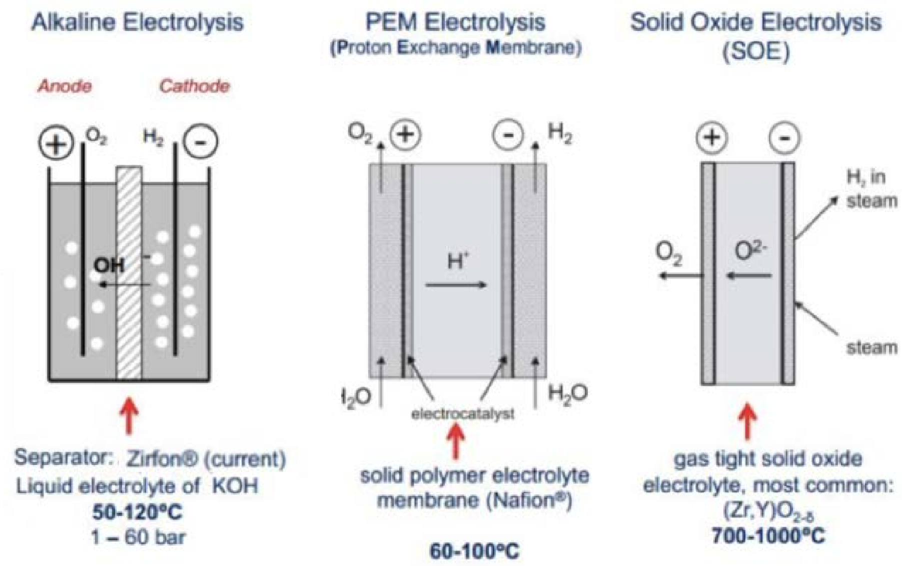


Figure 51: Main commercial technologies for electrolysers (source: Nikolic et al., 2010[75]).

"PEME AND SOE ARE THE MOST PROMISING TECHNOLOGIES IN TERMS OF ADVANCED MATERIALS DEVELOPMENT, WITH CONSIDERABLE INNOVATION POTENTIAL TO REDUCE COSTS AND IMPROVE EFFICIENCY

[75] V. M. Nikolic, G. S. Tasic, A. D. Maksic, D. P. Saponjic, S. M. Milovic, and M. P. Marceta Kaninski," Raising efficiency of hydrogen generation from alkaline water electrolysis - energy saving," International Journal of Hydrogen Energy, Nov.2010

The main features of the three types of electrolysers are summarised in Table 13.

Type	Development Status	System Size Range	Hydrogen Purity	Efficiency	Lifespan	Indicative System Cost
AKE	Commercial	+++ (0.25 - 760Nm^3 H_2/h, 1.8 – 5300kW)	++ (99.5 - 99.9998)	70%	++++ (60,000 – 90,000h)	+++ (1,000 – 1,200€/kW)
PEME	Commercial (applications <300kW)	++ (0.01 - 240Nm^3 H_2/h, 0.2 – 1,150kW)	+++ (99.9 - 99.9999)	70%	+++ (20,000 – 60,000h)	++ (1,900 – 2,300€/kW)
SOE	Research & Development	N/A	N/A	+ (85%)	+ (~1,000h)	N/A

Table 13: Main features of commercially available electrolysers (source: FCH[77]; SINTEF[78]; Shell[79])

PEME and SOE are the most promising technologies in terms of advanced materials development, for which there is considerable potential for innovation to reduce costs and improve efficiency[79]. PEME is already 1-10 MW with 20 MW in development (Figure 52). The main advantage of the PEME over AKE is in the absence of liquid electrolyte. The main challenge of the PEME material development is to find suitable replacements for rather scarce electrode materials. On the other hand, the deployment of AKE related systems (in which electrode materials use much cheaper and more abundant options) would be greatly boosted by further development of alkaline ion exchange membranes and increase of the pressure output to 30-60 bar.

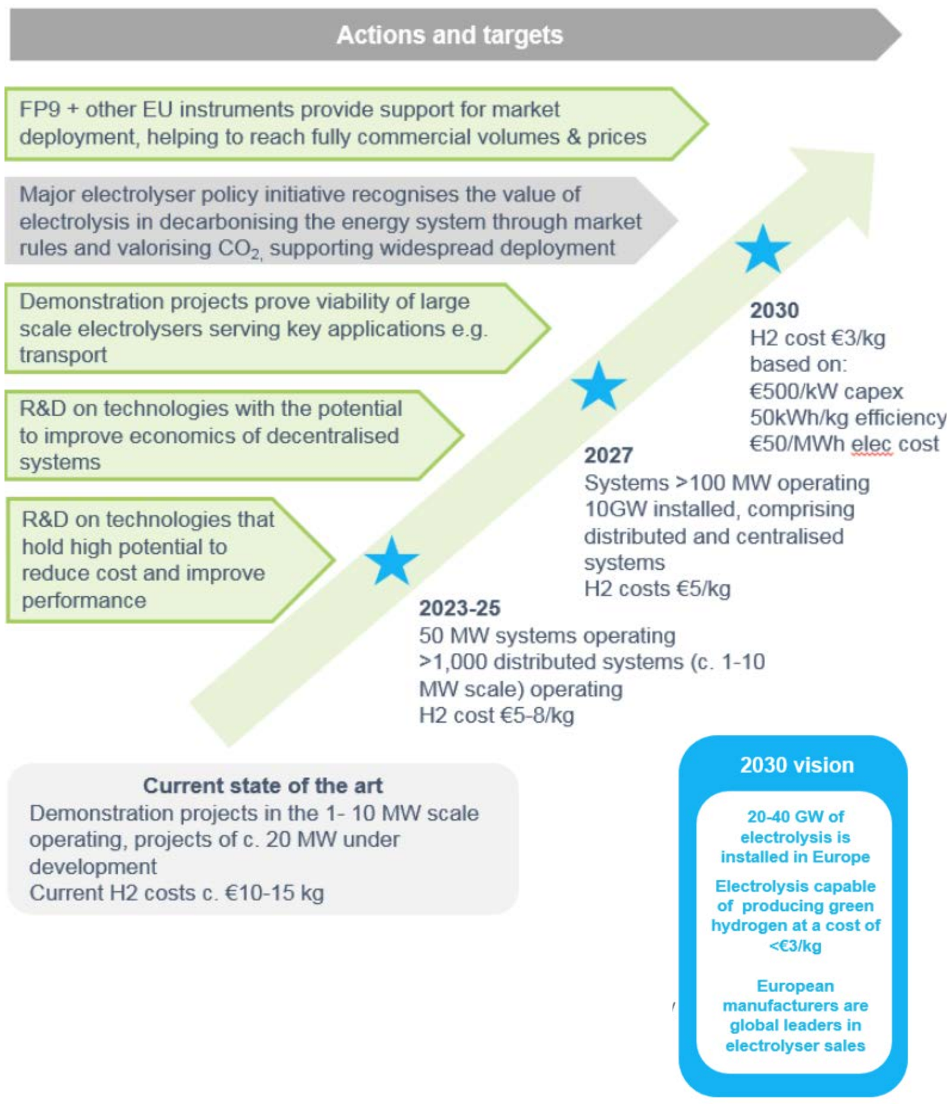


Figure 52: Current state of the art and future developments for PEME (source: Hydrogen Europe[80]).

[76] Study on development of water electrolysis in EU. Fuel cells an Hydrogen Joint Undertaking, Final Report, 2014

[77] Development of water electrolysis in the European Union. Fuel Cells and Hydrogen – A Joint Undertaking. Final Report, 2014

[78] Millet, P. Analysis of degradation processes in PEM water electrolysis cells. In 2nd International workshop on durability and degradation issues in PEM electrolysis cells and its components, 2016

[79] Shell hydrogen study Energy of the future? Sustainability Mobility through Fuel Cells and H2. Shell Deutschland Oil GmbH, 2017

[80] Hydrogen for Europe, Hydrogen, enabling a zero emission Europe Technology Roadmaps Full Pack September 2018

Technologies for (stationary) power generation

Stationary power applications operate at a fixed location for primary power, backup power (typically zhydrogen or methanol fuelled), or CHP (methane or hydrogen). The stationary sector includes both large-scale (200kW and higher) and small-scale (up to 200kW) and a wide range of markets.

The basic elements of a hydrogen consumption system (stationary fuel cells) are shown in Figure 53 for the hierarchy considered within the roadmap.

The main technologies for stationary applications are SOFC and to a lesser extent PEM, which are covered in the chapter of hydrogen for mobility applications. Compared to other electricity generation technologies, FCs have higher efficiencies and can be installed close to the point of use. However, deployment in Europe has been limited compared to North America and Asia[80].

A comparison of SOFC and PEM technologies for stationary applications is shown in Figure 54. Several commercially available products are presented and grouped for power generation and micro-CHP, with the name of the manufacturer indicated as well. In some cases, the reading of the temperature scale should be taken with caution, as most of these products operate within a temperature range.

Besides FCs, hydrogen can be converted into electricity using gas turbines. A gas turbine can operate with a variety of fuels. Currently the most common is natural gas. The switch to hydrogen-containing gases leads to combustion temperatures that are higher than conventional gas turbines, which then results in a lower mass flow rate (affecting the turbine/compressor matching) and to different compositions in outlet gases[80]. The increased reactivity of hydrogen, and the relatively higher adiabatic flame temperatures have an impact on the materials that can be used, requiring improvements in cooling schemes and thermal barrier coatings[81].

Other routes of hydrogen valorisation include the decarbonisation of the gas grid, by directly injecting the gas after blending it with methane. Blends of hydrogen up to 20% by volume are possible without pipeline or appliance conversion in the majority of gas grid[82].

Higher concentrations are desirable, but materials for gas transport and distribution, and for utilisation appliances would become a challenge and R&D activities are needed.

"MATERIALS FOR GAS TRANSPORT AND DISTRIBUTION, AND FOR UTILISATION APPLIANCES WOULD BECOME A CHALLENGE AND R&D ACTIVITIES ARE NEEDED"

[81] Chiesa, P., Lozza, G., Mazzocchi, L. Using hydrogen as gas turbine fuel. Journal of Engineering for Gas turbine and power, 2005

[82] Power-to-gas & turbines – a perfect combination in the future EU Turbines, November 2016

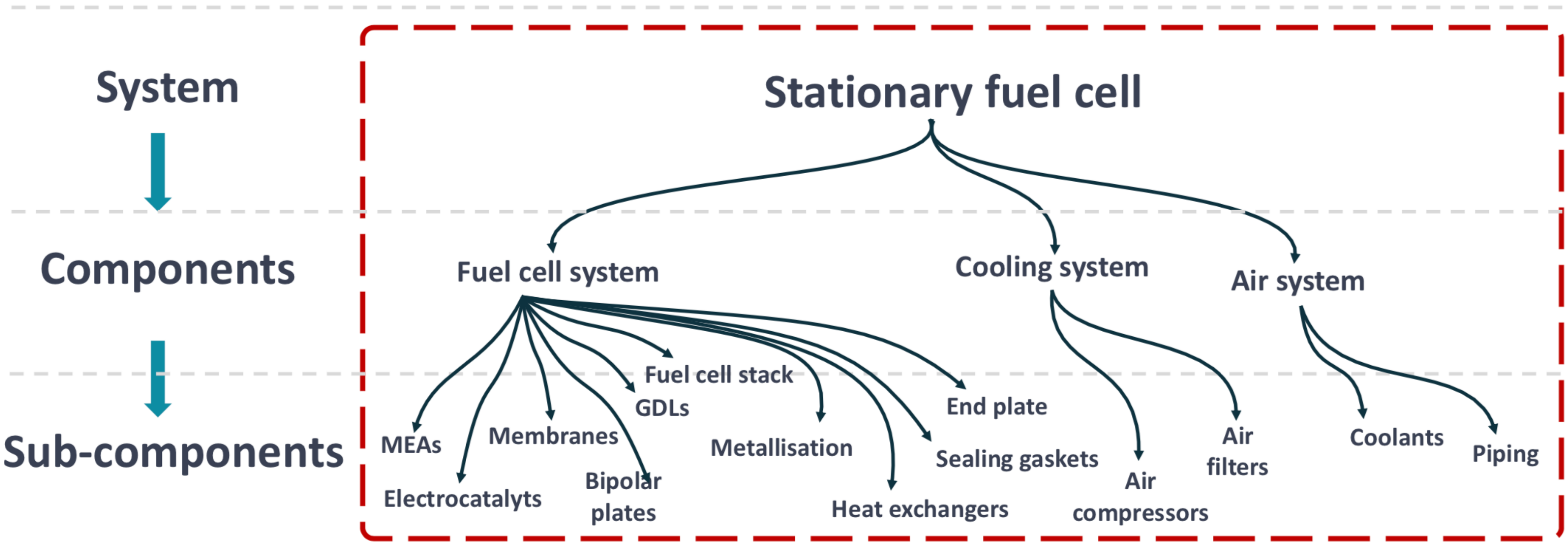


Figure 53: Component hierarchy of a stationary fuel cell system (source: Bax & Company).

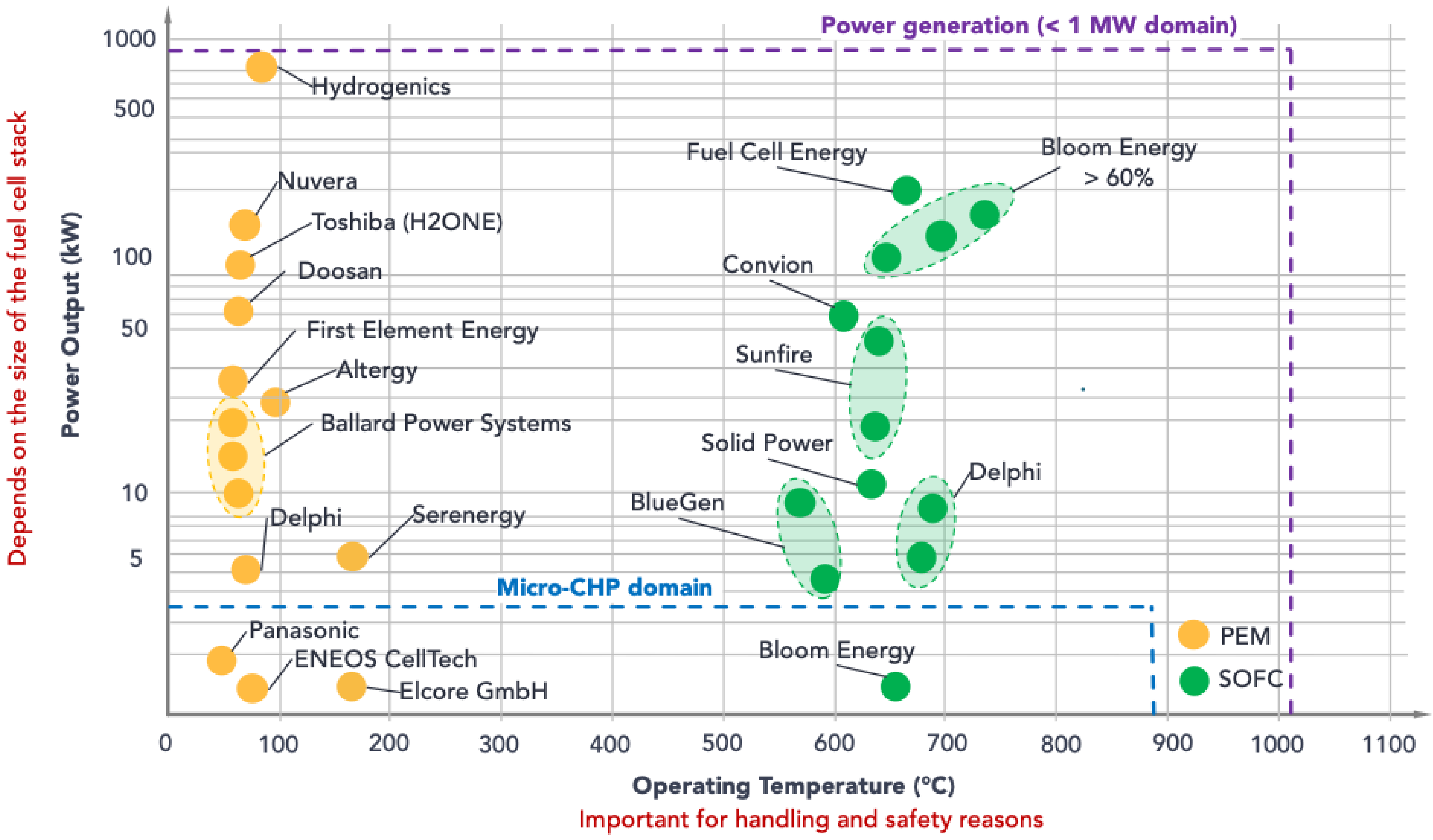


Figure 54: Power output vs. temperature of operation for several commercial PEM and SOFC (not exhaustive) (source: U.S. Department of Energy)[50].

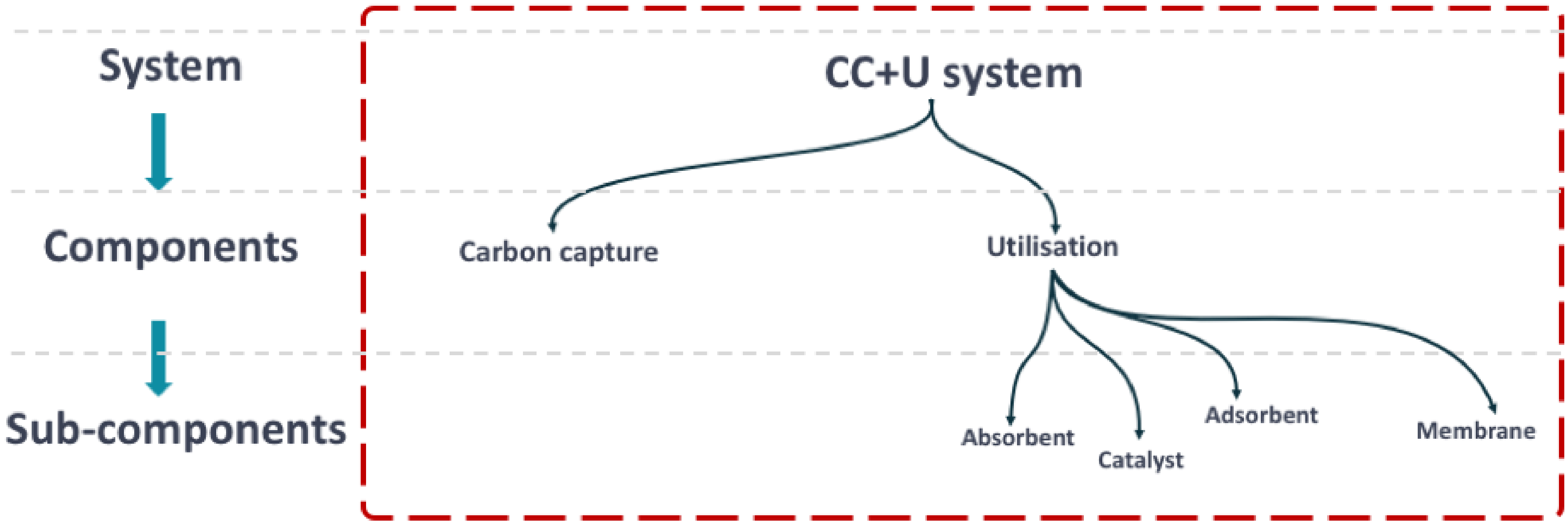


Figure 55: Component hierarchy of a stationary fuel cell system (source: Bax & Company)

Technologies for carbon capture and utilisation

The basic elements of a CCU system are shown in Figure 55 for the hierarchy considered within the roadmap.

The main technologies involved are those related to carbon capture, separation for purification purposes, and further utilisation. Regarding capture, there are three main CO_2 capture systems associated with different combustion processes: post-combustion, pre-combustion and oxyfuel combustion. Post-combustion technologies are the preferred option and usually are based on chemical absorption (scrubbing) or adsorption processes (e.g. membrane-based). In pre-combustion processes, the fuel is pre-treated before combustion (e.g. through gasification) while in oxyfuel combustion air is substituted by oxygen to reduce the amount of nitrogen in exhaust gases.

[83] The Future of gas. Transition to hydrogen in the gas grid. Dentons,January 2019

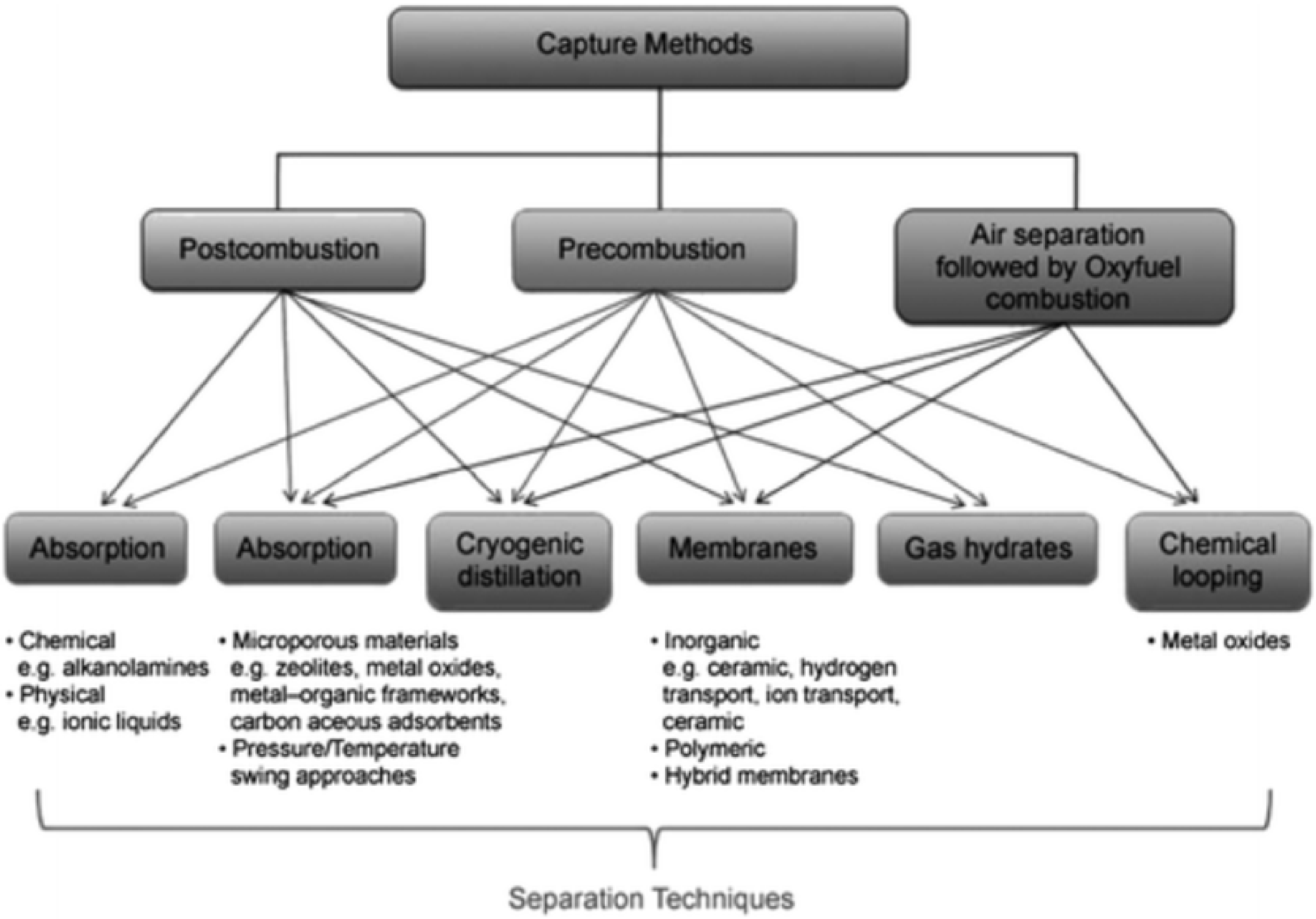


Figure 56: Technologies of CO_2 separation according to the capturing method (source: Leung et al., 2014[86]).

The main distinction of technologies is shown in Figure 56 for the different types of capturing methods mentioned before. Absorption is by far the most mature method, with the preferred option being monoethanolamine (MEA)[84].

Research and development related to materials will involve the development of higher- performance solvents, sorbents and membranes. For solvents and sorbents, enhanced separation kinetics entail shorter residence times and hence smaller reaction vessels, contributing to lower capital costs. For membranes, materials with enhanced permeability and selectivity also have similar impacts on both capital and operating costs[85].

[84] Wang, Y., Zhao, L., Otto, A., Robinius, M., Stolten, D. A review of post-combustion CO2 capture technologies from coal-fired power plants, 2017

[85] World Energy Council, World Energy Resources Carbon Capture & Storage 2016, 2016

In terms of utilisation, CO_2 has been used for centuries in many processes for pharmaceutical and food industries[86]. Research is exploring new chemical and biological utilization routes, as it is depicted in Figure 57. Research and development related to materials will focus on aspects such as catalysis science and technology.

The above mentioned technologies are however at different stages of technological readiness, from laboratory testing to commercial demonstration, for which their economic and environmental feasibility should be improved[89].

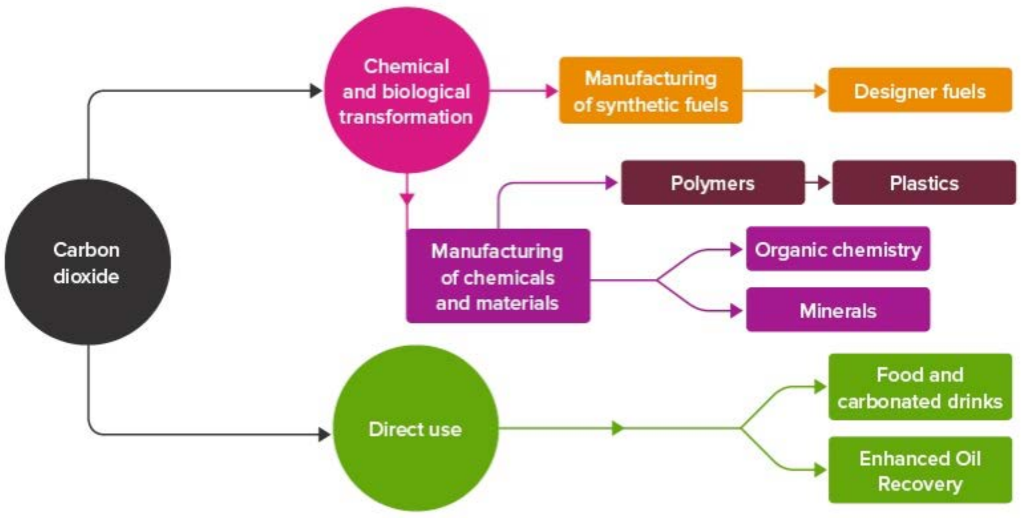
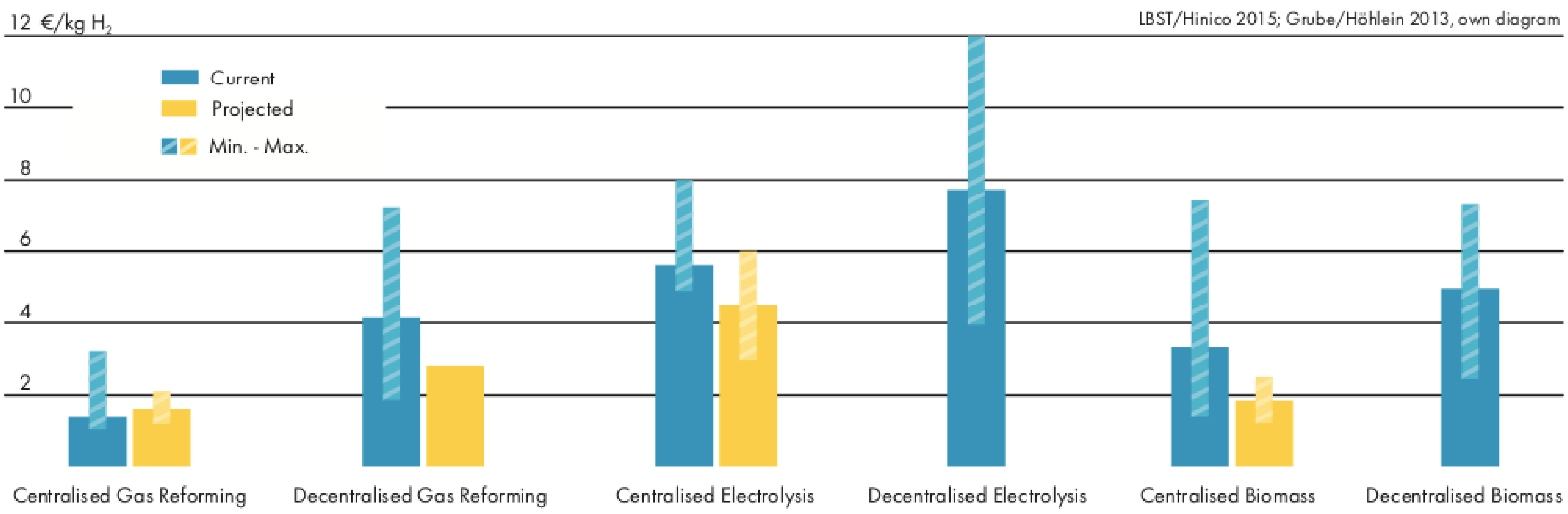


Figure 57: Utilization routes for CO_2 (source: The Royal Society[88])

Cost Structure
Hydrogen production

Steam-methane reforming of natural gas (SMR) is currently the most cost-efficient method of hydrogen production with a cost of less than 2 € per kg of hydrogen.

The alternative production methods entail higher costs, as depicted in Figure 58. The electricity price, in the considered references, varies between 6.5 – 10 € cents/kWh.



Hydrogen production costs for several technologies (source: Shell [90])

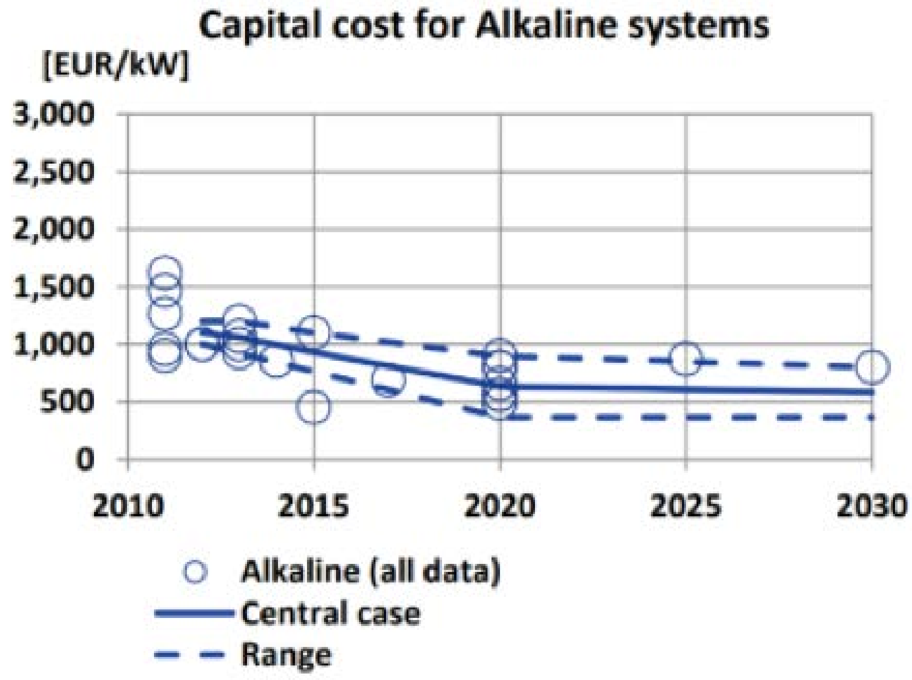
If hydrogen is produced at a cost between €1.5 – 3 per kg it would become competitive with conventional fuels for transport applications[80]. Electrolysis is currently the most expensive method (€10-15 per kg) due to capital costs and dependence on electricity costs. The spread of costs for centralised electrolysis plants is lower than those for decentralised because in the latter the plants

[86] Leung, D.Y.C., Caramanna, G., Mercedes Maroto-Valer, M. An overview of current status of carbon dioxide capture and storage technologies. Renewable and Sustainable Energy Reviews, 2014
[87] Kleij A, North M, & Urakawa A. 2017 CO2 Catalysis. ChemSusChem
[88] The Royal Society Available, The Potential and Limitations of Using Carbon Dioxide, 2017

"IF HYDROGEN IS PRODUCED AT A COST BETWEEN €1.5 – 3 PER KG IT WOULD BECOME COMPETITIVE WITH CONVENTIONAL FUELS FOR TRANSPORT APPLICATIONS"

are not used at optimum capacity and the variations in utilisation have a greater impact on production costs[90]. The capital costs of the two most important commercially available electrolysers are shown in Figure 59.

Currently available AKE systems cost ranges from 1,000 to 1,500 €/kW, plus installation. Although the system cost of PEME is about twice of AKE, in some markets, small PEME systems (<100 kW) are more competitive. Costs at around 1,000 €/kW (central case) are expected by 2020, although several manufacturers anticipate costs near 700 €/kW. For SOE, systems are available at a cost of roughly 2,000 €/kW, while the cost would approach 1,000 €/kW between 2020 and 2030. PEME typically requires expensive materials to achieve lifetimes and efficiencies comparable to commercial AKE. SOE requires materials that are stable at high temperatures in corrosive environments. For both technologies, most R&D activities should then focus on advanced materials and component developments.



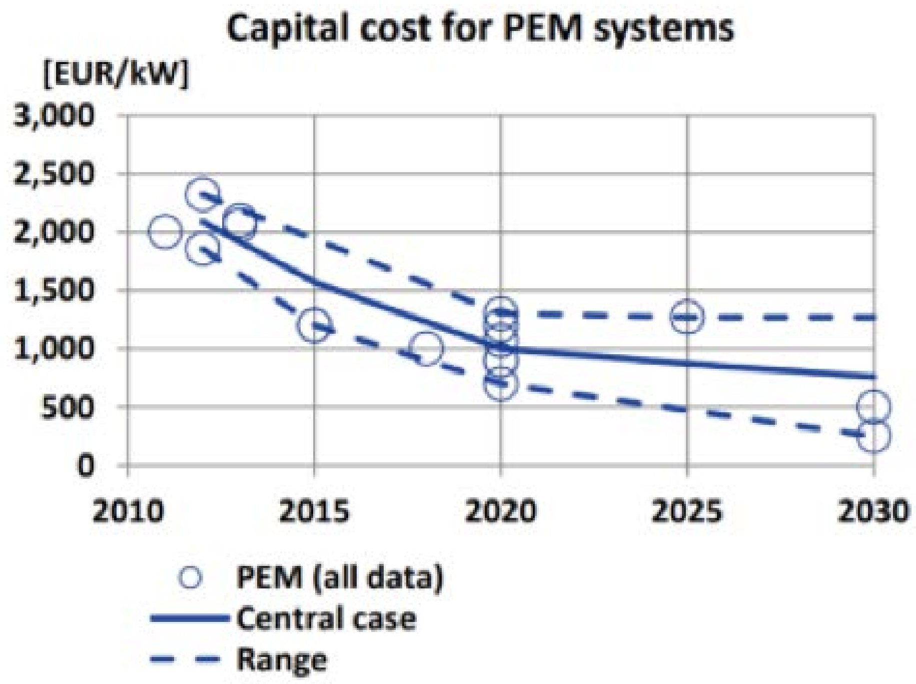


Figure 59: Capital costs for AKE and PEME electrolyser systems (source: Hydrogenics[91]).

[89] European Commission, Group of Chief Scientific Advisors, Novel carbon capture and utilization technologies, May 2018

[90] Shell Deutschland Oil GmbH, Shell hydrogen study Energy of the future? Sustainability Mobility through Fuel Cells and H2,2017

[91] Hydrogenics, Thomas, D. Cost reduction potential for electrolyser technology, June 2018

In some areas, PEME and SOE benefit from concurrent developments in PEM-FC and SOFC. The cost breakdown for AKE and PEME is shown in Figure 60.

In both cases, stack accounts for most of the cost. In PEME, bipolar plates represent more than half of the stack cost (Figure 61).

Power generation

A SOFC system includes multiple fuel cell stacks and the balance of plant (BOP), which encompasses fuel processor, support hardware, fuel and air supply, controls and sensors, and electrical equipment. The material costs of a 250kW system remain practically steady with the number of units produced, and for an amount of 50,000 units the cost of materials accounts for roughly 10%. The breakdown costs of materials per component are shown in Figure 61.

As can be seen, most of the cost (96%) accounts for end-plates, stack assembly, testing and conditioning. For end-plates, a nickel-chromium-iron-molybdenum alloy commercially known as HASTELLOYÒ is commonly used due to its oxidation resistance, fabricability and high temperature strength. The stack assembly is usually a handmade based process, involving tie rods and furnace brazed. The high cost of testing and conditioning results mainly from the scrap of failed stacks and the hydrogen/nitrogen fuel mixture used.

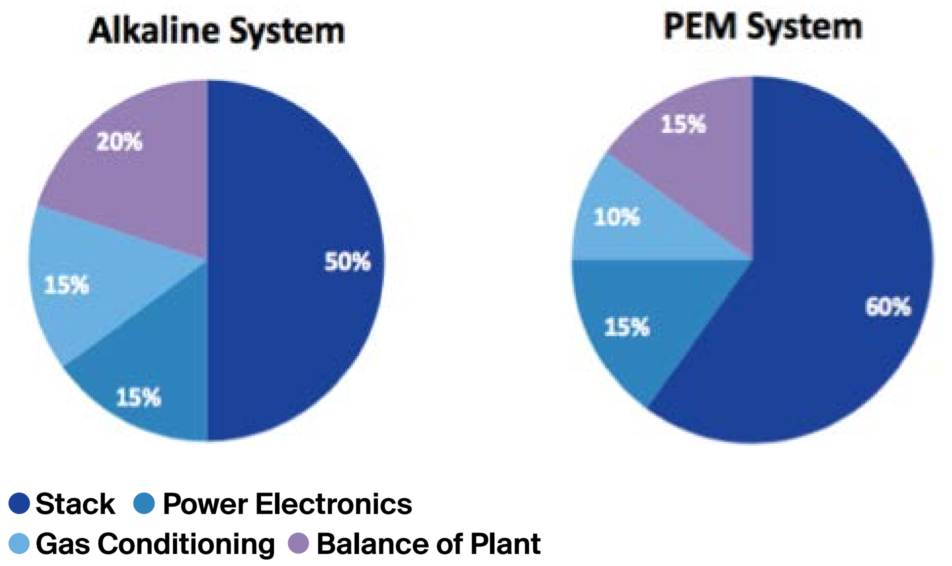


Figure 60: Indicative system breakdown for AKE and PEM electrolyser systems (source: E4Tech[92])

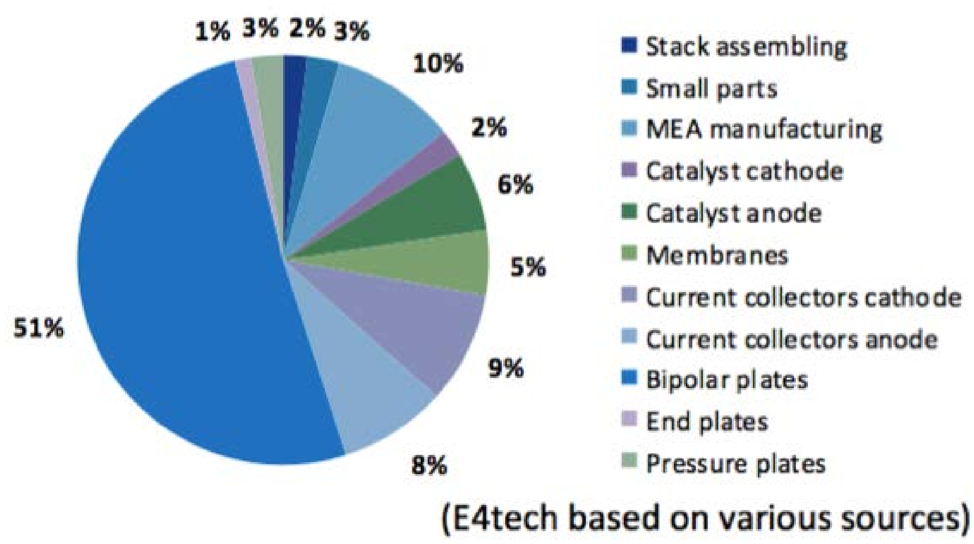


Figure 61: Indicative system breakdown for alkaline and PEM electrolyser systems (source: E4Tech[92])

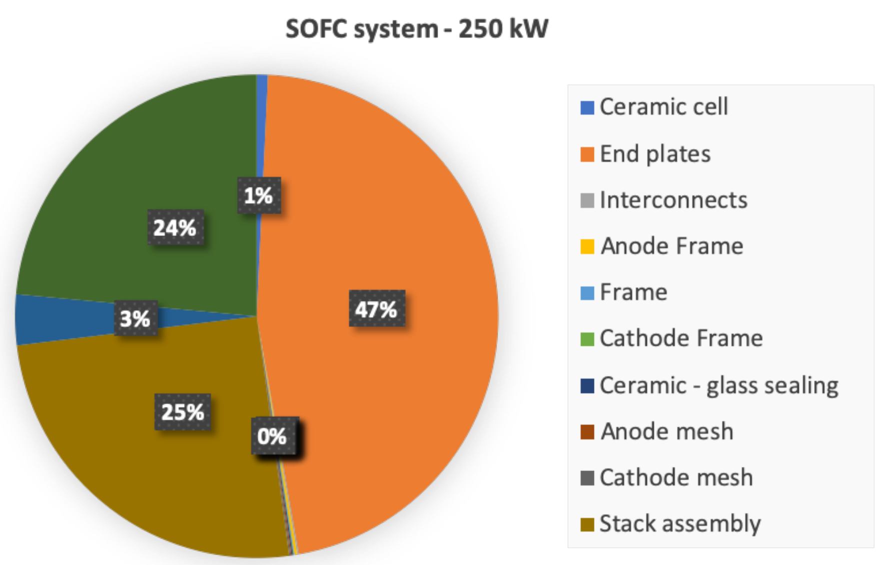


Figure 62: Breakdown cost of materials per component (source: Graph developed by Bax & Company, with data obtained from U.S. Department of Energy[93])

[92] Development of water electrolysis in the European Union. Fuel Cells and Hydrogen – A Joint Undertaking. Final Report, 2014

[93] U.S. Department of Energy, Manufacturing cost analysis of 100 and 250 kW Fuel cell systems for primary power and combined heat and power applications, January 2016

The current cost of FC-micro CHP is close to €13,000/kW[80]. In these applications, SOFC systems are less complex than PEMs due to simpler fuel processor and less needed heat exchangers. For both technologies, BOP (including hardware) accounts for most of the system total cost, as it can be seen in Figure 63.

The stack cost accounts for close to 15% and 22% for PEM and SOFC systems respectively, with the breakdown costs within stack mentioned in the chapter of hydrogen for mobility for the former and in the paragraphs above for the latter. Given their research stage, the cost breakdown of hydrogen turbines is not available.

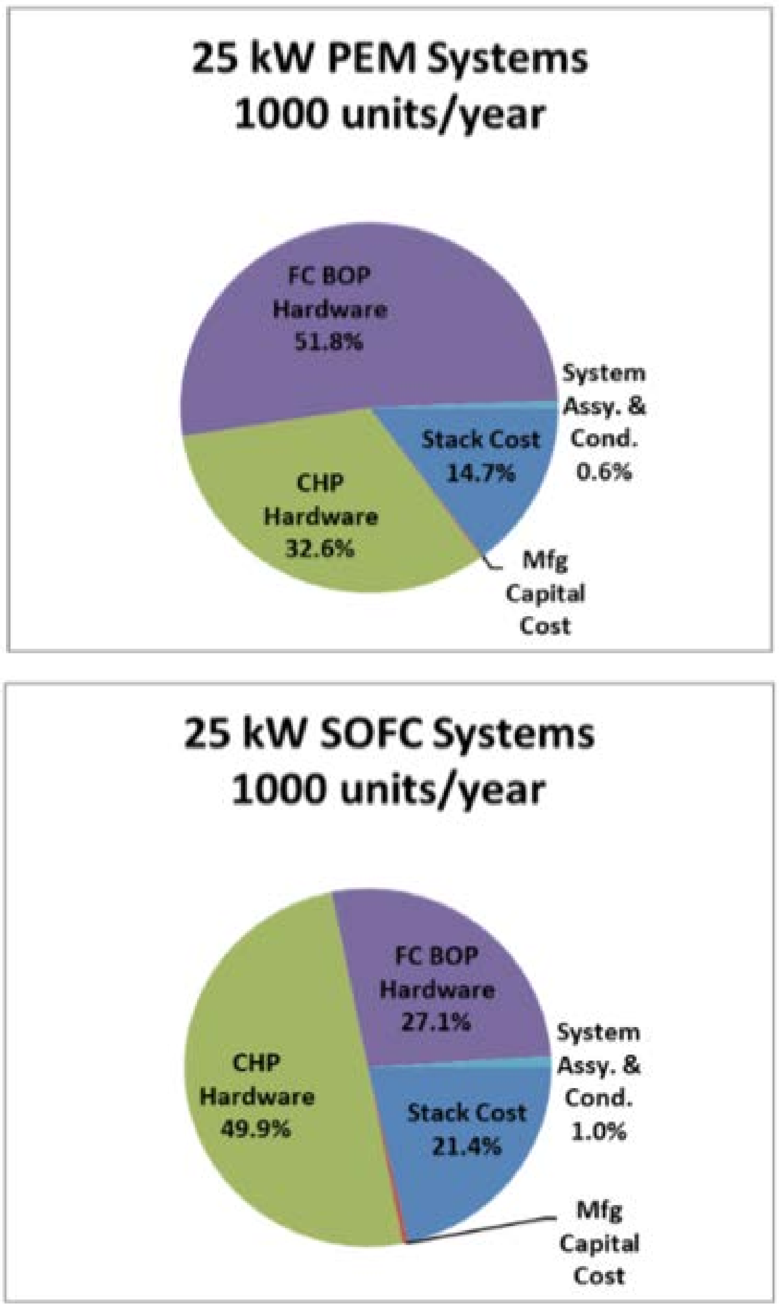


Figure 63: Breakdown cost of CHP fuel cell system for PEM and SOFC (source: U.S. Department of Energy[93]).

Carbon capture and utilisation

The current price of carbon capture is €60-90 per tonne of CO_2 captured and the Carbon Capture and Storage Association estimates that the costs will decline to €35-50 by early 2020s[94]. This cost depends on the source of carbon, transportation and to a large extent on the capture process, which is the most expensive part of the system. A cost comparison for different capture processes is shown in Table 14. The costs include CO_2 compression but exclude storage and transportation costs.

Capital cost is significantly higher for all types

Fuel type	Parameter	Capture technology			
		No capture	Post-combustion	Pre-combustion	Oxy-fuel
Coal fired	Thermal efficiency (% LHV)	44.0	34.8	31.5	35.4
	Capital cost ($/kW)	1410	1980	1820	2210
	Electricity cost (c/kWh)	5.4	7.5	6.9	7.8
	Cost of CO_2 avoided ($/t)	-	34	23	36
Gas Fired	Thermal efficiency (% LHV)	55.6	47.4	41.5	44.7
	Capital cost ($/kW)	500	870	1180	1530
	Electricity cost (c/kWh)	6.2	8.0	9.7	10.0
	Cost of CO_2 avoided ($/t)	-	58	112	102

Table 14: Cost comparison for different capture process (source: D.Y.C. Leung et al., 2014[95])

"THE CURRENT PRICE OF CARBON CAPTURE IS €60-90 PER TONNE OF CO_2 CAPTURED AND THE CARBON CAPTURE AND STORAGE ASSOCIATION ESTIMATES THAT THE COSTS WILL DECLINE TO €35-50 BY EARLY 2020"

[94] Evans, S. The cost of carbon capture: is it worth incorporating into the energy mix? Power Technology, October 2018

[95] Leung, D.Y.C., Caramanna, G., Maroto-Valer, M.M. An overview of current status of carbon dioxide capture and storage technolgies. Renewable and Sustainable Energy Reviews, 2014

of capturing technologies when coal is used as fuel, although at lower costs of CO_2 avoided (cost of reducing CO_2 emissions to the atmosphere while producing the same amount of product from a reference plant).

Both increased capital cost and levelised cost of electricity (LCOE) represent a significant hurdle preventing the expansion of CCS + U[96]. The trade-off between LCOE and CO_2 purity for different types of technologies is shown in Figure 60. The technologies with the highest and lowest LCOE are of pre-combustion type while those producing the highest grade of CO_2 are post-combustion and oxyfuel.

Regarding transportation and storage, related costs are likely to be lower in initial investment, but overall lifetime costs will be significant and could account for between 10% and 30% of the cost for each tonne of CO_2 sequestered.

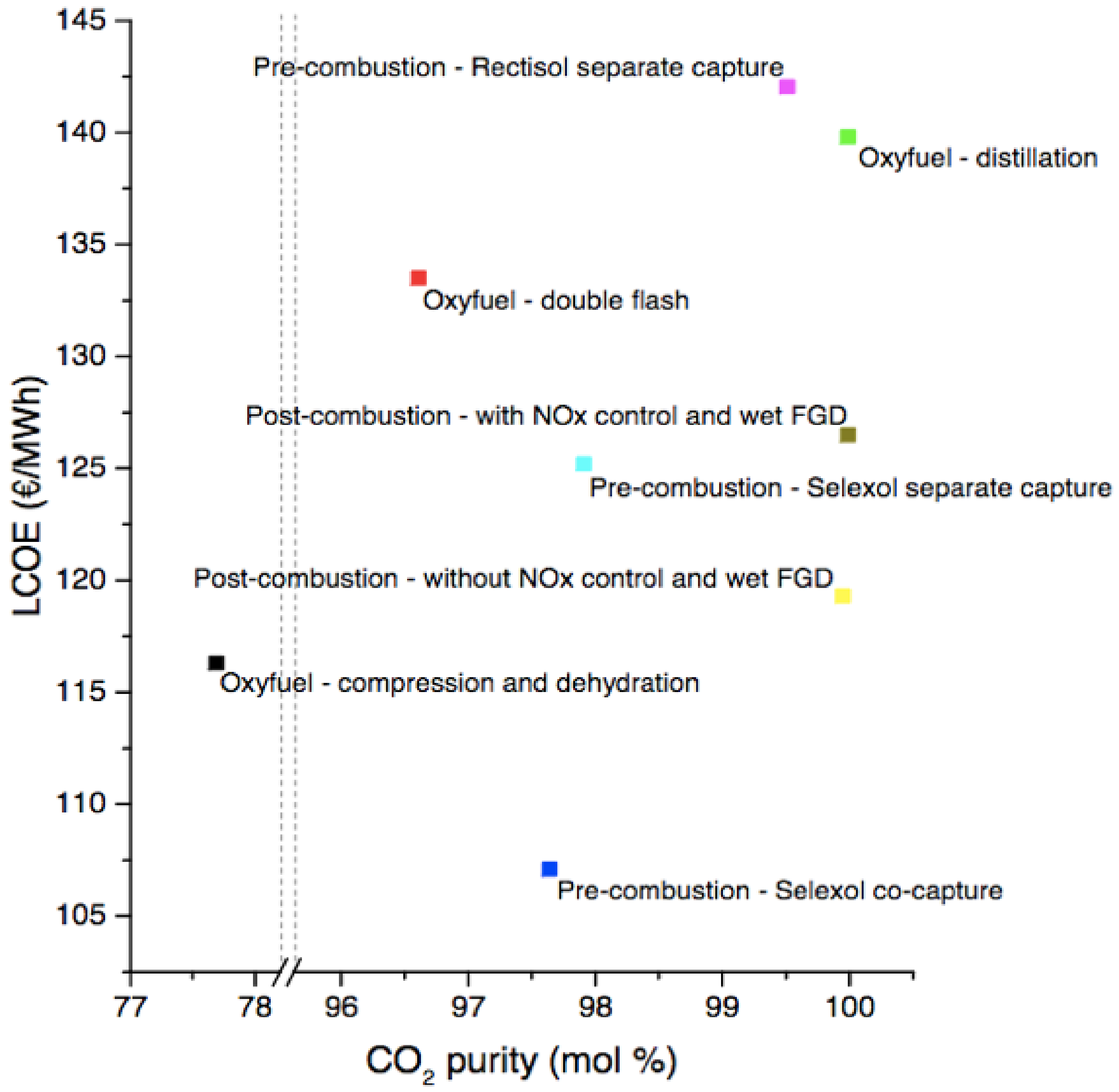


Figure 64: LCOE vs. CO_2 purity for different CO_2 capture technologies (source: Porter et al., 2016[97]).

[96] The Future of Carbon Capture and Storage, Report by Power Generation Research, September 2014.

[97] Porter, R.T.J., Fairweather, M., Kolster, C., Dowell, M.N., Shah, N., Woolley, R.M. Cost and performance of some carbon capture technology options for producing different quality CO_2 product streams. International Journal of Greenhouse Gas Control

European Landscape

Market and applications – Hydrogen production

Projections indicate that 5 million vehicles and 13 million households could be using hydrogen in Europe by 2030. The demand is expected to increase 10-fold by 2050 (Figure 65).

Today, only about 4% of global hydrogen production (65 million tonnes) comes from electrolysis[97]. However, the forecast for electrolysers deployment considers a significant increase towards 2020 close to 450 MWs shipped per year (Figure 66).

In terms of the type of technology, PEME and SOE are the dominating choices, due to their anticipated progress in efficiency performance and lowering of costs from advanced material development.

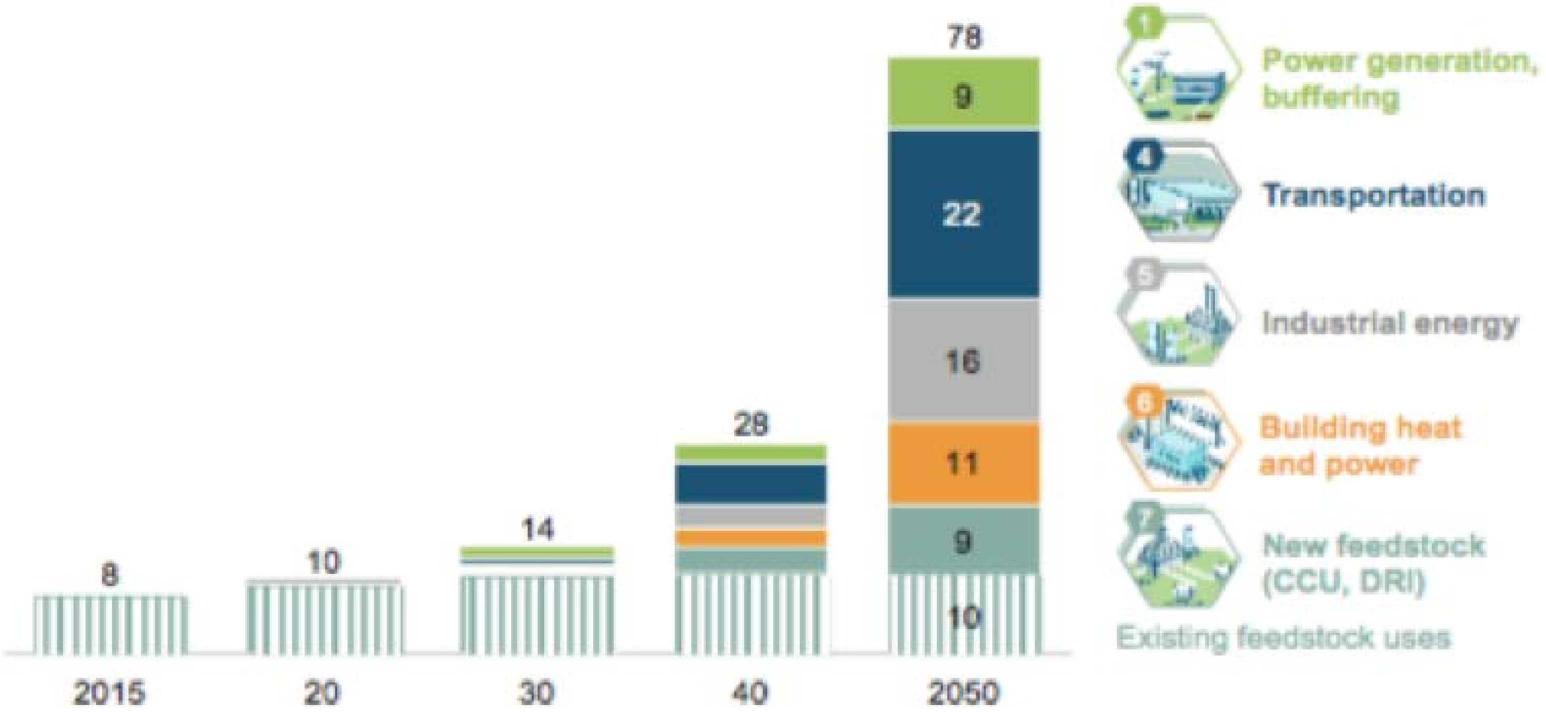


Figure 65: Market applications of hydrogen for 2050 (source: Hydrogen Europe[77])

[98] Development of water electrolysis in the European Union. Fuel Cells and Hydrogen – A Joint Undertaking. Final Report, 2014

Figure 66: Eletrolyser market deployment and forecast (source: 4th wave)

Market and applications

<u>Fuel cells for stationary applications</u>

The market for small and large stationary applications is distributed unevenly around the globe, being heavily dependent on subsidies from government support. This has resulted in dominating markets located in Asia (mostly Japan and Korea where support is favourable) and the United States. Most of the stationary power was manufactured in these regions. More than half of the fuel cell power shipped worldwide belong to the stationary applications sector (Figure 67).

The European market is still in the research and development phase. PEM FC is the preferred technology, due to their relatively low temperatures of operation and higher reliability. It is expected to achieve estimated revenues of around $180 million by 2018 at a CAGR of 90%. The main European markets for this technology are Germany, the UK and the Netherlands.

As far as SOFC are concerned, they are expected to grow at a significantly lower CAGR, close to 15%, which entails having potential revenues of $3.8 million by 2018. For this technology, the main markets are also Germany and the UK, and to some extent, Italy.

Several SOFC manufacturers are in the process of entering the Japanese market with small commercial systems, which could contribute to the overall values for 2018. About 76 MWs of this technology were shipped globally in 2017, mostly from Bloom Energy and installed in the United States for onsite power generation.

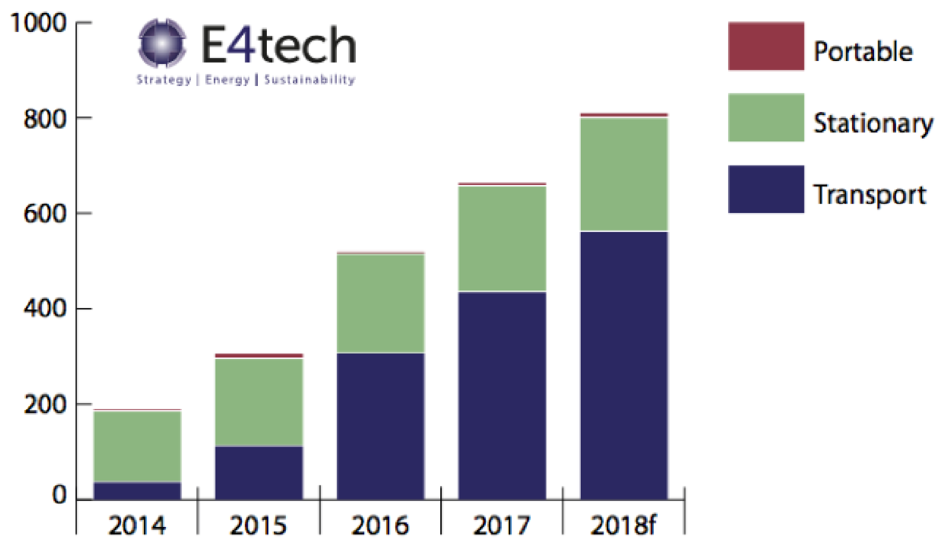


Figure 67: Megawatts of fuel cells shipped worldwide by application area (source: E4Tech[37])

"PEM FC IS THE PREFERRED TECHNOLOGY, DUE TO THEIR RELATIVELY LOW TEMPERATURES OF OPERATION AND HIGHER RELIABILITY"

"AT A GLOBAL SCALE, OVER 30 MILLION TONS OF CO_2 ARE CAPTURED IN LARGE-SCALE FACILITIES FOR USE OR STORAGE; MORE THAN 20 MILLION TONNES ONLY IN NORTH AMERICA"

Market and applications

Carbon capture and utilisation

At a global scale, over 30 million tons of CO_2 are captured in large-scale facilities for use or storage; more than 20 million tonnes only in North America. Most of the CO_2 that is captured comes from the production of chemicals and petrochemicals, iron, steel, and cement. The sector of chemicals and petrochemicals accounts for the largest share, with CCU + storage activities linked to the production of ammonia, methanol, ethylene, propylene and aromatics[99]. The market in 2017 was estimated at roughly $3 billion and is expected to grow at a CAGR of almost 24%, reaching $20 billion by 2026[100]. Pre-combustion capture technologies accounted for the largest share (close to 75%) in 2017. This kind of technologies have a lower energy cost. However, the post-combustion capture segment is expected to grow at the highest CAGR of all, 16% from 2018 to 2026, due to the anticipated progress in amine systems and heat integration systems[100].

The market performance depends heavily on several factors including economic feasibility, the scale of operations, location, government regulations, and pressure on the industry for environmental sustainability.

[99] International Energy Agency, Carbon capture, utilization and storage, 2018

[100] Statistics Market Research Consulting Pvt Ltd, Carbon Capture, Utilization & Storage - Global Market Outlook (2017-2026)

Value chain and key players for hydrogen production

The value chain of hydrogen production by electrolysis involves several actors, as illustrated in Figure 68. Starting with renewable energy producers and electrolysis, the value chain further involves actors related to compression, storage, transport and system integration.

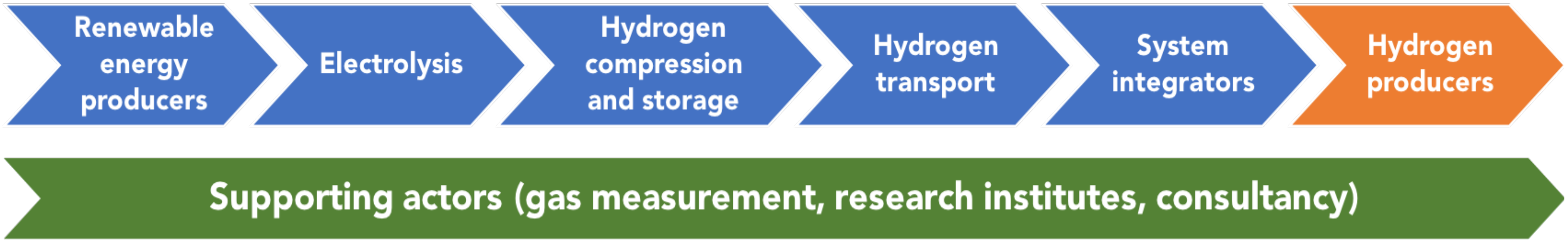


Figure 68: Power to gas value chain (source: Power to Gas Roadmap to Flanders[39])

Focusing on electrolysis, Europe has a strong presence worldwide, both in component supply and in final product manufacture. The European expertise covers the three main technologies: PEME, AKE and SOE. In fact, the largest PEM electrolyser currently operating is the 6MW PEM system at Energie Park Mainz in Germany (installed by Siemens, Linde AG and others), with a 75% conversion efficiency[59].

Other European companies that are well placed along the value chain are Air Liquide, Linde, Air products, Equinor, Nel, McPhy, Hydrogenics, ITM Power, Sunfire, and Areva H2Gen among others.

This existing hydrogen industry and its supply chain are expected to serve as a platform for future energy uses of hydrogen, contributing to secure high level manufacturing jobs[70].

" THE LARGEST PEM ELECTROLYSER CURRENTLY OPERATING IS THE 6MW PEM SYSTEM AT ENERGIE PARK MAINZ IN GERMANY "

Stationary FCs

The value chain and main key players were already considered in the chapter of hydrogen for mobility applications. However, it should be added that there is a strong Europe-based supply chain for fuel cell micro-CHP, which has been developed in part due to the Fuel Cells and Hydrogen Joint Undertaking (FCH JU) funded projects. Several system integrators are present for both electrolyser systems and FCs, such as Bosch, Valliant, Ceragen, SOLIDpower, Viessmann, as well as stack developers such as Elcomax, ElringKlinger, Serengy, Ceres Power, Sunfire and Hexis.

European commercial installations have typically lagged Asia and North America, mainly due to the relatively less experience at commercial scale and lack of funding mechanisms for commercialisation. This has resulted in a smaller fleet of micro-CHP fuel cell systems compared to the hundreds of units that are already installed in Korea and the United States[59].

The European stationary fuel cell industry must overcome several challenges related to the high capital and operating costs, lack of effective technological development to accelerate commercialisation, lack of supportive legislation, and competition from existing technologies.

"THERE IS A STRONG EUROPE-BASED SUPPLY CHAIN FOR FUEL CELL MICRO-CHP, WHICH HAS BEEN DEVELOPED IN PART DUE TO THE FUEL CELLS AND HYDROGEN JOINT UNDERTAKING (FCH JU) FUNDED PROJECTS"

Carbon capture and utilisation

Currently, North America is dominating the market provided a rising government support, growing oilfields, and increasing demand for clean technology. Some of the key players in the global market include Dioxide Materials Inc., AkerSolutions, Integrated Carbon Sequestration Pty. Ltd., E3tec Service Llc., Enn Group Co. Ltd. ,Lanzatech Inc., Skyonic Corp., Novomer Inc., Carbon Cycle Ltd., Basf SE, Mbd Energy Ltd., Solidia Technologies Inc., Empower Materials Inc., Liquid Light Inc, Integrated Carbon Sequestration Pty. Ltd., Joule Unlimited Inc., Schlumberger Limited, Linde AG , Fluor Corporation and Exxonmobil Corporation[100].

Table 15 below presents a SWOT analysis for the European electrolyser landscape, including storage and transportation.

Value Chain Step	Strengths	Weaknesses	Opportunities	Threats
Electrolysis	• Plenty of natural resources for renewable energy production. • Favourable policy and directives framework (H_2 programmes). • Full value chain (Figure 64). • Great expertise for advanced materials and energy. • Full range of demonstration projects. • Emerging interest in zero emission zones in cities. • Effective support from public-private partnership (e.g. FCH JT). • Major electrolyser players located in Europe. • Strong electrolyser deployment.	• Limited number of uniform codes and standards. • Lack of mainstream public awareness. • SOFC is still immature, requiring further research on improving performance. • For alkaline and PEM, there is limited availability and high costs for small electrolysers. • Lack of after sales support. • Weak supply network (in terms of specialized consultants, engineers, entrepreneurs). • Lack of strong incentives. • Poor experience of potential end-users. • Inadequate commercialisation plan.	• Balancing the grid. • Potential of clustering supply chain actors. • Green hydrogen production. • Logistics sector might be deployed. • Emergence of large-scale markets for H_2. • Job opportunities in the whole value chain. • The EU is in pole position to commercialize storage and especially large-scale storage by electrolysis.	• Competition from other global locations. • Competition from other energy storage zero emission technologies. • Overpromising and underperforming • If produced at large scale, key components might start to come from China.
Compression and storage	• Potential for high density energy storage. • Electricity supply systems and chemical industry in favour of triggering large scale storage technologies. • Full range of demonstrations in EU. • Existing experience in handling of compressed gases and cutting-edge technologies.	• Additional costs and safety aspects. • Lack of ownership of joint strategy/roadmap. • A strongly interdisciplinary joint characterisation and demonstration platform for multi-functionality hybrid storage systems involving different kinds of manufacturers and utilities is missing.	• New process variants can lead to significant costs reduction, efficiency increase and new market applications. • Developments in several storage possibilities could trigger the involvement and inclusion of new value chain actors. • Market for reinforced composites is gaining strength.	• Competitiveness with other energy storage applications to provide grid services, such as Li-ion batteries. • Technologies such as liquid or solid storage (e.g. metal hydrides) are still at low TRL values, which hinders their deployment at the short term.
Transport	• Strong push from the mobility sector. • Expertise in cutting-edge technologies, favouring the development of innovative solutions for transport.	• Lack and uneven distribution of refuelling infrastructure. • High costs. • Lack of ownership of joint strategy/roadmap • Lack of awareness causing safety perceptions. • Large investments. • Limited volume injection in the grid allowed by current rules (2%), although methanation could lift to 100%. • Gas turbines and burners are sensitive to varied H_2 concentration. • Missing codes and standards.	• Synergies to other Power-to-X technologies and to CCU (Power-to-industry). • The market of power-to-gas is very interesting since CO_2 is a valuable source, which could trigger the deployment of a regional economy (e.g. SMEs involve in offering new solutions).	• Lock-in effects might appear within the value chain, hampering economic deployment. • Suppliers of key components not available, additionally hindered by external markets such as China. • Limited window opportunity. • Low acceptance level due to safety concerns among consumers.

Table 15: SWOT analysis of electrolysis value chain for the European landscape (Sources: HyTrEC[101]; EASE[102]; Jülich[103]; Roadmap to Flanders[39]; EU-Japan[104]; Tsoutsos et al.[105])

[101] Hydrogen Transport Economy for the North Sea Region, A Joint Hydrogen Strategy Framework for the North Sea Region,2015
[102] European Association for Storage and Energy (EASE) and European Energy Renewable Association (EERA), Joint EASE EERA recommendation for a European Energy Storage Technology Development roadmap towards 2030
[103] Jülich GmbH, Comparative analysis of infrastructures: hydrogen fueling and electric charging of vehicles. 2018
[104] EU-Japan Centre for industrial cooperation, Hydrogen technology market in Japan, 2016
[105] Tsoutsos, T.D., Zoulias, E.Y., Lymberopoulos, N., Glöckner, R. Analysis of the barriers for the hydrogen energy technology in stand-alone power systems

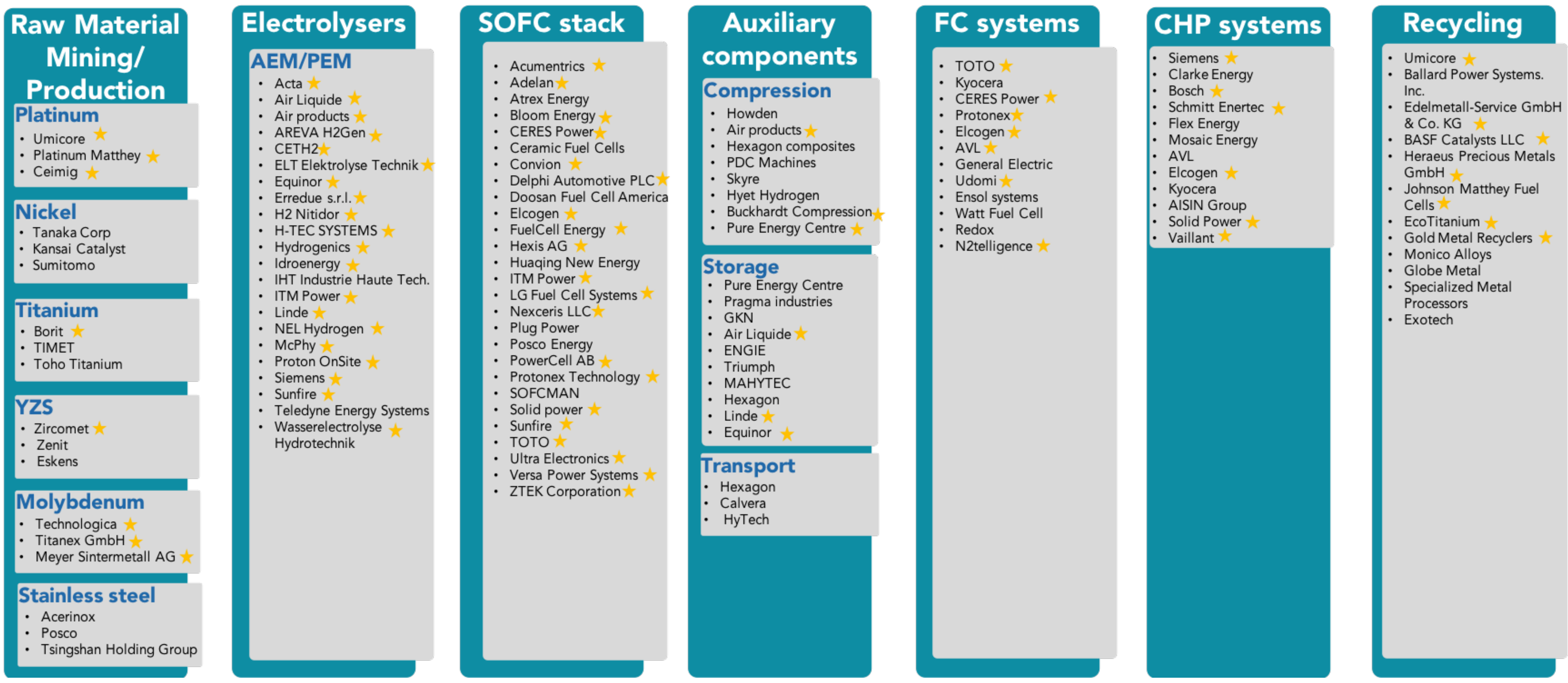


Figure 69 above illustrates the steps of the value chain for hydrogen production, along with the main players. European organisations are marked with a star.

As mentioned before,Manufacturing Equipment Testing Equipment Europe is strong in manufacturing of electrolysers, mainly AKE and PEME. However, SOE is expected to attract a lot of attention in the upcoming years.

More than half of all suppliers of electrolysers are located in Europe, including Nel (NO), McPhy (FR), Siemens (DE), ITM Power (UK), Sunfire (DE) and Areva H2Gen (FR).

Figure 69: Value chain and main players for hydrogen and fuel cells for stationary applications (non-exhaustive) (adapted by Bax & Company, sources: online web search, E4Tech, U.S. Department of Energy[50]).

"EUROPE IS STRONG IN MANUFACTURING OF ELECTROLYSERS, MAINLY AKE AND PEME. HOWEVER, SOE IS EXPECTED TO ATTRACT A LOT OF ATTENTION IN THE UPCOMING YEARS"

Current Status/Market Overview

Main trends

Hydrogen can enable full renewable energy system, providing the sector integration needed for the energy system transition and decarbonize energy end uses. The most important roles that hydrogen can play in energy transition are shown in Figure 70.

Hydrogen is a flexible energy carrier that can offer economically viable and socially beneficial solutions across different energy sectors: renewables, power generation, transportation, industry, building heat and power, among others.

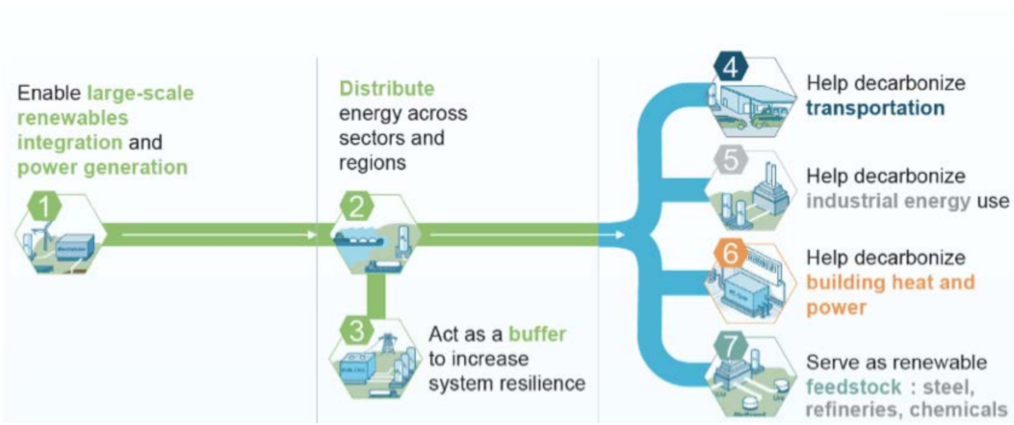


Figure 70: The seven roles of hydrogen towards decarbonization of major sectors (source: Hydrogen Europe[80])

It can potentially reduce CO_2 emissions by decarbonising heat cost effectively, as it can be seen in Figure 71 where the cost (€) per tonne of CO_2 is presented for different options. As the figure shows, hydrogen entails the lowest value of abatement.

With the increase in the renewable share of the energy mix that is expected in the next years, hydrogen can play a key role in balancing the varied electricity in the grid (Figure 72).

The need for hydrogen storage increases exponentially with the variable renewable share, for which the role of hydrogen in the upcoming years is heavily relying on its capacity to balance renewable electricity and hence secure energy transition.

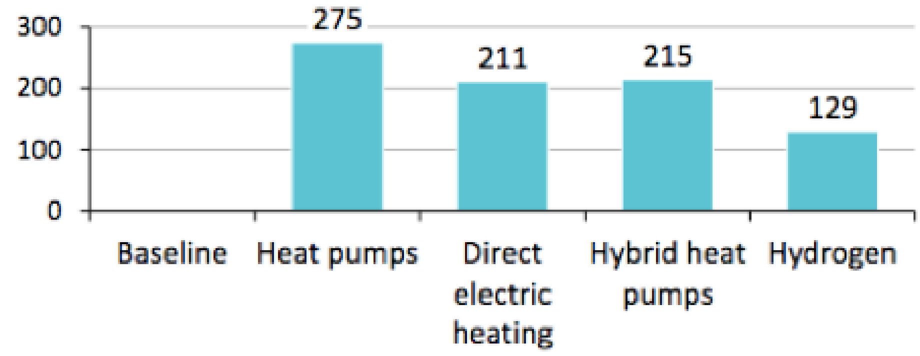


Figure 71: Abatement cost (€ per tonne of CO_2) for different decarbonizing heat options (source: Hydrogen Europe[80])

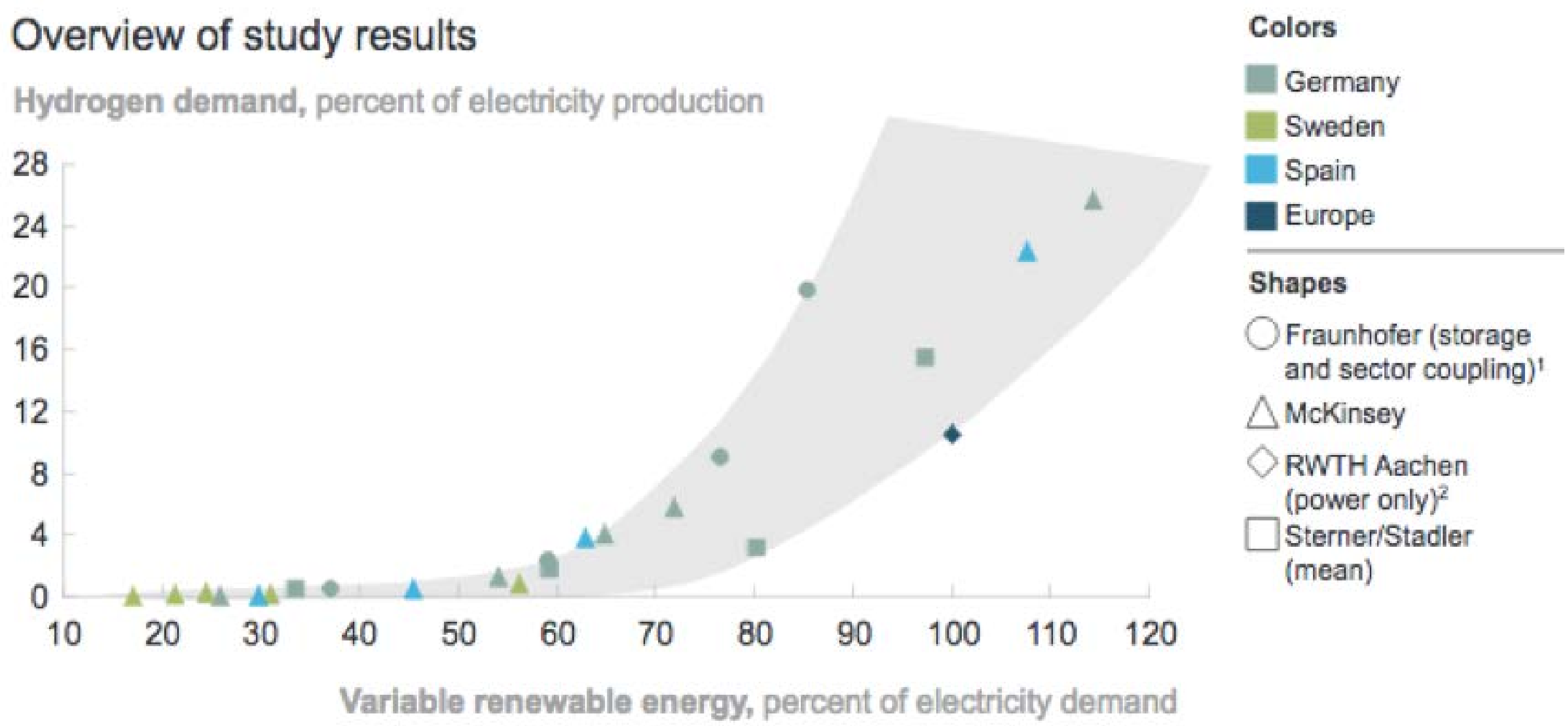


Figure 72: Hydrogen demand vs. variable renewable energy for different EU countries (source: Hydrogen scaling up[106])

[106] Hydrogen scaling up A sustainable pathway for the global energy transition. Hydrogen Council November 2017

Table 16 below summarises the main materials related challenges that need to be addressed for hydrogen for stationary applications and CCU within the next 10-15 years in order to increase Europe's competitiveness. The challenges were identified by the EMIRI community in workshops that took place throughout 2018.

Challenge	Application		
	H_2 Production	H_2 Use	CCU
• Reduce the costs of the system by developing new advanced materials and components	•••	•	••
• Improve performance by enhancing systems efficiency and conversion yield	•••	•	••
• Increase H_2 purity and pressure at the outlet	•••		
• Enhance the durability of equipment by increasing lifetime of stack, gas path components, membranes, catalyst and sorbents	•••	•	••
• Reduce the use of critical raw materials	•		
• Increase sustainability aspects related to recyclability	••	•	••
• Increase the multifunctionality of components	•		

• PEME • SOE • Alternative H_2 production • SOFC and turbines • Capturing technologies • Utilisation technologies

Table 16: Main materials related challenges to be addressed.

"HYDROGEN IS A FLEXIBLE ENERGY CARRIER THAT CAN OFFER ECONOMICALLY VIABLE AND SOCIALLY BENEFICIAL SOLUTIONS ACROSS DIFFERENT ENERGY SECTORS"

Proposed R&D topics

Table 17 below summarises the suggested calls to be included in the Horizon Europe framework program, based on the challenges identified above.

Identifier	Call Title	Type
H1S	Advanced materials for PEM electrolysers	RIA
H2S	Advanced materials for SO electrolysers (incl. co-electrolysis)	RIA
H3S	Advanced materials for the generation of clean hydrogen and/or syngas (not through electrolysis)	RIA
H4S	Advanced materials to enable carbon capture and purification (make CO_2 ready for utilisation)	IA
H5S	Advanced materials for electricity generation from H_2 (e.g. SOFC, gas turbines, or combination)	RIA
H6S	Advanced materials for catalytic conversion of CO_2 into fuels, chemicals, and e-fuels	RIA

Table 17: Suggested materials related calls for hydrogen for stationary applications & CCU technologies

Figure 73 below illustrates the importance and urgency of each call.

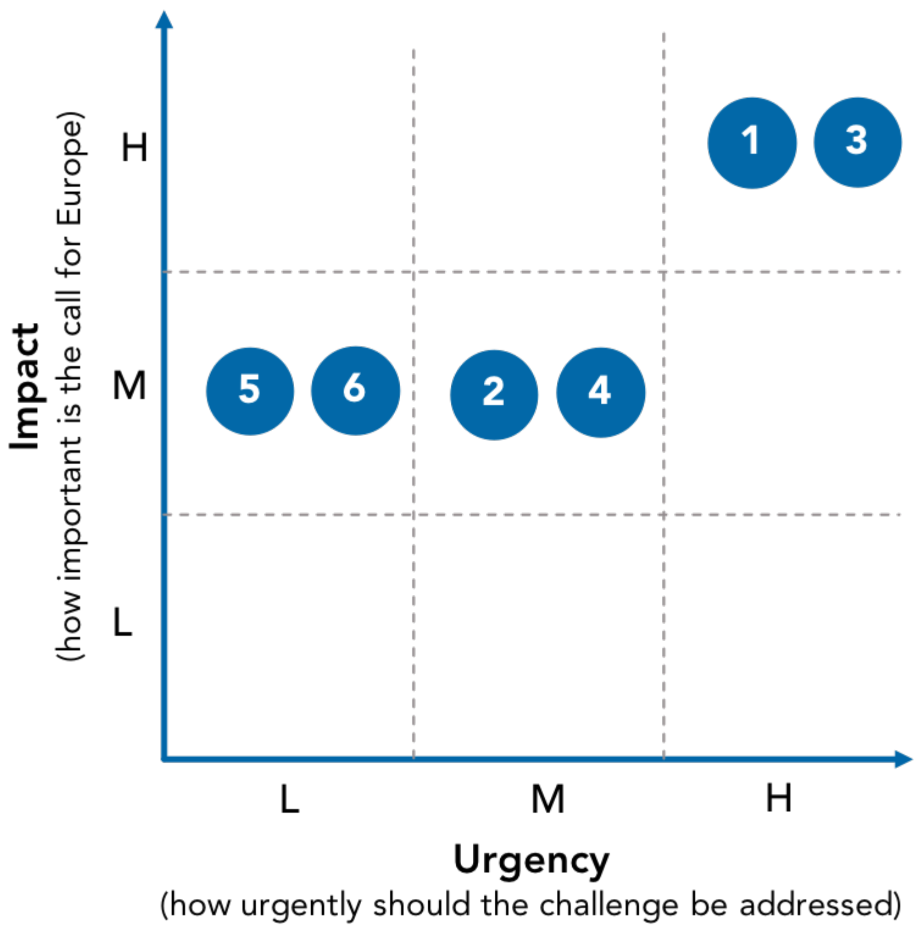


Figure 73: Prioritisation of hydrogen for stationary applications & CCU calls

4

SOLAR ENERGY HARVESTING

92 4. Solar Energy Harvesting

Solar energy has emerged as one of the most promising RES technologies which can contribute to the decarbonisation of the energy sector. This is due to the low cost and the large degree of expertise in the field. Harvesting of energy from the sun – and subsequent transformation to electricity – is mainly performed in two ways.

(PV) technologies are among the fastest growing renewable energy technologies and are expected to play a major role in the future global energy mix. In 2017, 99 GW of PV was installed worldwide (9 GW in Europe), leading to a total installed capacity of 404 GW worldwide (114 GW in Europe). According to an IEA report published in 2014, PV is expected to cover up to 16 % of global electricity demand in 2050, which will correspond to a total installed capacity of 4.5 TW, with an expected total investment of over US$7.8 trillion between 2015 and 2050[107]. However, due to the increased completeness of PV (which is already today one of the cheapest power generation technologies[108]), the International Technology Roadmap for Photovoltaics (ITRPV) has built more ambitious scenarios, suggesting a total installed capacity between 9 TW and 23 TW by 2050[109].

Concentrated solar power

(CSP) technologies, while still much lower in terms of global installed capacity compared to PV, are clearly attracting considerable interest. In terms of installed capacity and electricity generation, Europe is the global leader with an installed capacity of 2.3 GW, and total electricity generation of 5.6 TWh in 2017[110]. The European Solar Industry Initiative forecasts total installed CSP capacity in Europe could grow to 30 GW by 2020 and 60 GW by 2030[111]. This represents 2.4% and 4.3% of projected EU-27 electricity capacity in 2020 and 2030 respectively.

" PV IS EXPECTED TO COVER UP TO 16 % OF GLOBAL ELECTRICITY DEMAND IN 2050, WHICH WILL CORRESPOND TO A TOTAL INSTALLED CAPACITY OF 4.5 TW, WITH AN EXPECTED TOTAL INVESTMENT OF OVER US$7.8 TRILLION BETWEEN 2015 AND 2050

[107] International Energy Agency (IEA), Technology Roadmap. Solar Photovoltaic Energy, 2014 107
[108] Fraunhofer ISE, Levelized cost of electricity – renewable energy technologies, March 2018 108
[109] International Technology Roadmap for Photovoltaics (ITRPV), 2018
[110] IRENA, Solar Energy Data, 2018
[111] Emerging Energy Research, 2010

Technology Overview

PV modules are semiconductor devices that convert sunlight directly into electricity. A wide range of PV technologies is available on the market, using different types of materials, suitable for specific ranges of applications. Despite these differences, they all comprise a combination of interconnected PV cells and auxiliary components to form a PV module. PV cells are devices made from wafers of semi-conducting materials consisting of a positive P-type layer and a negative N-type layer joined together to form a "PN-junction". When exposed to sunlight, the photogenerated electrons move from the P-type layer to the N-type layer generating an electric current.

Figure 74 below shows the structure of a solar cell, as well as the hierarchy considered within the roadmap.

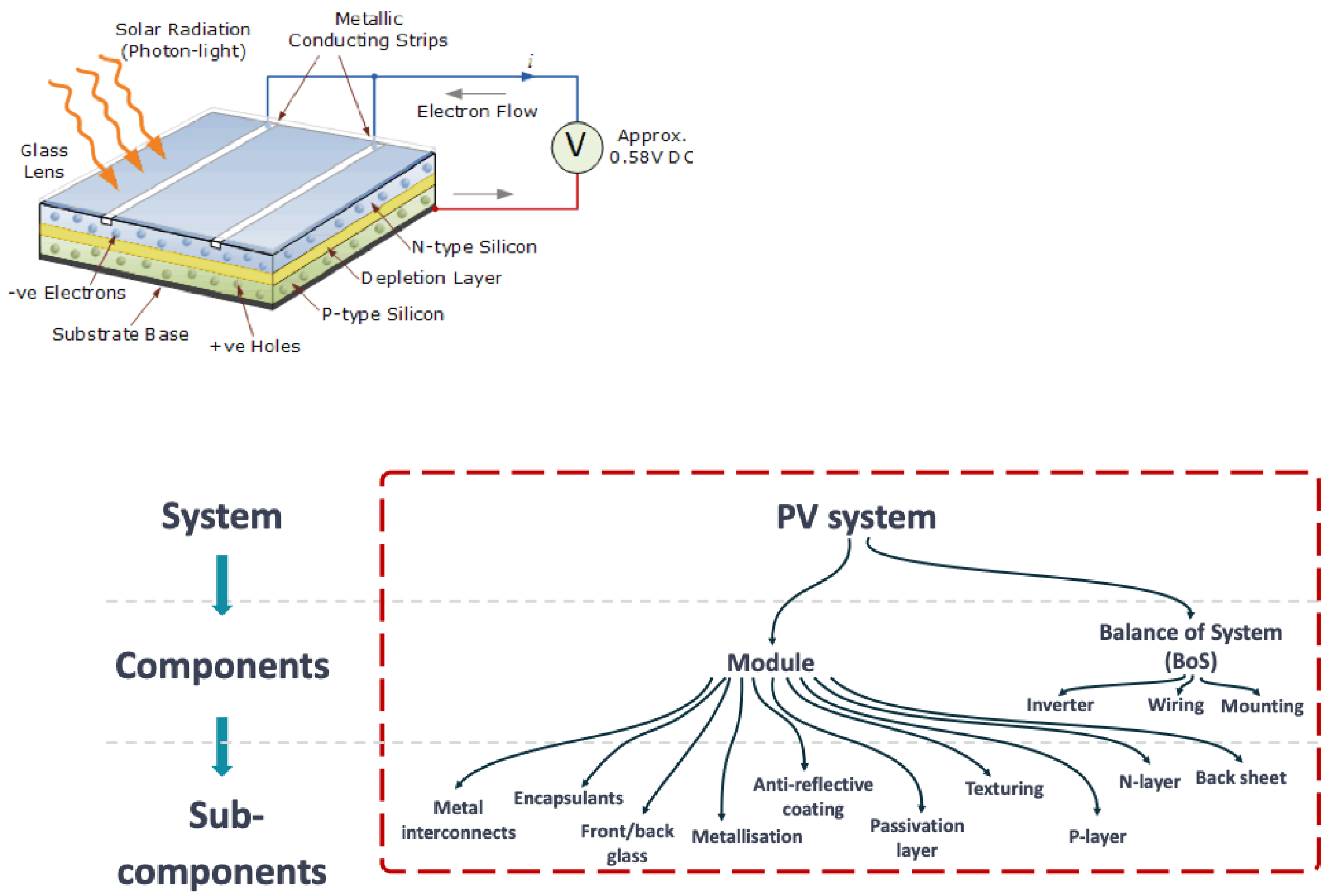


Figure 74: Main sub-components of a solar cell (top), component hierarchy (bottom) (source: Gupta[112], Bax & Company)

[112] Gupta, Pramod K. et al., Natural and environment favourable Dye Used as Light Sensitizer in Dye Sensitized Solar Cell: A Critical Review, 2017

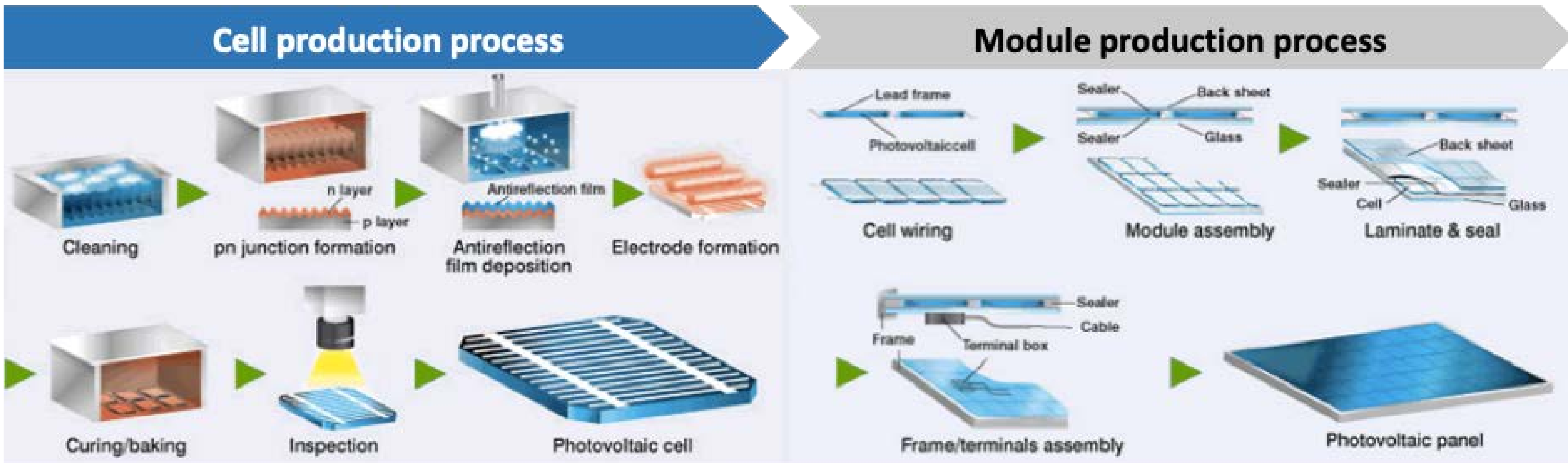


Figure 75: Silicon solar module manufacturing process (adapted by Bax & Company, source: Think-Solar-Power)

Solar module production includes multiple steps. Figure 75 below illustrates the manufacturing process for PV panels.

Besides harvesting through PV panels, solar energy can be also converted to electricity through heat by concentrated solar power used in large-scale solar thermoelectric plants (STE) of several thousand square meters at high solar irradiance. STE plants make use of the sun's normal irradiation, utilizing mirror configurations and optimal sun orientation to concentrate solar energy into receptor tubes. The receptors transmit heat through a heat transfer fluid (HTF) – either thermal oils, molten salt, or steam. Once the HTF has been heated up it can either be stored in molten salts tanks or it can be converted into steam for driving downstream a steam turbine which is connected to a generator that finally produces electricity.

CSP plants can either use parabolic trough technology or tower technology. In both cases, the principle is to concentrate sun irradiation in receiver systems in which HTF flows for collecting sun's heat. As of today, every single future CSP plant in the world will be built with Thermal Energy Storage using molten salt tanks. This capability of storing thermal energy makes CSP a dispatchable renewable energy technology. The CSP market is dominated by parabolic trough collectors and solar tower type plants, but linear Fresnel technologies are upcoming. A CSP plant is illustrated in Figure 72.
The rest of this chapter focuses on PV technologies. This is due to the considerably larger market potential

of PV compared to CSP, the higher overall improvement potential of PV technologies with investments in material R&D, and the focus of EMIRI members on PV rather than CSP.

There are several types of PV solar cells—differing in the semiconductor materials used and their layering—falling into three broad technologies: crystalline silicon, thin-film, and multi- junction.

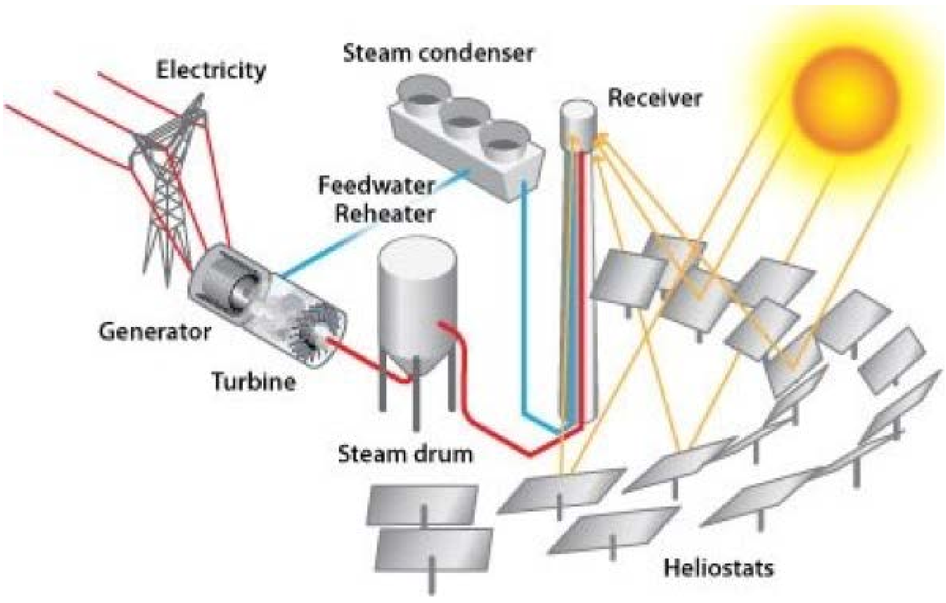


Figure 76: Power tower concentrating solar system components. (source: US Dept. of Energy)

"WAFER-BASED CRYSTALLINE SILICON (C-SI) HAS DOMINATED THE PHOTOVOLTAIC INDUSTRY SINCE THE DAWN OF THE SOLAR PV ERA, CURRENTLY ACCOUNTING FOR ABOUT 94% OF THE MARKET"

Crystalline silicon technologies

Wafer-based crystalline silicon (c-Si) has dominated the photovoltaic industry since the dawn of the solar PV era, currently accounting for about 94% of the market[113]. The large market share can be attributed to the high performances, low cost and high durability of the technology. Crystalline silicon cells are classified into two main types depending on how the Si wafers are produced;

Single crystalline silicon (sc-Si), sometimes also called monocrystalline (mono c-Si)
Multi crystalline silicon (mc-Si), sometimes referred to as polycrystalline (poly c-Si)

Thin-film technologies

Thin-film solar cells are made by depositions of multiple, very thin layers of semi-conductor materials. Film thickness in thin-films varies from a few nanometres (nm) to tens of micrometres (μm) – much thinner than conventional c-Si, which uses silicon wafers of up to 200 μm. After years of R&D efforts, thin films are beginning to be deployed in commercial applications. Thin-film technologies currently account for about 6% of total global PV production. The three types of thin-film solar cells which have reached mass production are:

Thin film silicon: amorphous silicon (a-Si) and micro-crystalline silicon (μ-Si)
$Cu(In,Ga)(Se,S)_2$ (CIGS),
Cadmium telluride (CdTe).
Other promising thin-film technologies include organic solar cells (OPV), perovskite solar cells (PSC), $Cu_2ZnSn(Se,S)_4$ (CZTS), and III-V epitaxial thin films.

[113] Fraunhofer ISE, Photovoltaic report, March 2019

Multi-junction technologies

Multi-junction (MJ) solar cells involve the use of several different materials stacked in multiple layers, or "junctions". As the junctions have different band-gaps, MJ technologies allow to capture the energy contained in a larger range of wavelengths of the incident light, increasing the efficiency compared to other technologies. As a result, they show great performance potential. MJ solar cells can be built by combining crystalline silicon with thin films (crystalline silicon/perovskite tandem, crystalline silicon/CZTS tandem, etc.), or by combining thin films with different materials and/or bandgaps (thin-film silicon, OPV, perovskites, etc.). A new promising field concerns the monolithic integration of III-V and IV based compounds for high efficiency four junction solar cells. MJ solar cells have different levels of maturity: some technologies have already reached the commercial stage (III-V MJ for space and terrestrial, high concentration applications, thin-film silicon MJ, etc.) while others are still at the development stage (notably the tandem cells based on crystalline silicon, which show a great potential for improving the current crystalline silicon technology[109] and reaching efficiencies beyond 30%), or the MJ cells based on the integration of III-V and SiGeSn[114].

Figure 77 below, shows the structure of a crystalline silicon-based tandem cell, using a perovskite thin film as a top cell, with the different layers of materials integrated into a single stack.

"MJ TECHNOLOGIES ALLOW TO CAPTURE THE ENERGY CONTAINED IN A LARGER RANGE OF WAVELENGTHS OF THE INCIDENT LIGHT, INCREASING THE EFFICIENCY COMPARED TO OTHER TECHNOLOGIES"

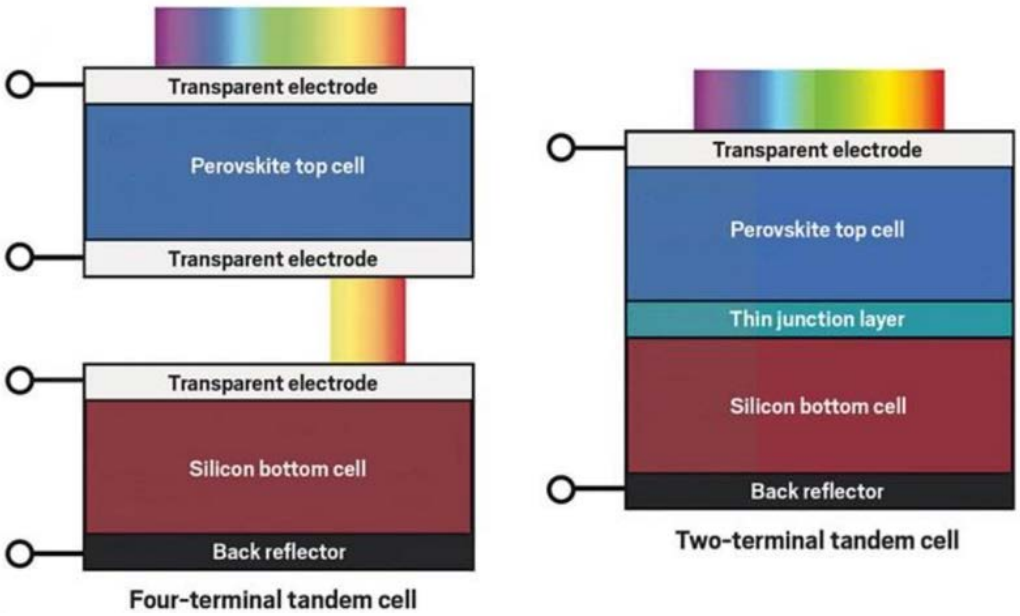


Figure 77: Structure of perovskite silicon-based tandem solar cell (source: Advanced Material Interfaces)

[114] R. Roucka et al., "Demonstrating Dilute-Tin Alloy SiGeSn for Use in Multijunction Photovoltaics: Single- and Multijunction Solar cells with a 1.0-eV SiGeSn Junction," IEEE J.Photovoltaics,2016

Type	Technology	Performance			Main Applications			
		Record cell efficiency[114]	Commercial module efficiency[113]	Module cost[113]	Rooftop	Building integrated	Ground-mounted	Space
Single junction	sc-Si	+++	+++	+	•	•	•	
	mc-Si	++	++	+	•	•	•	
	CdTe	++	++	+			•	
	CIGS	++	++	+	•	•	•	
	CZTS	+	N/A	N/A	•	•	•	
	OPV	+	N/A	N/A		•		
	Perovskite	++	N/A	N/A	•	•	•	
Multi-junctions	III-V MJ	++++	+++	--				•
	Thin-film Si MJ	+	+			•	•	
	Crystalline silicon/perovskite tandem	+++	N/A	N/A	•	•	•	
	CIGS/perovskite tandem	++	N/A	N/A	•	•	•	

Table 18: PV technologies

Record cell efficiency refers to the best solar cell efficiency obtained at laboratory level. It is measured in percentage; the percentage of energy transformed into electricity from the total energy harvested by the cell.

Commercial module efficiency refers to the efficiency of average commercial modules (if available). It is measured in percentage; the percentage of energy transformed into electricity from the total energy harvested by the module. Module cost refers to module cost per unit of output power (in €/Wp).

The main technologies along with their main attributes and applications, are presented in Table 18.

[115] M. A. Green et al., Solar efficiency tables (version 53), 2019

Figure 78 illustrates the evolution of cell efficiencies of the main PV technologies demonstrating the potential for efficiency improvement up to the theoretical efficiency limits.

New emerging materials represent a great opportunity to increase the efficiency of solar cells. Looking at solar efficiency records, the efficiency of multi-junction PV cells is the highest, and has increased more sharply than for other technologies. Similarly, the efficiency of perovskite-based cells has increased significantly in the last three years.

Despite the rapid progress of novel technologies, c-Si based PV technologies have historically clearly dominated the market and are expected to maintain a great share of the market for the next decades, as they still offer the best performance-cost ratio of all the commercially available PV technologies.

Figure 79 shows a comparison of efficiencies on cell and module level for the different technologies. Record OPV minimodule efficiency is 9.7, achieved by Toshiba in 2014[112].

"NEW EMERGING MATERIALS REPRESENT A GREAT OPPORTUNITY TO INCREASE THE EFFICIENCY OF SOLAR CELLS"

DESPITE THE RAPID PROGRESS OF NOVEL TECHNOLOGIES, C-SI BASED PV TECHNOLOGIES HAVE HISTORICALLY CLEARLY DOMINATED THE MARKET AND ARE EXPECTED TO MAINTAIN A GREAT SHARE OF THE MARKET FOR THE NEXT DECADES"

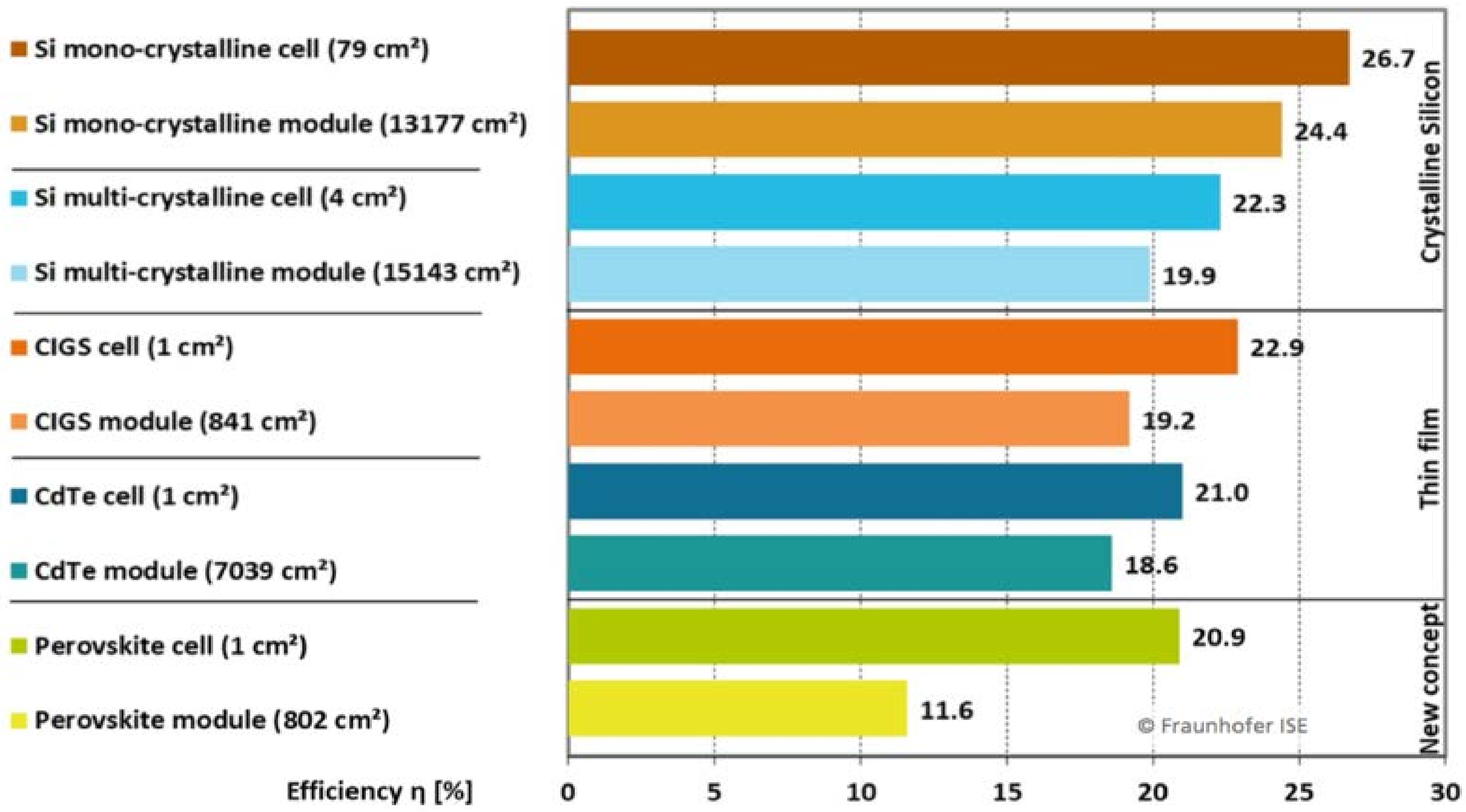


Figure 79: Comparison of efficiencies between different single junction PV technologies (sources: Fraunhofer ISE[113], Green[115])

[116] NREL, Best research cell efficiencies, 2019

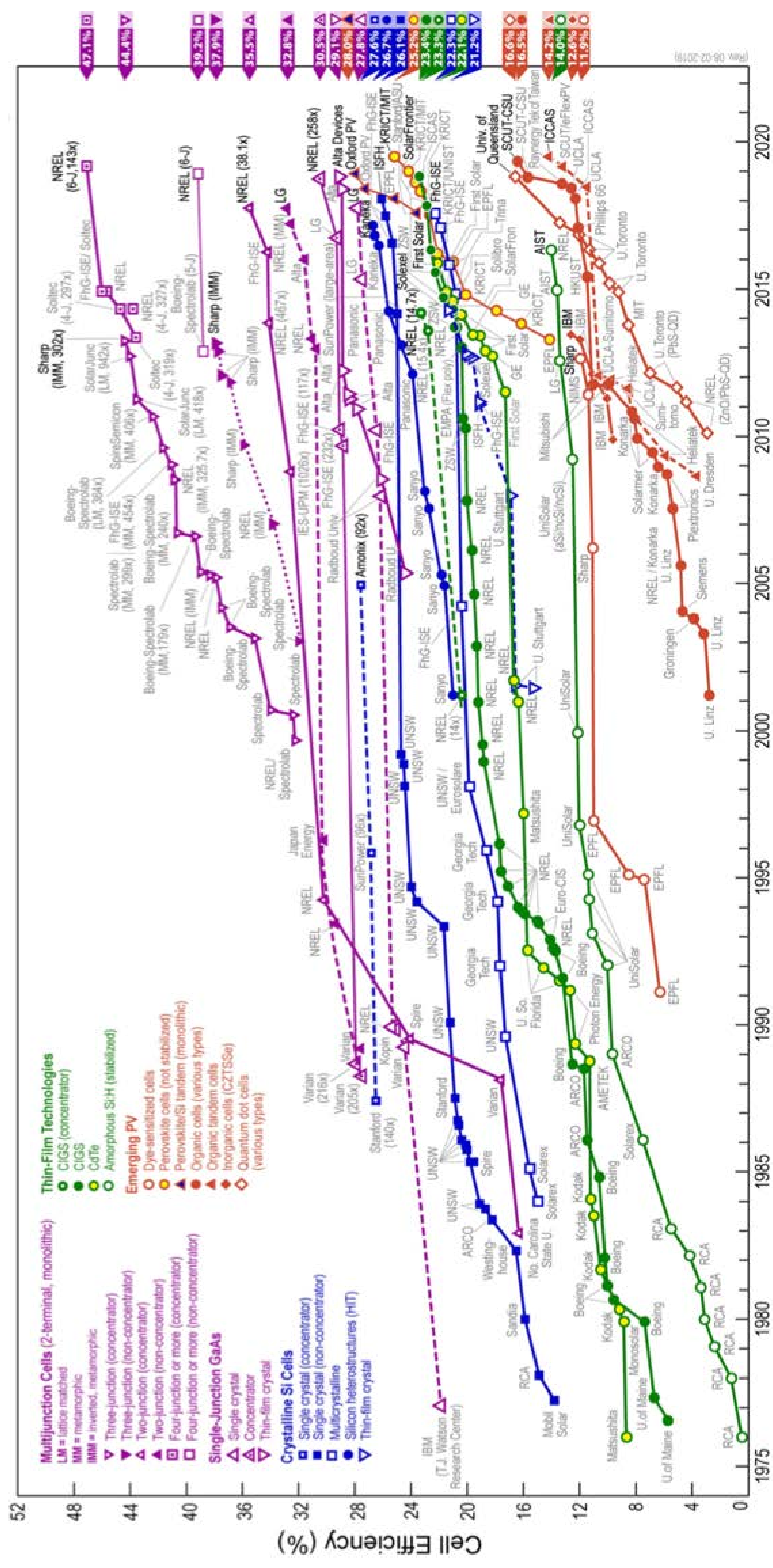


Figure 78: Development of laboratory solar cell efficiencies (source: NREL[116])

To further increase the efficiency of mass-produced c-Si modules, innovations will focus on the high efficiency cell designs. The industry-standard cell architecture (Aluminium Back Surface Field, Al-BSF) is expected to be replaced by more sophisticated structures, such as PERC (Passivated Emitter and Rear Cell), silicon heterojunction (SHJ) and interdigitated back-contact (IBC) cells. PERC cells can achieve higher efficiency – via the inclusion of a dielectric (insulating) layer at the back side, improved reflection – by virtue of its optical properties – and reduced surface recombination of the minority charge carriers. Figure 80 shows the schematics of an Al-BSF cell and a PERC cell.

Figure 81 represents the market share evolution of the different c-Si cell designs over the next decade. The current industrial standard design, BSF, is predicted to steadily concede market share to the PERC family. However, even as the industry embraces the PERC structure, large-scale manufacturing of even higher efficiency devices is growing at the same time. These include the silicon heterojunction (SHJ) cell, which uses layers of amorphous (non-crystalline) silicon to reduce recombination at the surfaces of the crystalline silicon wafer, the inter-digitated back contact (IBC) cell, that eliminates the busbars on the top of the cell leaving the front side free of shading, and crystalline silicon-based tandem cells for enhanced absorption of sunlight.

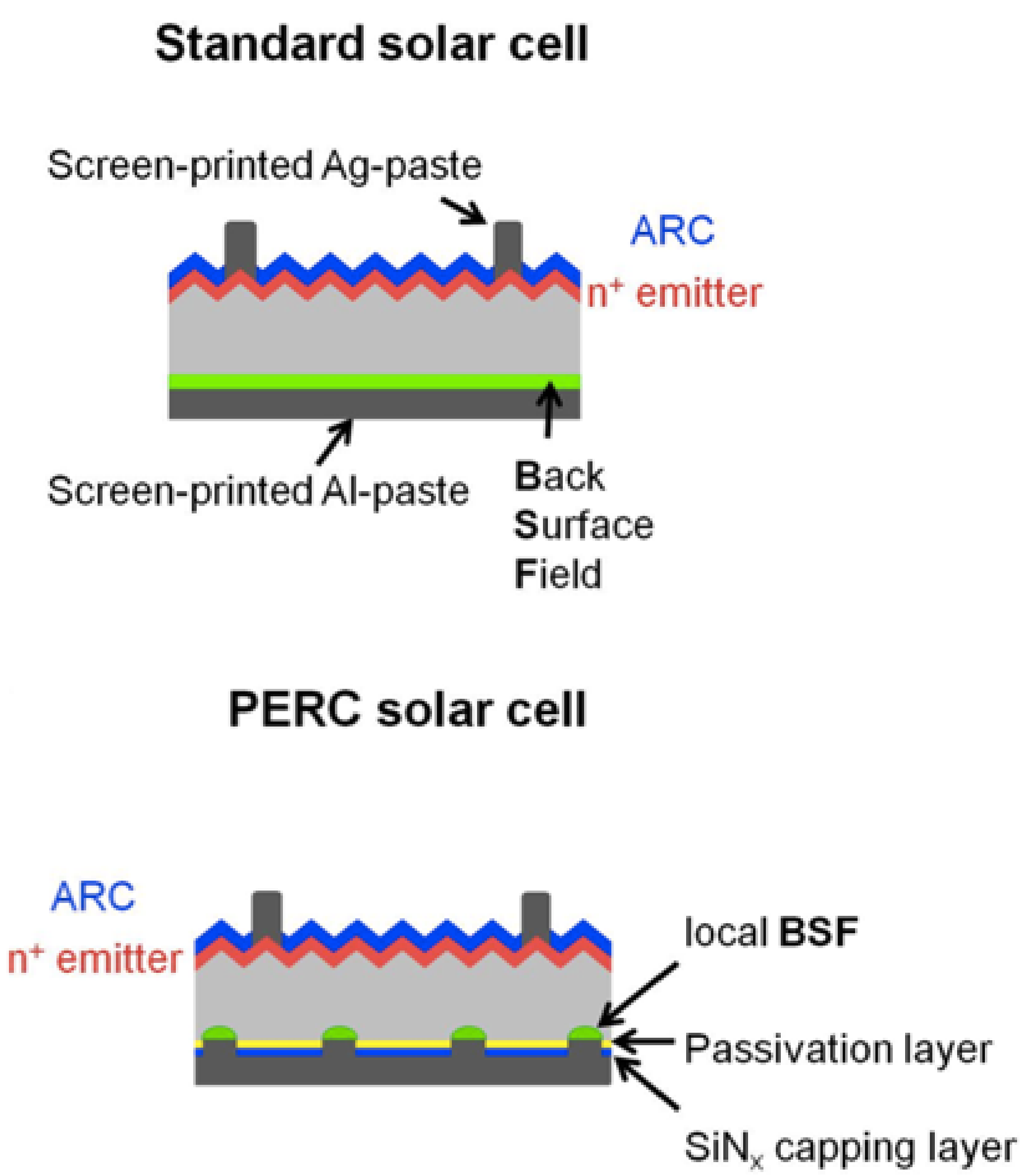


Figure 80: Comparison between BSF and PERL cell architectures. (source: ISFH[117])

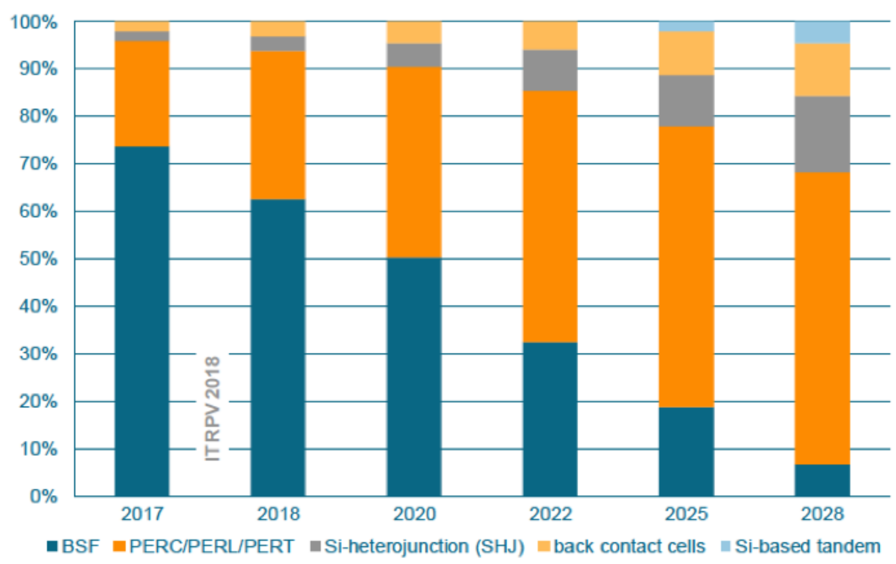


Figure 81: Worldwide market shares for different cell technologies (source: ITRPV[109])

[117] Institute for Solar Energy Research Hamelin, IFSH

Cost Structure

This section presents an overview of the cost breakdown and evolution in the last years. Figures focus on c-Si systems, as it is the one with the most comprehensive cost data among the prevalent technologies.

Figure 82 below shows the price evolution of c-Si modules with separate price trends for silicon, wafers, cells and modules. The inset shows the comparison of the proportion of prices attributable to each cost inductor and its evolution over the last years.

Materials play a very important role in the cost structure of PV modules, which means that research and innovation activities on advanced materials will be key to decrease the cost of PV technologies. According to the US Department of Energy (DoE), materials represent more than 60% of the total cost of a PV module.[118]

Looking at the main applications of photovoltaic technologies in the next decade, expected to be decentralised systems connected to the grid (rooftop, building integrated), the total cost of a large solar PV system (>100 kW) will decrease by 35%. As can be seen in Figure 83, the cost of solar modules is expected to decrease by 56% by 2028 as continuous research is expected to increase efficiencies and decrease costs.

Projections show a drastic decrease in the costs for PV systems, allowing to meet the cost targets for PV electricity generation in the Declaration of Intent (DoI) between EU industry, Member States and the Commission, of 20% lower turn-key system costs by 2020 and 50% by 2030, compared to 2015 levels[119] .

The learning curve shows that in the last 37 years, the module price decreased by 24% with each doubling of the accumulated module production. Cost reductions result from economies of scale, technological improvements, raw material cost, and others. Large deviations from the learning curve were caused by large market fluctuations, mainly between 2005 and 2008, due to silicon shortage as installed production capacity was not enough to meet the growing demand driven by governmental programmes for the deployment of solar PV.

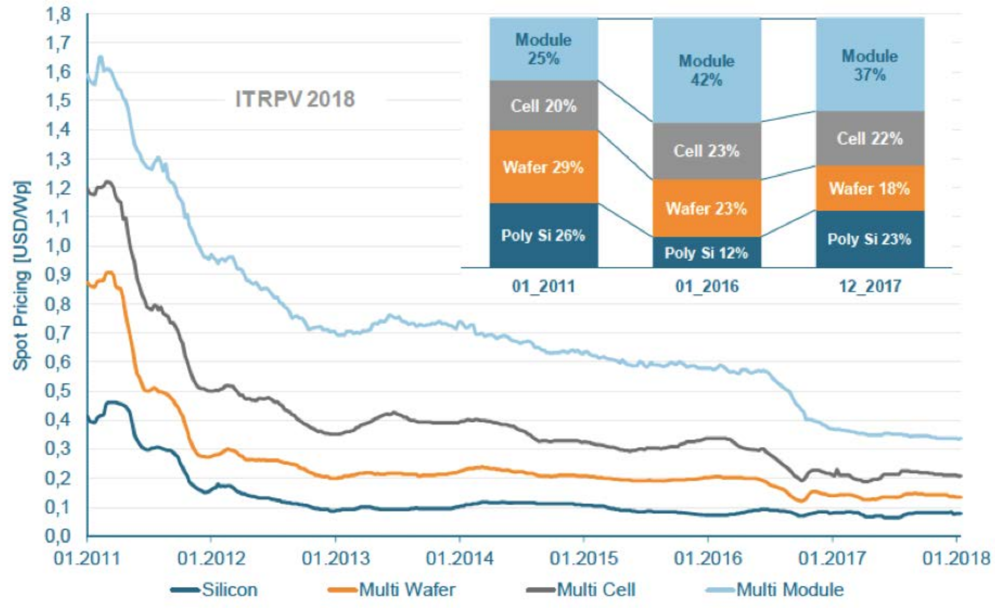


Figure 82: c-Si module component cost breakdown evolution (source: IRTPV[109])

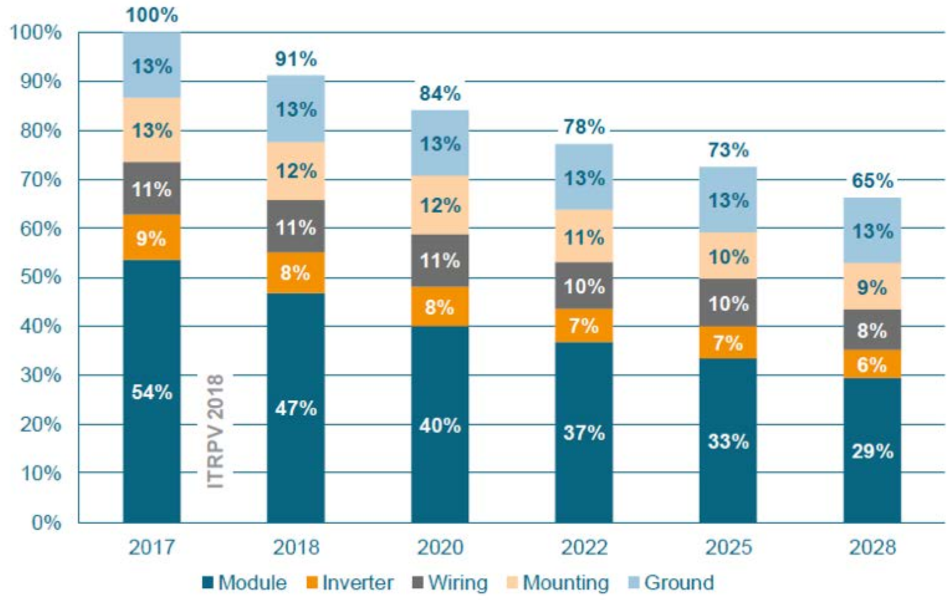


Figure 83: Relative system cost development for systems >100 kW in Europe (source: ITRPV[109])

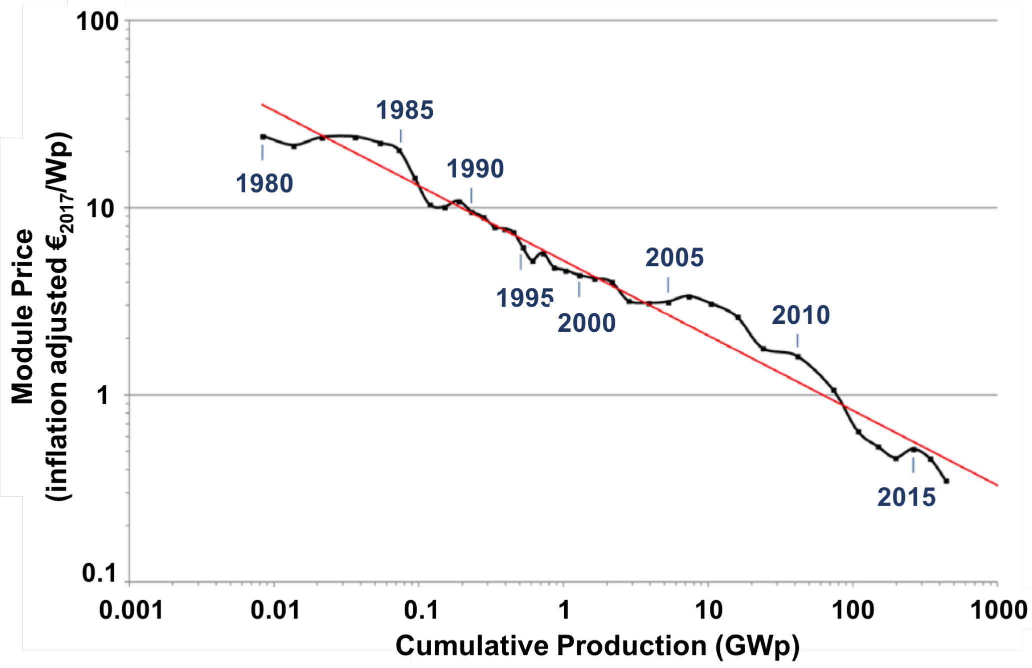


Figure 84: Learning curve for module price as a function of cumulative PV module shipments (source: Fraunhofer ISE[113])

[118] Clean Energy Manufacturing Analysis Center (CEMAC), 2015 Research Highlights, 2015.

[119] European Commission, Integrated SET Plan, Declaration on Photovoltaics (PV)

Market and applications

In 2017, in Europe, the residential segment accounted for 26% of the annual PV installations, the commercial segment 18%, the industrial segment 20% and the utility market 36%[120]. That means that about two thirds of solar systems in Europe found their place on the roof of buildings (residential, commercial and industrial) in 2017. According to Solar Power Europe, this dominance is expected to continue. In recent years, given the growing strategic interest in Zero-Energy Buildings (ZEB) and Plus Energy Buildings (PEB) for achieving EU policy goals, residential and commercial applications are emerging as areas offering strong growth potential.

"ABOUT TWO THIRDS OF SOLAR SYSTEMS IN EUROPE FOUND THEIR PLACE ON THE ROOF OF BUILDINGS

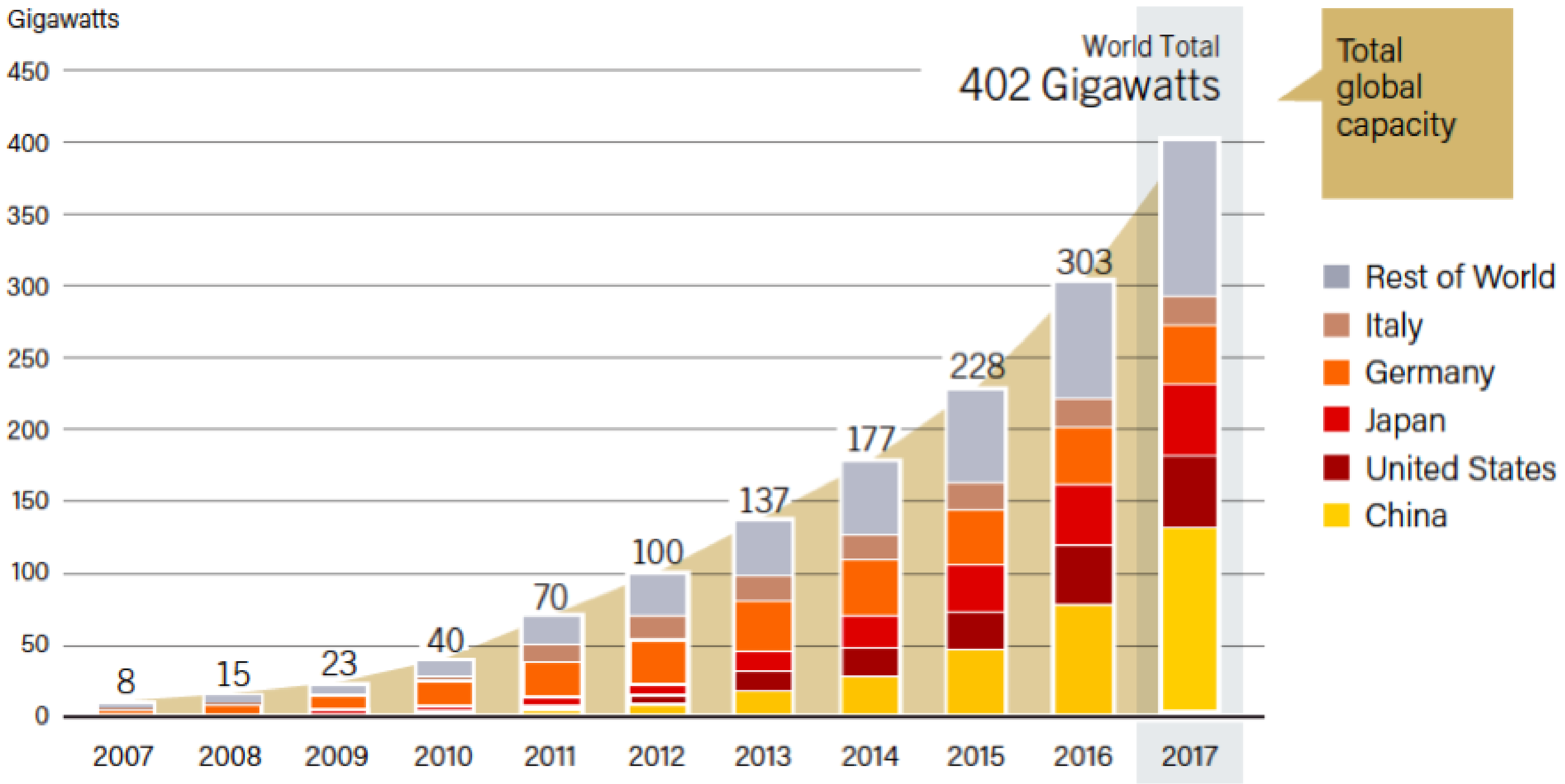


Figure 85: Installed solar PV global capacity, by country or region (source: REN21[121])

[120] Solar Power Europe, Global market outlook, 2018.
[121] REN21, Renewables 2018 Global Status Report, 2018

Residential and commercial applications can be divided between ones consisting of modules installed on building rooftops, and ones that integrate PV elements into the building envelope replacing conventional construction materials, known as building integrated photovoltaics (BIPV). BIPV is related to the development of cost-efficient technologies that introduce new functionalities for energy generation, allowing for the combination of new materials and concepts for energy harvesting with energy efficient building materials.
Focusing on installed capacity, among the leading countries, China has seen the highest increase since 2013, followed by Japan. Italy is the world leader in PV share in annual electricity generation, followed by Germany. Forecasts for the next decade indicate that Europe will be among the frontrunners with Italy obtaining 9% of the total electricity generation from PV, while Japan is expected to be second, with 8%.

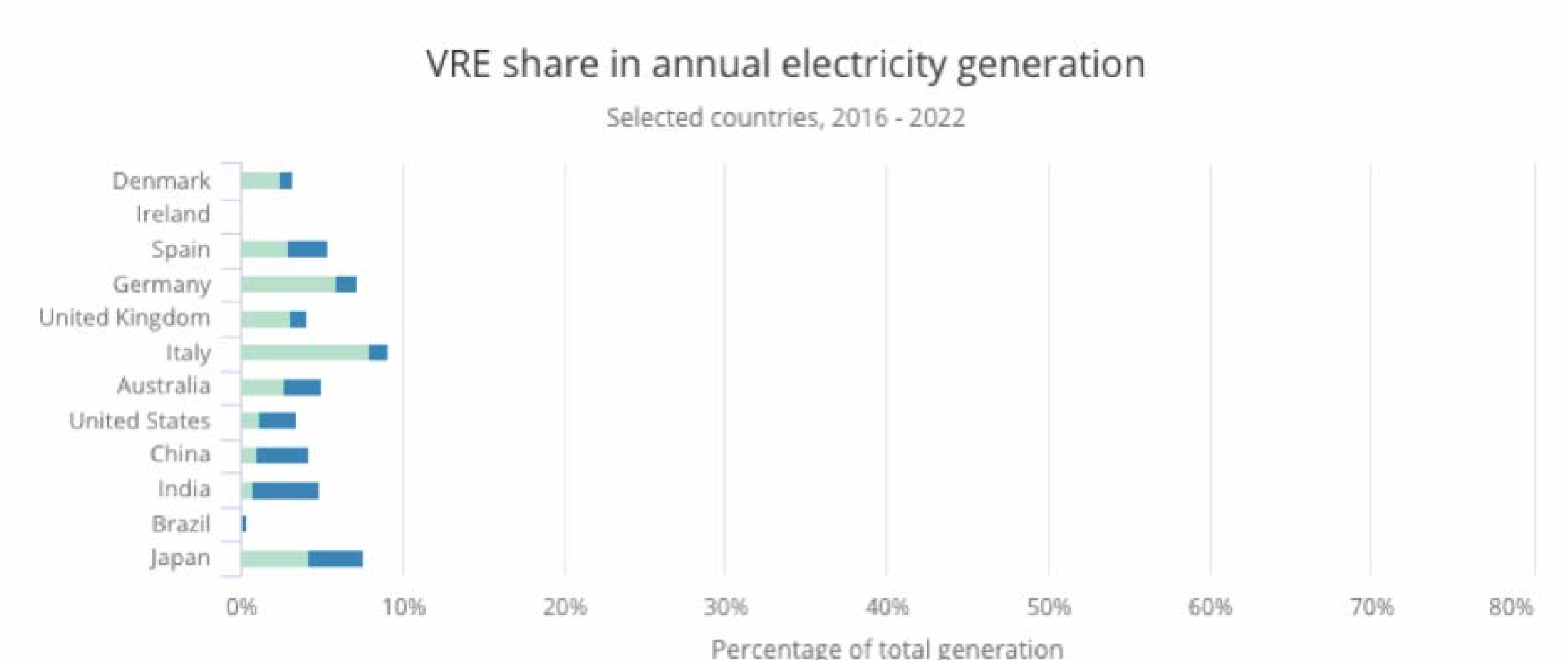


Figure 86: PV share in annual electricity generation (source: IEA[122])

[122] IEA, Renewables 2018. Market analysis and forecast from 2018 to 2023, 2018

As Figure 87 below shows, the European solar market progressed rapidly between 2008 and 2011. As a result, cumulated capacity grew by 90% (47,700MW). The solar market suffered from a considerable slowdown in 2012- 2013 largely caused by regulatory changes in several countries (e.g. Germany, Spain and Belgium) where public policies evolved to limit prosumers.

Examples are grid fees and the reduction/termination of incentive schemes. Home owners are therefore more cautious and have refrained from investing in PV on a large scale in recent years.

In parallel with the growth of the European market, productivity gains resulted in a decrease of 23% for the average solar PV system price in Europe over the period 2014-2016. In 2016, the average price for rooftop systems and for ground-mounted systems was 1,6€/W and 0.9€/W respectively. Assuming similar market trends for the next three to four years, the European PV market would surpass 150 billion euros.

When it comes to concentrated solar power technologies, while still much lower in terms of global installed capacity compared to PV, they are clearly attracting considerable interest. In terms of installed capacity and electricity generation, Europe is the global leader with an installed capacity of 2.3 GW, and total electricity generation of 5.6 TWh in 2017[106]. Interest is growing in the rest of the world with projects being launched in North Africa, the Middle East, India, China and South Africa. A significant part of the deployment will be located in developing countries where commercial and collaborative approaches can be undertaken for the mutual benefit of both parties. Europe as a pioneer in this technology and could utilise this to export technology to installations outside Europe. The European Solar Industry Initiative forecasts that the total installed CSP capacity in Europe could grow to 20 GW by 2030[124].This represent 2.4% of projected EU-27 electricity capacity in 2030.

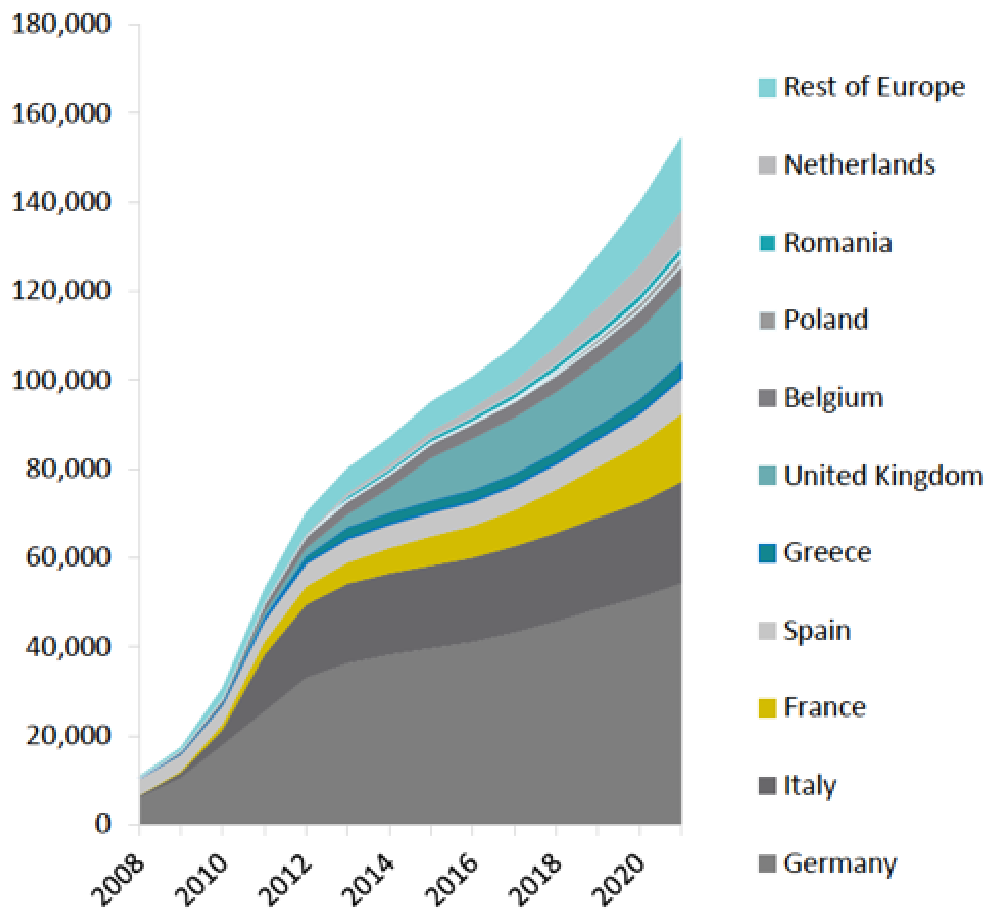


Figure 87: Cumulative installed capacity (MW) per country per year (source: Solar Power Europe[123])

" IN THE NEXT THREE TO FOUR YEARS, THE EUROPEAN PV MARKET WOULD SURPASS 150 BILLION EUROS.

[123] Solar Power Europe, Solar PV Jobs & value added in Europe, November 2017
[124] Emerging Energy Research, 2010

Value chain and key players

The PV value chain includes multiple steps, and presents opportunities for several stakeholders, from material suppliers to manufacturers to a multitude of sectors benefitting

Value Chain Step	Strengths	Weaknesses	Opportunities	Threats
Advanced Materials	• Good position in PV and CSP academic research and research capacity in industry • Strong knowledge and infrastructure in recycling technologies • Several leading European players in active materials • Major material and high-end processing equipment suppliers for CSP in Europe; market shares up to 50%	• Complete value chain is not covered in Europe • Not making full use of the existing IP in Europe	• Develop full value chain in Europe in order to have the whole market in Europe • Develop new materials enabling the development of upcoming technologies (e.g. high-efficiency crystalline silicon, tandem, BIPV) • Use the good expertise in semiconductor industry and digitalisation (industry 4.0) in Europe to gain a competitive advantage • Become the dominant player in developing improved technologies for recycling of PV modules • Improve materials to help reduce the total cost of the system	• Manufacturing infrastructure of European players could be developed outside Europe • Increasing energy cost increases the cost of production for active materials can favour other, less energy-intensive power generation technologies • Increasing expertise and IP outside of Europe
Solar Cell/Modules Making	• Strong cooperation between industry and academia • Modelling & simulation expertise • Strong, world level silicon wafer industry	• Shrinking manufacturing capacity in Europe • Cell design skills • Manufacturing capacity outside Europe – mainly in Asia	• Use the good expertise in digitalisation (industry 4.0) in Europe to gain a competitive advantage • Open new markets by electrifying rural dwellings in developing, Mediterranean countries eager to cooperate with Europe • Develop manufacturing capacity for the upcoming technologies (e.g. high-efficiency crystalline silicon, tandem, BIPV) before Asia dominates	• Slow expected ROI (5-10 years) • Dependence on companies outside of Europe
Integration into Applications	• High public acceptance of PV technologies • Existing European standards • Several European end-users (mainly in the fields of CPV and grid distributed) • Operational CSP installations have predictable and stable source of energy following the demand curve with capacity factor > 50% all the year long	• Lack of harmonisation of the Member States' policies and regulatory frameworks • Direct Normal Irradiation (which determines CSP profitability) is larger in some areas outside Europe (California, Chile Algeria, South Africa,..), but still remains high in Southern countries (Spain, Portugal, Italy, Greece, Cyprus,..) • End-market of CSP is still limited as the level of worldwide implementation of CSP is only 3GW	• Strong interest from companies to increase reliability of systems (with the aim of decreasing maintenance costs) • Coordinate PV developments with ones in stationary batteries to create robust energy generation and storage systems • Increasing number of policies that accelerate uptake of RES at national or local level • Technology and legal base to create a "closed loop" PV industry (using recycling for modules) • Significant market anticipated in EU for both PV and CSP • Demand for new materials and upgraded equipment to continue CSP efficiency increase and cost reduction in and outside Europe (MENA region) • Cost saving in CSP by 50% is expected by 2025	• Companies see emerging technologies with reluctance (mainly due to high cost and non-proven reliability) • Most investors focus on CAPEX than OPEX since it has short-term impact (which pushes cheaper technologies with potentially lower efficiencies and higher maintenance costs)

Table 19: SWOT analysis of solar energy harvesting technologies for the European landscape (sources: EMIRI community[125], EC[126])

[125] Input from EMIRI workshops

[126] European Commission, Strengths, Weaknesses, Opportunities and Threats in Energy Research, 2005

Players in the CSP value chain are listed in *italics*

*Other components include: glass, coating, back sheets, encapsulants, metallisation, etc.
**Includes silicon, thin film and multi-junction technologies
***BoS includes: inverters, cables, mounting systems, and other components

Figure 88: PV/CSP value chain and main players (non-exhaustive) (adapted by Bax & Company, sources: EC[127], ENF Solar, HIS Markit, Solar Power Europe)

Figure 88 above illustrates the steps of the value chain, along with the main players. European organisations are marked with a star. As can be seen, Europe is quite strong in advanced materials, novel technology cell and module production, as well as manufacturing equipment, but is lacking capacity in silicon cell and module manufacturing.

" EUROPE IS QUITE STRONG IN ADVANCED MATERIALS, NOVEL TECHNOLOGY CELL AND MODULE PRODUCTION, AS WELL AS MANUFACTURING EQUIPMENT, BUT IS LACKING CAPACITY IN SILICON CELL AND MODULE MANUFACTURING.

[127] JRC Science for policy report, PV Status Report 2017

The PV industry has changed dramatically over the last few years. In Europe, the rapid growth of the PV market has not resulted in a similar growth in the production capacity of solar cells and modules. Following an initial globally strong position, the EU PV industry market share shrunk from approximately 35% in 2009 to around 5% of the total MWp produced (Figure 89), due to strong competition. China has become the major manufacturing country for solar cells and modules, followed by Taiwan. Amongst the 20 biggest cell manufacturers in 2016, only one had solar cell production facilities in Europe.

Despite the decrease in manufacturing capacity, Figure 86 shows that the PV industry in Europe still contributes to creating a positive socio-economic value. After a very strong drop in job creation between 2008 and 2016, a recovery is forecasted through to 2021, with an expected creation of more than 170,000 FTE jobs. This recovery may be explained in larger quantities due to the strategic plans developed by European countries to increase the shares of renewables in the energy mix, resulting in ambitious forecasts of new installed capacities and large investments.

In terms of the PV value chain, downstream activities, meaning services provided within the PV industry such as engineering/studies/ administration, installation, operations & maintenance and decommissioning, are expected to represent the largest job share.

For Europe to regain a leading player role in the solar cell manufacturing market, policy efforts are needed to revitalise the European PV manufacturing industry. Europe still has an excellent PV R&D infrastructure along the value chain, and some world-leading material manufacturers and production tool suppliers, but it will only be possible to maintain this in the long run if industry players along the value chain, including PV manufacturing, are operating in Europe. In particular, Europe can play a leading role in the manufacturing of emerging technologies, including high-efficiency crystalline silicon (silicon heterojunction cells, back-contact cells, tandem cells) and BIPV.

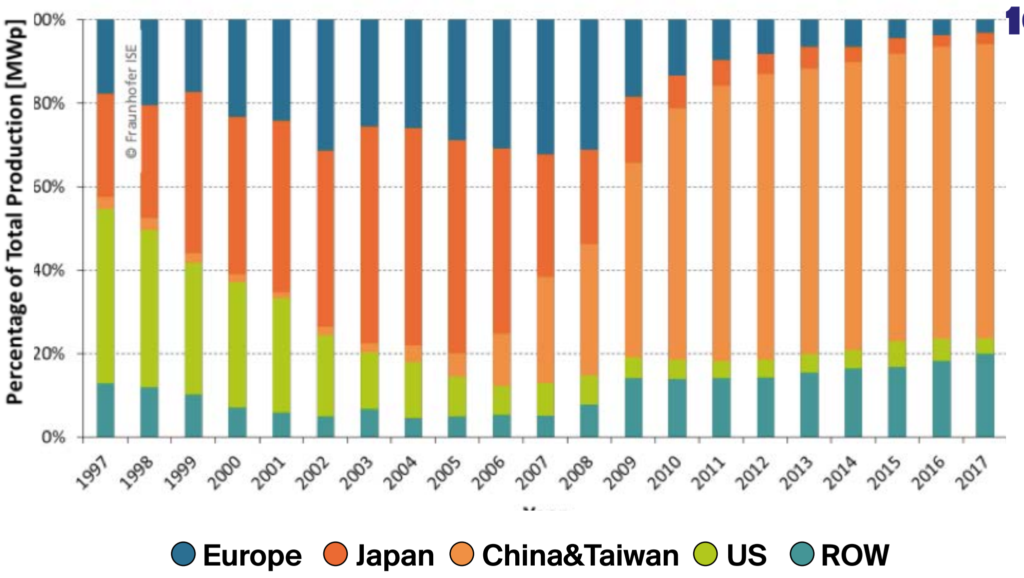


Figure 89: PV module production by region (source: Fraunhofer ISE)

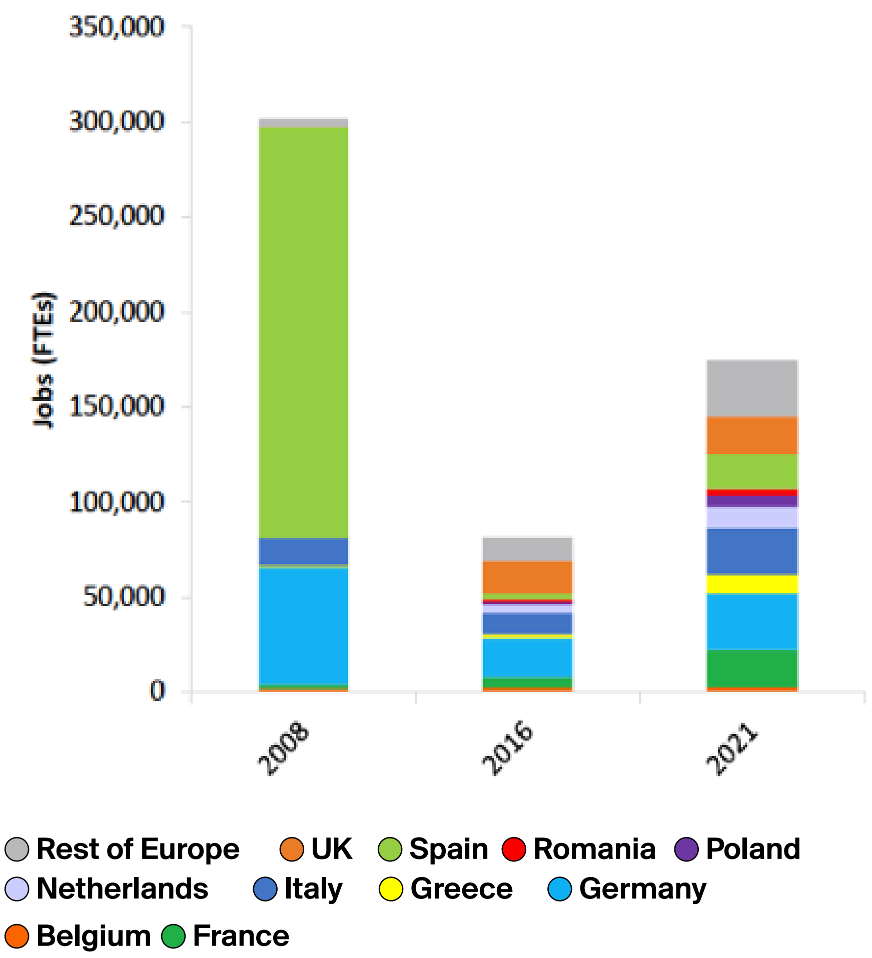


Figure 90: Direct and indirect jobs, up- and downstream, supported by the PV industry in EU 28 (source: Solar Power Europe[123])

"
EUROPE CAN PLAY A LEADING ROLE IN THE MANUFACTURING OF EMERGING TECHNOLOGIES, INCLUDING HIGH EFFICIENCY CRYSTALLINE SILICON

"
FOR EUROPE TO REGAIN A LEADING PLAYER ROLE IN THE SOLAR CELL MANUFACTURING MARKET, POLICY EFFORTS ARE NEEDED TO REVITALISE THE EUROPEAN PV MANUFACTURING INDUSTRY

Current Status/Market Overview

Main trends

This section lists the main trends that drive the growth of the global PV market.

Small-scale decentralised installations

Small solar systems are the backbone of a digitalized, decarbonized, distributed and democratized energy system (4D), which empowers consumers and territories (e.g. households, hospitals, public buildings, hotels, etc.) with cleaner, cheaper and local electricity. They have the potential to support the competitiveness of local businesses, revive rural areas and foster sector-coupling synergies at all levels of society, enabling future economic growth and job creation.

Driven by environmental sensitivity and – in cases – financial incentives, decentralised energy harvesting installations in residential or commercial buildings have been increasing. Combined with the decreasing prices of PV panels, this trend contributes to increasing the demand for PV panels.

Figure 91 below depicts the growing market of residential PV installations, with Europe being a frontrunner.

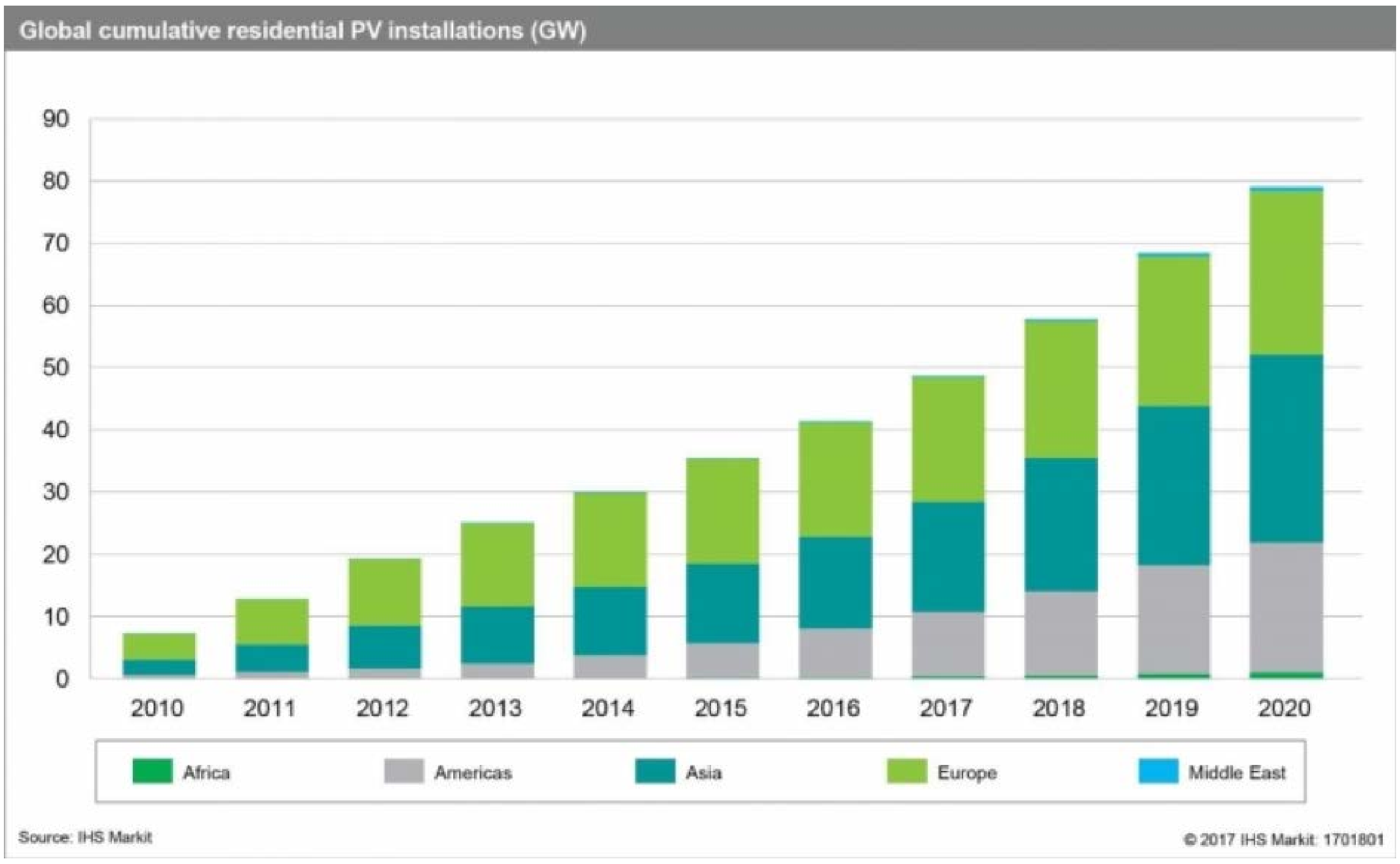


Figure 91: Global cumulative residential PV installations, in GW (source: HIS Markit)

The integration of high shares of variable renewable energies (VRE) into energy systems requires the modification of policies, standards, and market and regulatory frameworks to effectively harness the benefits that can be derived from renewables, while ensuring system reliability and security of supply. Table 20 below mentions some of these supporting policies to the deployment of distributed renewable energy generation.

Battery energy storage

A major trend linked to the deployment of solar is its co-location with stationary battery storage. Storage adds flexibility and hence accelerates deployment of solar PV.

Since the solar supply curve is variable and coincides only partially with the demand curve, combining solar harvesting and energy storage allows storing the surplus energy generated during daylight and use it when demand is high. These capabilities make it possible for solar and storage to operate with the functional equivalence to fossil-based generators. As a result, fluctuations in the energy prices are reduced, while improving system reliability and operation.

Figure 92 below shows the increasing global market for distributed solar-plus-storage systems in the residential, commercial and off-grid/remote sector market segments. The numbers reflect the increasing importance of distributed solar PV; in the next decade, solar and battery storage systems will reach 27.4GW worldwide and are expected to be worth more than US$49.1 billion, with Asia and Europe leading the way.

Country	Regulatory policies		Fiscal Incentives and Public Financing		
	Feed-in tariff	Net metering/ billing	Reduction in taxes	Energy production payment	Public loans, grants or subsidies
Australia	◖	◖			•
Belgium		◖	•		◖
Canada	◖	◖	•		•
China	•		•	•	•
Denmark	•	•	•		•
France	•		•		•
Germany	•		•		•
Italy	•	•	•		•
Japan	•		•		•
Netherlands	•	•		•	•
Norway			•		•
Spain				•	•
Sweden	•		•		•
United Kingdom	•		•	•	•
United States	◖	◖	•		•

• Existing national policy or tender framework (could include sub-national)
◖ Existing sub-national policy or tender framework (but no national)

Table 20: Renewable energy support policies (source: Bax & Company based on Renewables 2018 Global Status Report; REN21[121])

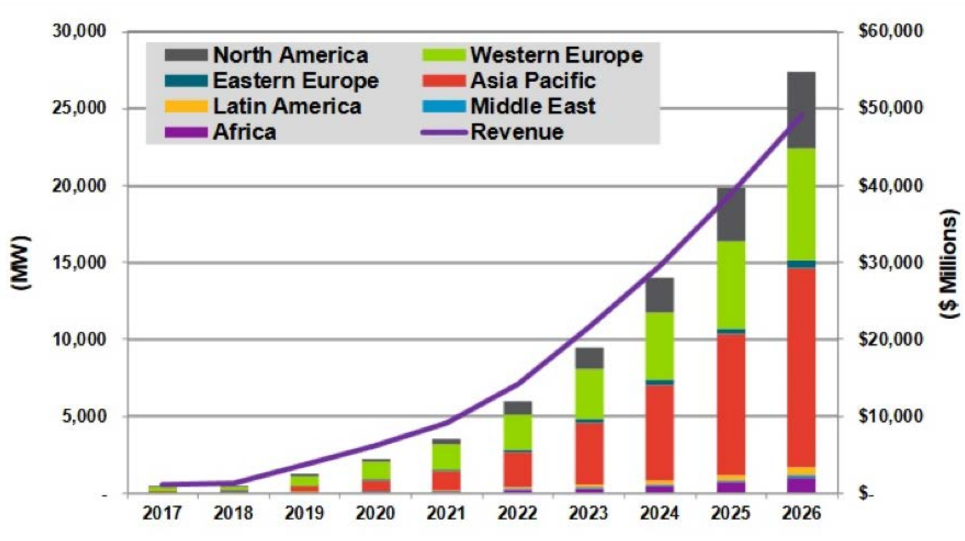


Figure 92: Installed PV-plus-energy storage power capacity and vendor revenue by region (source: Navigant Research[128])

[128] Navigant Research, Distributed Solar PV Plus Energy Storage Systems, 2017

Main challenges

Table 21 below summarises the main materials related challenges that need to be addressed – per technology and application sector – within the next 10-15 years in order to increase Europe's competitiveness. The challenges were identified by the EMIRI community in workshops that took place throughout 2018.

Challenge	Application			
			BIPV	
	Grid distributed	Grid centralised	Opaque elements	(semi) transparent
• Reduce the cost of electricity generation	●●●	●●●	●●	●●
• Reduce the weight of components to achieve lightweight solar modules	●●●	●●	●●	●●
• Increase the reliability and expected lifetime of modules	●●●	●●●	●●	●●
• Improve the efficiency and performance ratio of solar modules	●●●	●●	●●	●●
• Reduce the cost of photovoltaic modules	●●●	●●	●●	●●
• Reduce the ecological footprint and increase the recyclability of module components	●●●	●●		
• Develop modularization and customizable design strategies			●●	●●
• Develop non-intrusive solar modules	●●●		●●	●●
• Increase mechanical flexibility for the integration of PV on building elements			●●	●●
• Further develop absorber and find alternative HTF material to achieve higher working temperatures, reliability, and overall higher efficiency		●		

Table 21: Main materials related challenges to be addressed

Proposed R&D topics

Table 22 below summarises the suggested calls to be included in the Horizon Europe framework program, based on the challenges identified above.

Identifier	Call Title	Type
SP1	Innovative materials and production processes for high-performance crystalline silicon photovoltaics	IA
SP2	Innovative materials and production processes for cost-effective and sustainable crystalline silicon photovoltaics	IA
SP3	Materials and processes for silicon-based tandem photovoltaics with perovskite top cell absorbers	IA
SP4	Materials and processes for advanced cost-efficient thin-film PV	RIA
SP5	BIPV for opaque elements (incl. c-Si & thin-film)	IA
SP6	Materials and processes for next generation (semi)transparent BIPV	RIA
SP7	Materials and processes for silicon-based tandem photovoltaics with advanced top cell absorbers	RIA
SP8	Advanced materials and coatings and innovative designs for durable and more efficient solar energy harvesting in Concentrated Solar Power (CSP)	RIA
SP9	Materials and processes for next generation cost effective MJ cells and arrays for CPV and Space	RIA

Table 22: Suggested materials related calls for solar energy harvesting technologies

Figure 93 below illustrates the importance and urgency of each call.

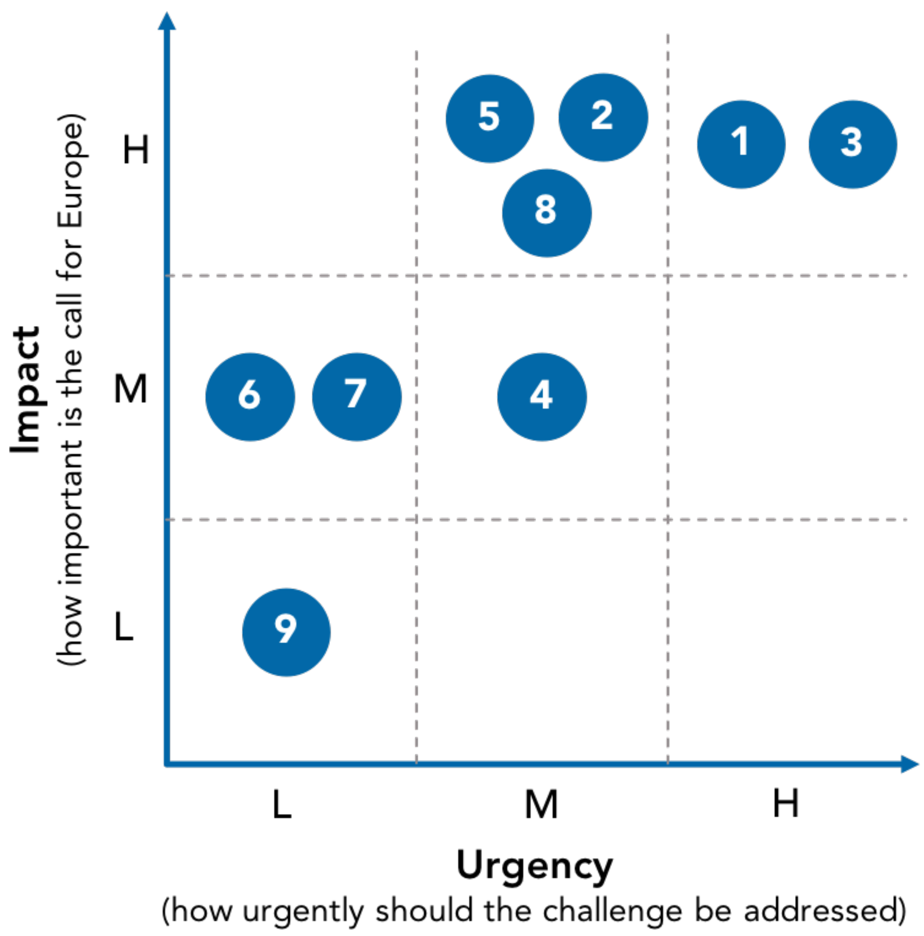
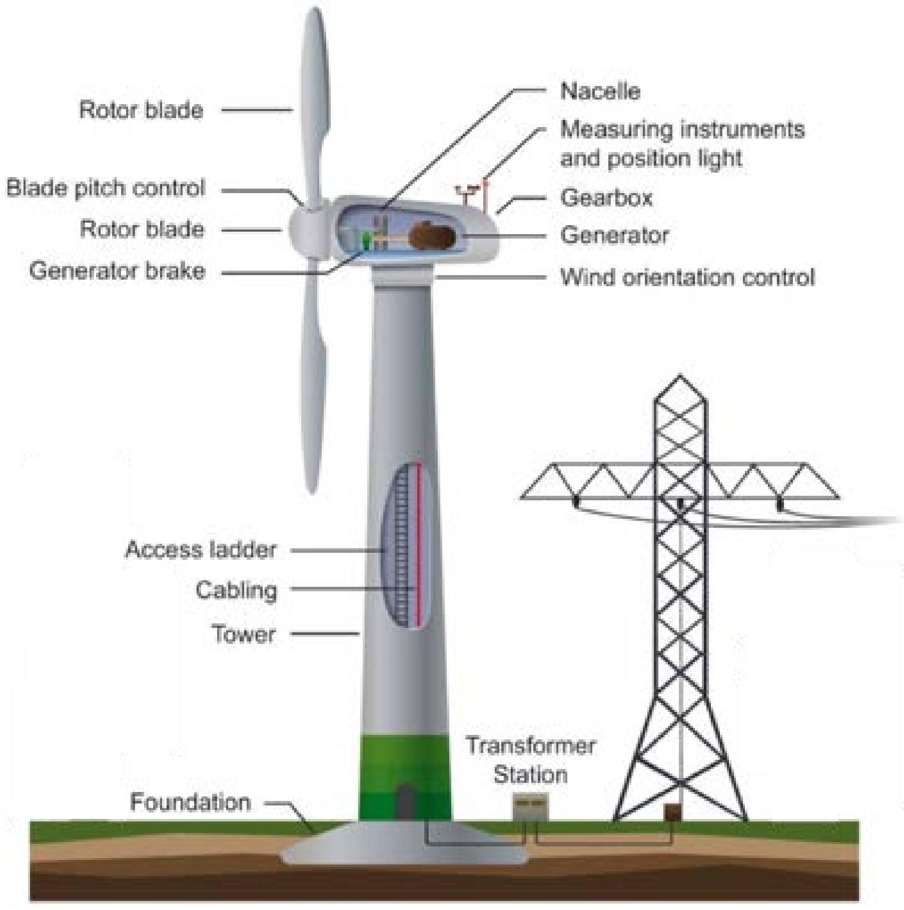


Figure 93: Prioritisation of solar energy harvesting calls

5

WIND ENERGY HARVESTING

Wind power has been used by humankind since antiquity as a large-scale source of power. However, during the nineteenth and twentieth century, its importance as an energy source declined due to the low cost and high availability of thermal cycles based on fossil fuels. The end of the twentieth century saw the rebirth of wind power, with the start of mass production of small capacity wind turbines that pioneered the development of the modern wind power industry of today. Currently, wind power is one of the fastest-growing renewable energy technologies. Global installed wind-generation capacity – including onshore and offshore – has increased by a factor of almost 50 in the past two decades, jumping from 7.5 gigawatts (GW) in 1997 to some 514 GW by 2017 [129] .



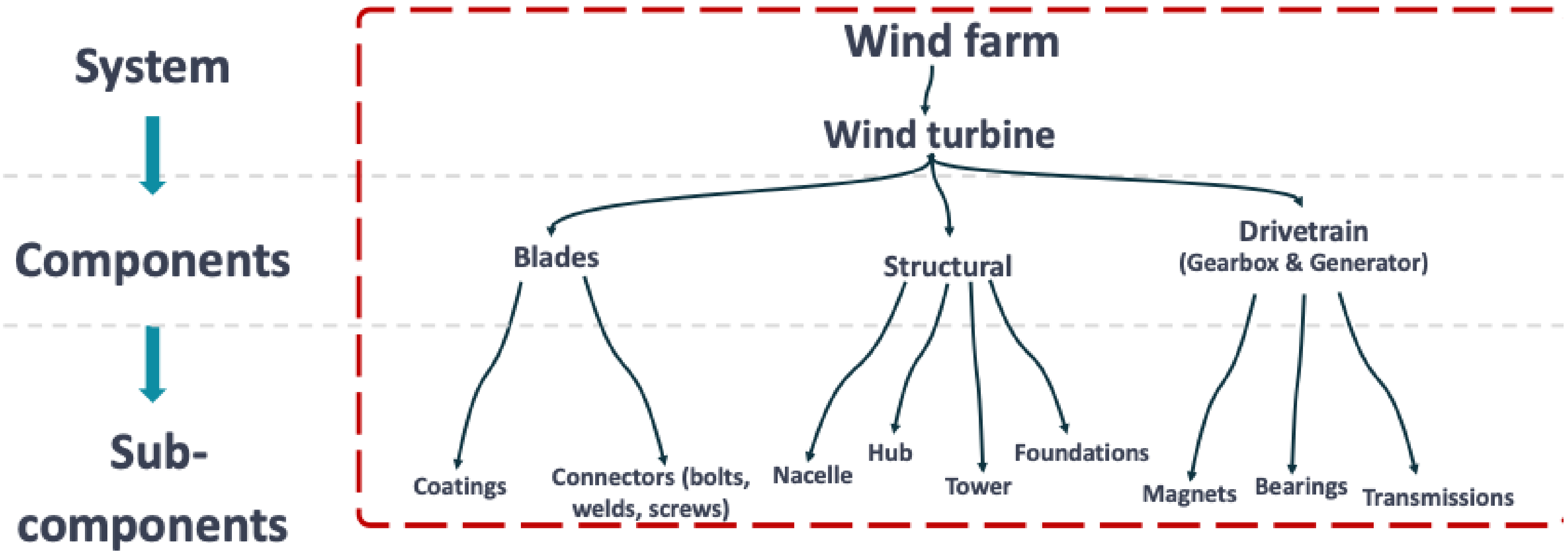


Figure 94: Main components of a wind turbine (top), component hierarchy (bottom) (source: UKA Group, Bax & Company)

Technology overview

Wind is used to produce electricity using the kinetic energy created by air in motion. This is transformed into electrical energy using wind turbines or wind energy conversion systems. Wind first hits the turbine's blades, causing them to rotate and turn the turbine which is connected to the axle of the rotor hub. This transforms

[129] International Renewable Energy Agency (IRENA), Wind energy data, 2018

the linear kinetic energy to angular kinetic (rotational) energy, and subsequently to electrical energy through electromagnetism, by moving a shaft which is connected to a generator.
Most modern large-scale wind turbines have three blades rotating around the horizontal axis (the axis of the drive shaft). These wind turbines account for almost all utility-scale wind turbines installed. Vertical-axis wind turbines exist, but they are theoretically less aerodynamically efficient than horizontal-axis turbines and their applications are rather limited and therefore are omitted from the present chapter.

Figure 94 shows the structure and main components of a geared wind turbine, as well as the hierarchy considered within the roadmap.

Wind turbine production includes multiple step

Figure 95 below illustrates the manufacturing process for wind turbine blades. As a wind turbine consists of three main parts with inherently different roles, in the following section we elaborate on the functioning principles of each of them.

"GLOBAL INSTALLED WIND GENERATION CAPACITY – INCLUDING ONSHORE AND OFFSHORE – HAS INCREASED BY A FACTOR OF ALMOST 50 IN THE PAST TWO DECADES, JUMPING FROM 7.5 GW IN 1997 TO SOME 514 GW BY 2017"

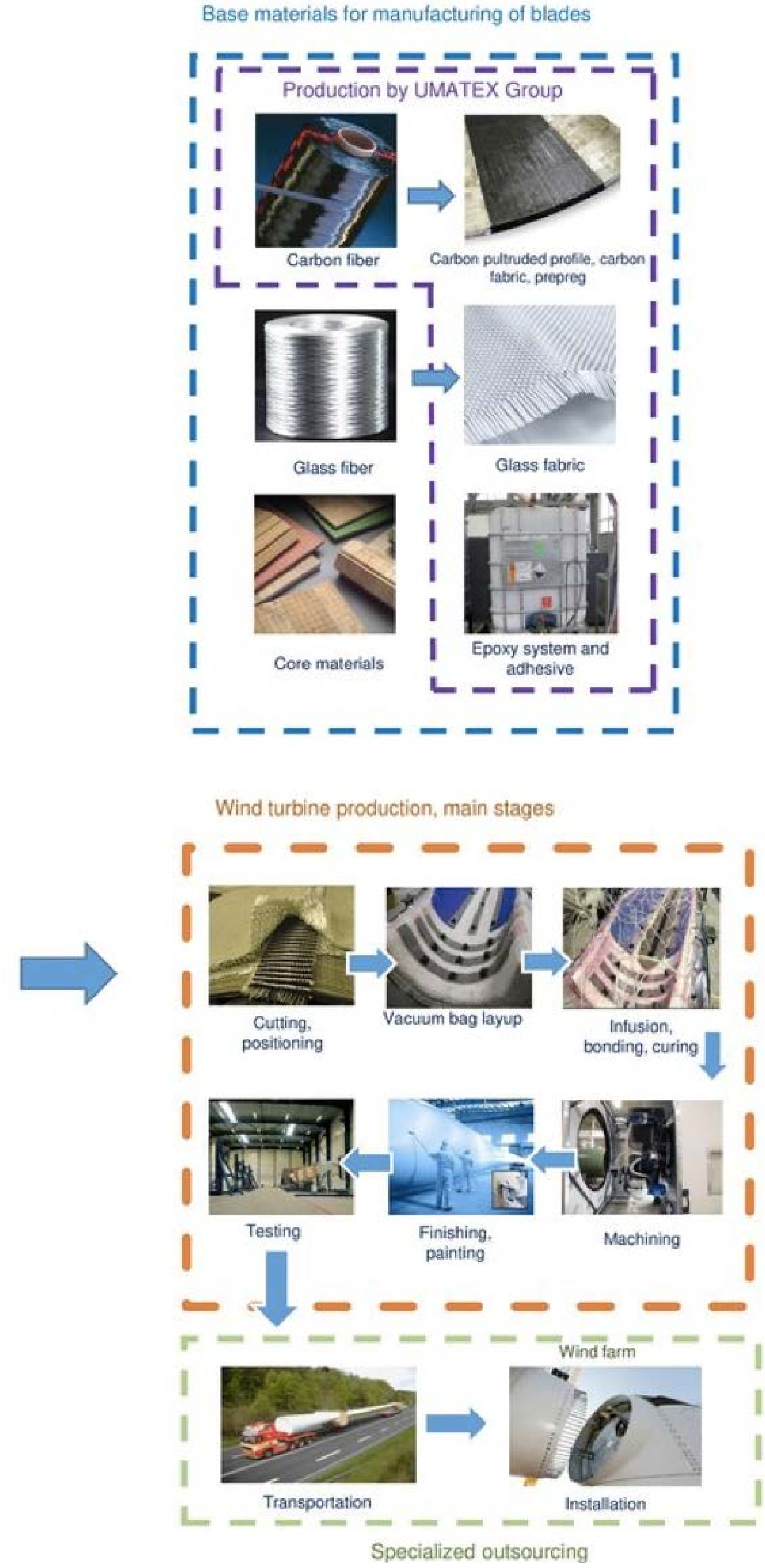


Figure 95: Wind turbine blade manufacturing process (adapted by Bax & Company, source: Umatex Group)

Rotor/Blades

The moving rotor (including the blades) is a key component and contributes the most to the cost of a wind turbine. Materials used need to meet requirements of low weight, high strength, stiffness and fatigue resistance, as well as resistance to environmental impacts like rain erosion, fouling or sunlight.

The structure of blades usually consists of a spar composed of materials formed of fibreglass and carbon pre-coated with epoxy resin acting as the inner part of the blade. The spar is then covered by outer laminated shells of fibreglass, moulded and cured in halves, then joined using an epoxy adhesive.

As rotor sizes are increasing, advanced materials and/or multi material solutions and designs for blades are required to improve cost-effectiveness, while reducing fatigue loading, and sustainability.

To protect and enhance the durability of blades, paint/coating materials are applied on their surface. These coating materials for blades need to meet requirements towards erosion resistance, self-cleaning, anti-icing, anti-scratch properties and reduced friction for the blades, thus reducing aerodynamic noise. Figure 96 shows the main parts (spar and shell) and materials of a wind turbine blade.

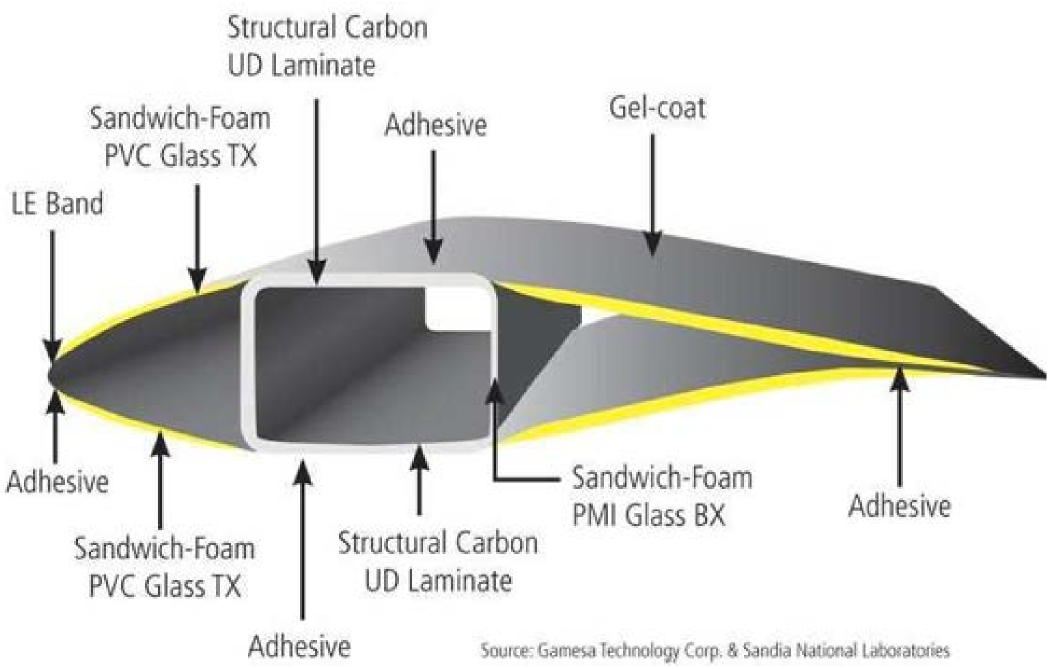


Figure 96: Details of a wind turbine blade
(source: Gamesa & Sandia National Laboratories)

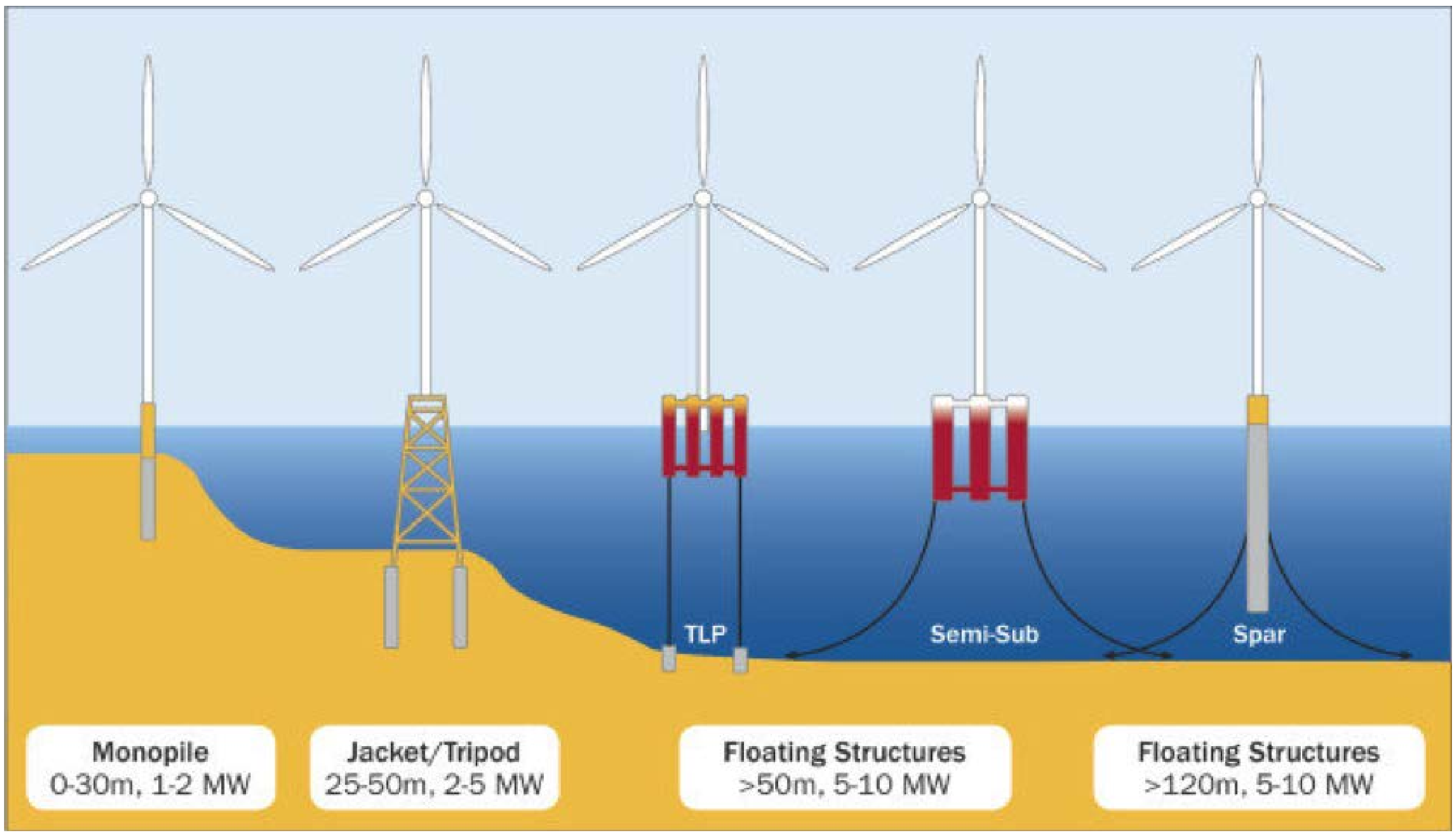


Figure 97: Types of offshore wind turbine foundations
(source: Principle Power)

Structural parts

Structural components are needed to offer mechanical support for all the mobile parts of the turbine. The main structural components are:

Tower, made from tubular steel, or steel lattice, or concrete supports the structure of the turbine. As wind speed increases with height, taller towers enable turbines to capture more energy and generate more electricity. Consequently, advanced materials need to tackle the increasing needs with regard to robustness, for which understanding of their fatigue properties is necessary. Additionally, lightweight materials could contribute to lower transport and construction costs.

Nacelle, sitting on top of the tower and housing the drivetrain and generator. A tradeoff between lightweight and corrosion protection is the key parameter for advanced materials to be used.

Hub, that connects the blades to the drivetrain, transmitting the loads generated by the blades. Consequently, its materials need to withstand aerodynamic and induced loads, therefore steel (welded or cast) is generally the most used material.

Foundations, as in any other mechanical structure, transfer the vertical load, as well as the horizontal dynamic loads to the ground. Foundations for onshore wind turbine consist of gravity-based models made of concrete reinforced with steel, whereas in offshore wind (see Figure 93), typically monopile or jacket foundations are used, while recently new floating concepts, based on mooring lines and cables that fix the turbine to the seabed are being deployed with the potential to reduce installation costs.

As corrosion especially affects the metallic parts of the wind turbine structure, protective systems (e.g. coatings) are applied to their surface to enhance the durability of all parts. Materials used need to meet requirements about adherence and durability under conditions where corrosion, fatigue and eventually friction are combined.

Research is also being initiated today into extending the life time of structural parts to enable the extension of a turbine's life time or the reuse of old structures in new repowering.

Drivetrain

The drivetrain of a wind turbine is composed of the elements needed to produce electricity.

Depending on the type of connection between these elements, wind turbines can be classified into geared and direct drive machines. Figure 98 depicts the differences between both configurations.

In the case of direct drive machines, the generator is directly coupled to the rotor, without a gearbox.

Whereas, for geared machines, the gearbox connects the low-speed shaft to the high-speed shaft and increases the rotational speed to produce electricity. It is one of the most critical components of the wind turbine. With regard to cost, it is one of the most expensive components with high reliability requirements as gearbox failures lead to the most significant downtime. Larger machines are featuring medium speed gearboxes as these reduce the high wear associated with high-speed gearboxes.

The power generator is housed in the nacelle and converts the mechanical energy to electrical energy. The alternating current is produced by a magnetic field induced by permanent magnets, which include critical raw materials (e.g. neodymium). Therefore, new designs focused on increasing the performance of magnets to enable lightweight generator design, while using alternative materials to rare earths are being developed.

The power converter is often housed inside the tower of the turbine and controls the power flow. It is used to optimise the energy production of the wind turbine. Depending on the drive train arrangement, different types of power converters are in use. Two types of power converters dominate the market, the partial rate power converter used in geared turbines with DFIG (type C drive train configuration in Figure 95) and the full power converters used in direct drive and the hybrid drive configurations (types D, E and F in Figure 95). Due to grid compliance rules, the full converter is becoming the most favourable solution. More reliable and durable power converter solutions are a special area of focus for the wind industry.

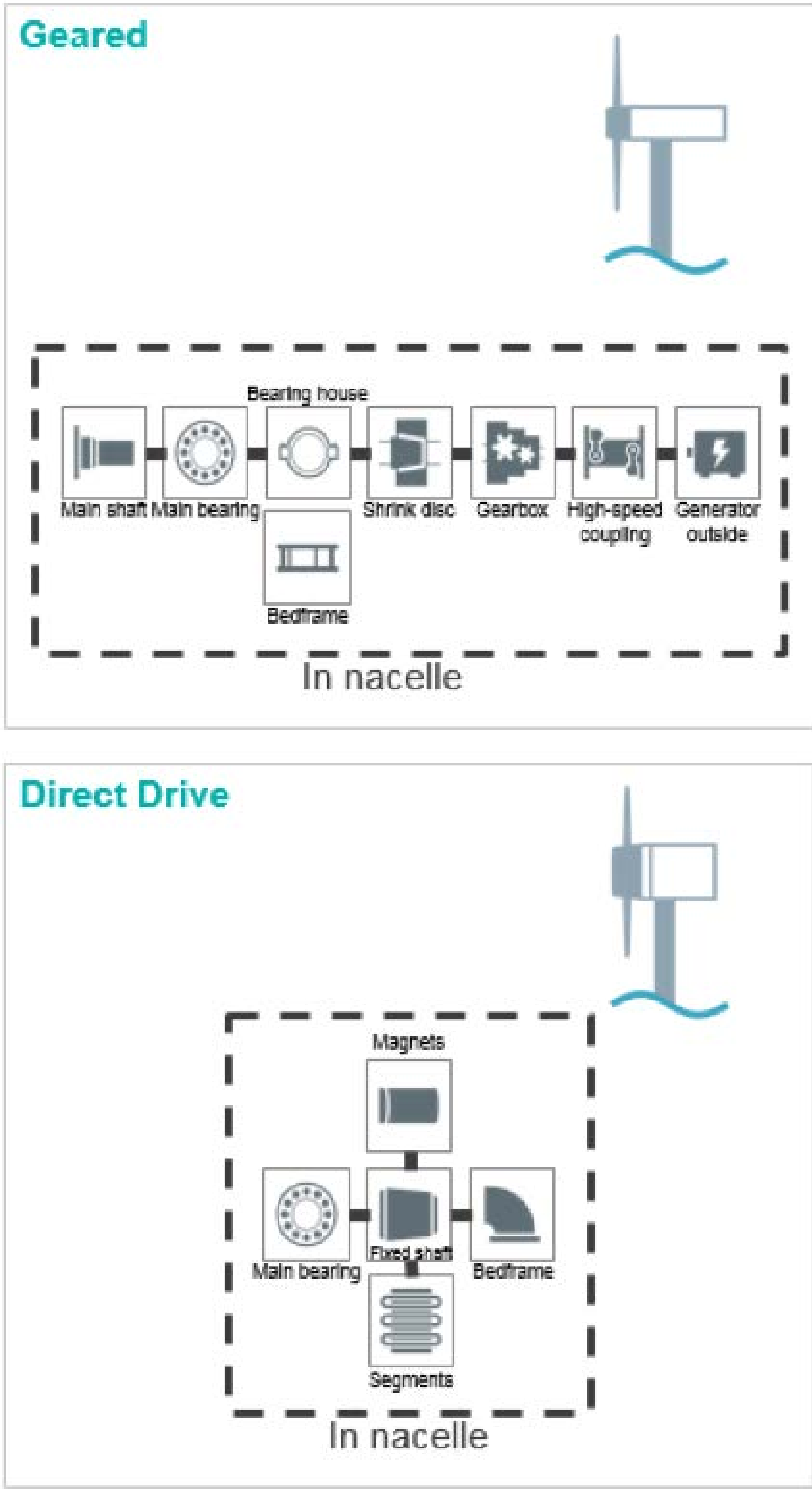
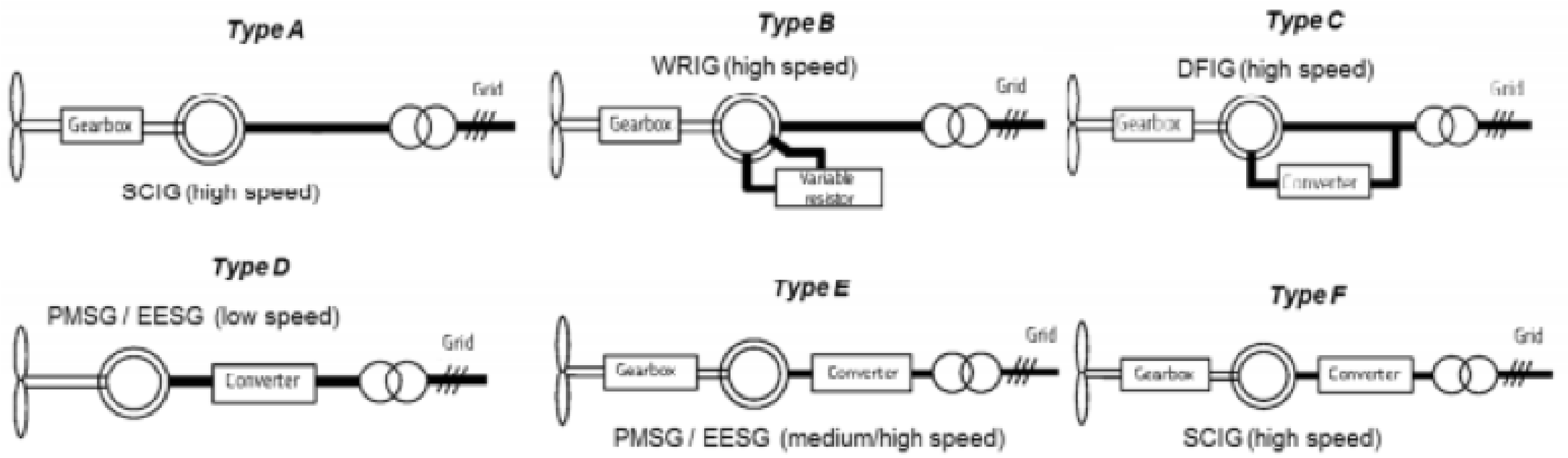


Figure 98: Comparison between geared and direct drive wind turbines (source: Siemens Gamesa Renewable Energy A/S)



A	Geared and high-speed SCIG (Squirrel Cage Induction Generator)
B	Geared and high-speed WRIG (Wound-Rotor Induction Generator)
C	Geared and high-speed DFIG (Doubly-Fed Induction Generator)
D	Direct drive configuration and low-speed PMSG (Permanent Magnet Synchronous Generator) or EESG (Electrically Excited Synchronous Generator) with full power converter. Type D-PMSG has PMSG and Type D-EESG has EESG
E	Geared and medium/high-speed PMSG (Type E-PMSG) or EESG (Type E-EESG) with full power converter
F	Geared and high-speed SCIG with full power converter

JRC (2017)

Figure 99: Wind turbine types according to drive train configuration (source: JRC[130])

Wind turbines can be classified based on the drivetrain components: gearbox (geared or gearless), electric generator (synchronous or asynchronous) and power converter (partial, full or none). The different types of drive train configurations are shown§ in Figure 99 above.

In summary, types A, B and C correspond to the conventional geared high-speed wind turbines, type D is the direct drive configuration and types E and F represent hybrid arrangements.

The global wind market is mainly dominated by conventional geared high-speed wind turbines with type C configuration and to a lesser extent by direct drive configuration type D, especially in Europe and Asia.

"THE GLOBAL WIND MARKET IS MAINLY DOMINATED BY CONVENTIONAL GEARED HIGH-SPEED WIND TURBINES WITH TYPE C CONFIGURATION AND TO A LESSER EXTENT BY DIRECT DRIVE CONFIGURATION"

[130] Joint Research Centre (JRC), Supply chain of renewable energy technologies in Europe, 2017

As Figure 100 below shows, the general trend in turbine design has been to increase the height of the tower, the length of the blades and the power capacity. Rotors with larger swept area and higher reach provide greater energy capture, and thus greater efficiency as well as the economy of scale advantages. But they are also more complex to build, transport and deploy. Current developments are already exceeding the expected trends shown in Figure 100, as the largest and most powerful wind turbine to date, featuring a 12 MW nominal capacity and 220 m rotor able to provide up to 65% capacity factor[131]. In recent years however, the development of low wind machines with large rotors to adapt to the falling number of high wind sites available, is becoming more common.

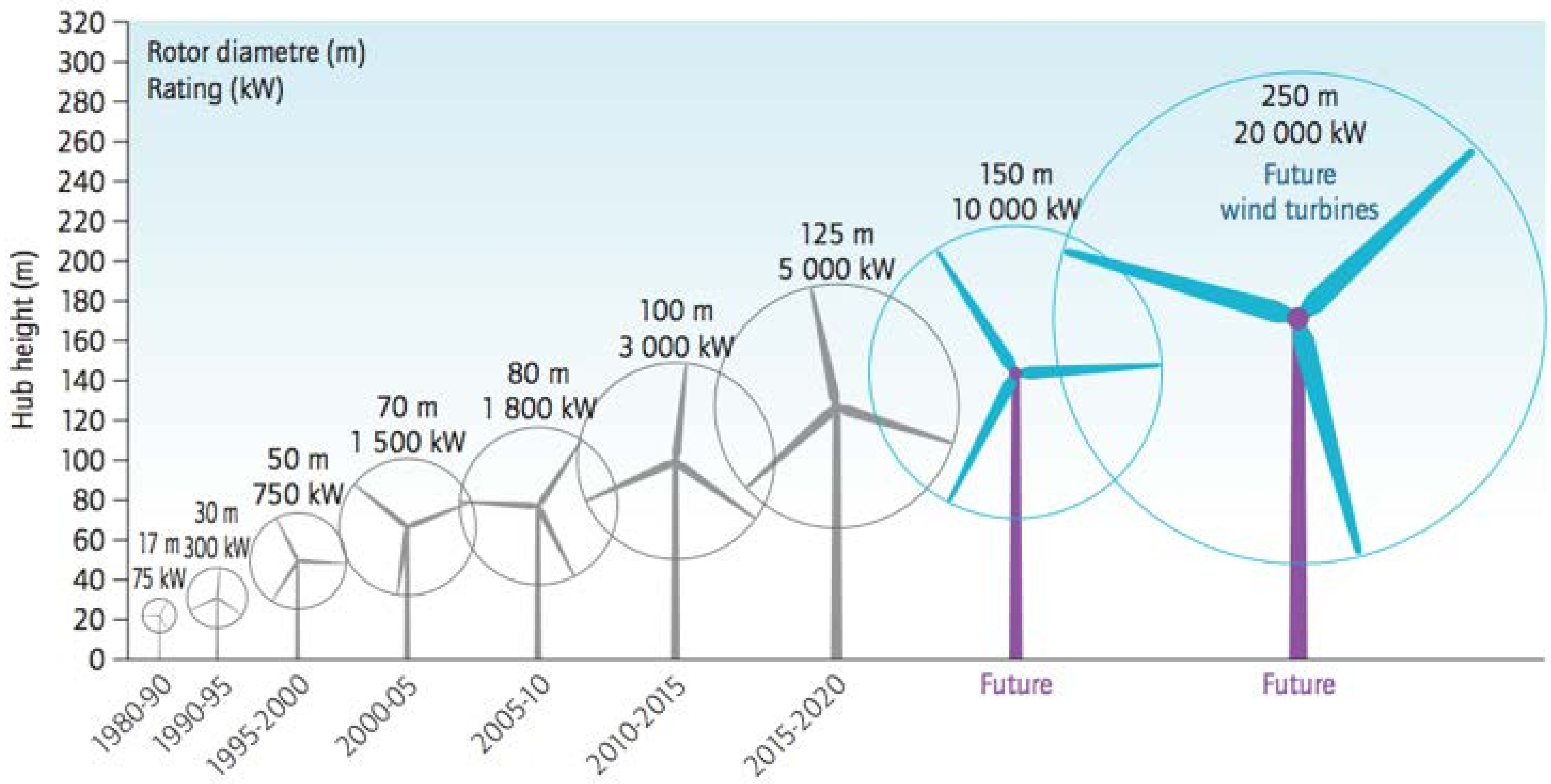


Figure 100: Growth in size of wind turbines since 1980 and prospects. (source: IEA[132])

Another reason for the trend towards larger turbines and longer blades was to increase capacity factors, as this is determined by the quality of the wind resource and the technology employed. Larger turbines and longer blades would thus contribute to reduced installation costs and amortise project development costs.

"FOR ONSHORE WIND FARMS, THE TOTAL INSTALLED COSTS DECREASED 70% GLOBALLY FROM €4,400/KW IN 1983 TO €1,300/KW IN 2017"

[131] General Electric, Haliade-X offshore wind turbine platform, 2018

As a result, capacity factors have increased globally following a consistent trend. As Figure 101 shows, the global average capacity factor for onshore wind increased nearly 45% from 20% in 1983 to 29% in 2017, while for offshore wind, the average capacity factor increased by 56%, to reach 42% in 2017.

A final reason for the growth in size is driven by the growing offshore market, where increased size reduces the number of expensive foundations and hence drives down the LCOE for wind.

Cost structure

Large scale wind farms involve both capital and variable costs, such as Operation and Maintenance (O&M) costs. For onshore wind farms, the total installed costs decreased 70% globally from 4400€/kW in 1983 to 1300 €/kW in 2017[133]. Offshore wind farms have significantly higher lead times. Planning and construction are more complex in comparison with onshore wind projects, increasing total installed costs. In 2016, the average installed cost for European offshore wind farms were 4200 €/kW[128]. However, offshore wind projects, due to their scale and size, drive the large-scale industrialization of wind.

O&M costs for onshore wind farms depend on whether they are measured as initial full-service contracts (13 to 27 €/kW/year) or as full-service renewal contracts 20 to 40 €/kW/year). For offshore wind farms, O&M costs are higher than those for onshore wind, mainly due to the higher costs of access to the site and of performing maintenance on towers and cabling. O&M costs for Europe are estimated to be between 98 €/kW/year and 126 €/kW/year[128].

Figure 102 below illustrates the comparison of cost breakdown between onshore and offshore wind farms.

The installed cost of a wind project is dominated by the capital cost (CAPEX) for the wind turbines. It can represent up to 65% of onshore wind power plant project costs and up to 50% for offshore projects.

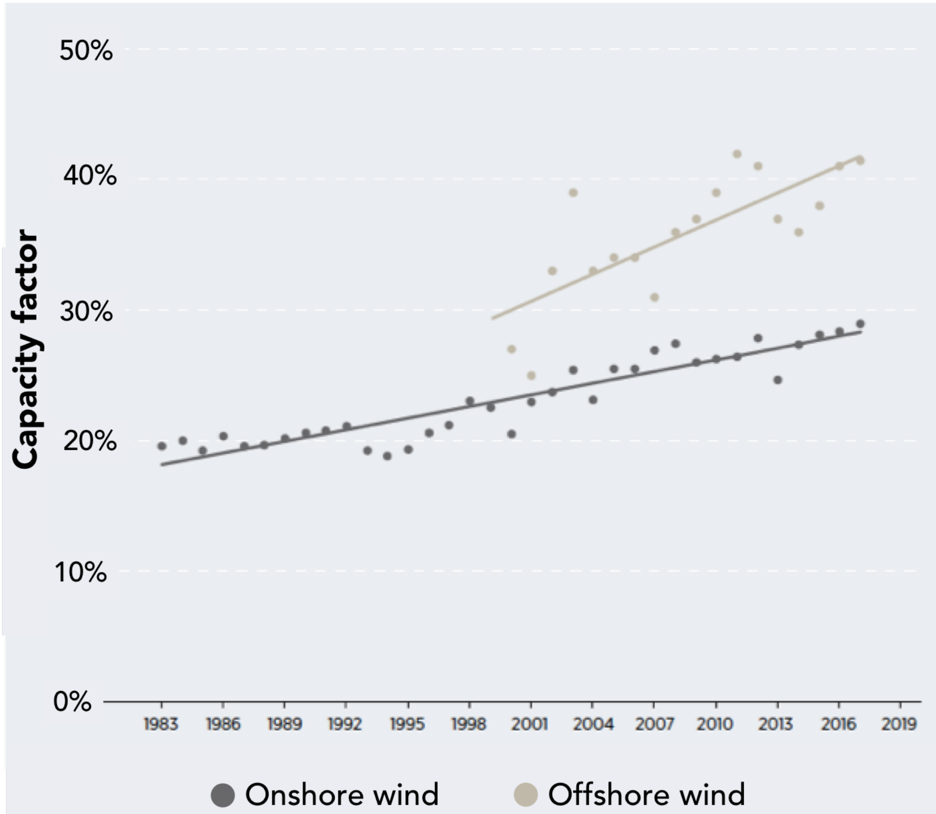


Figure 101: Global weighted average capacity for onshore and offshore wind power capacity additions (source: IRENA[132])

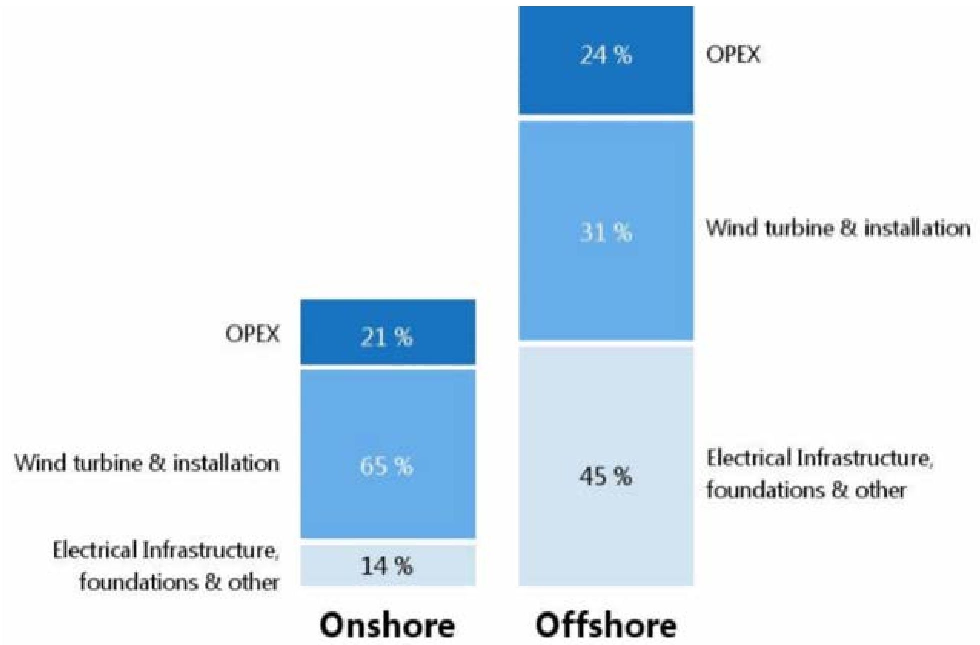


Figure 102: Cost comparison between onshore and offshore wind projects (source: Duan [134])

"IN 2016, THE AVERAGE INSTALLED COST FOR EUROPEAN OFFSHORE WIND FARMS WERE €4,200/KW. HOWEVER, OFFSHORE WIND PROJECTS, DUE TO THEIR SCALE AND SIZE, DRIVE THE LARGE-SCALE INDUSTRIALIZATION OF WIND"

[132] International Energy Agency (IEA), Technology roadmap. Wind Energy, 2013,
[133] IRENA, Renewable Power Generation Costs in 2017, 2018.
[134] Duan, Fei, Wind Energy Cost Analysis, Helsinki Metropolia University of Applied Sciences, August 2017

As Figure 103 shows, turbine prices have declined 45% in the last ten years, with global turbine contracts for delivery in the second half of 2018 averaging USD 1,030/kW (≈ 912 €/kW).

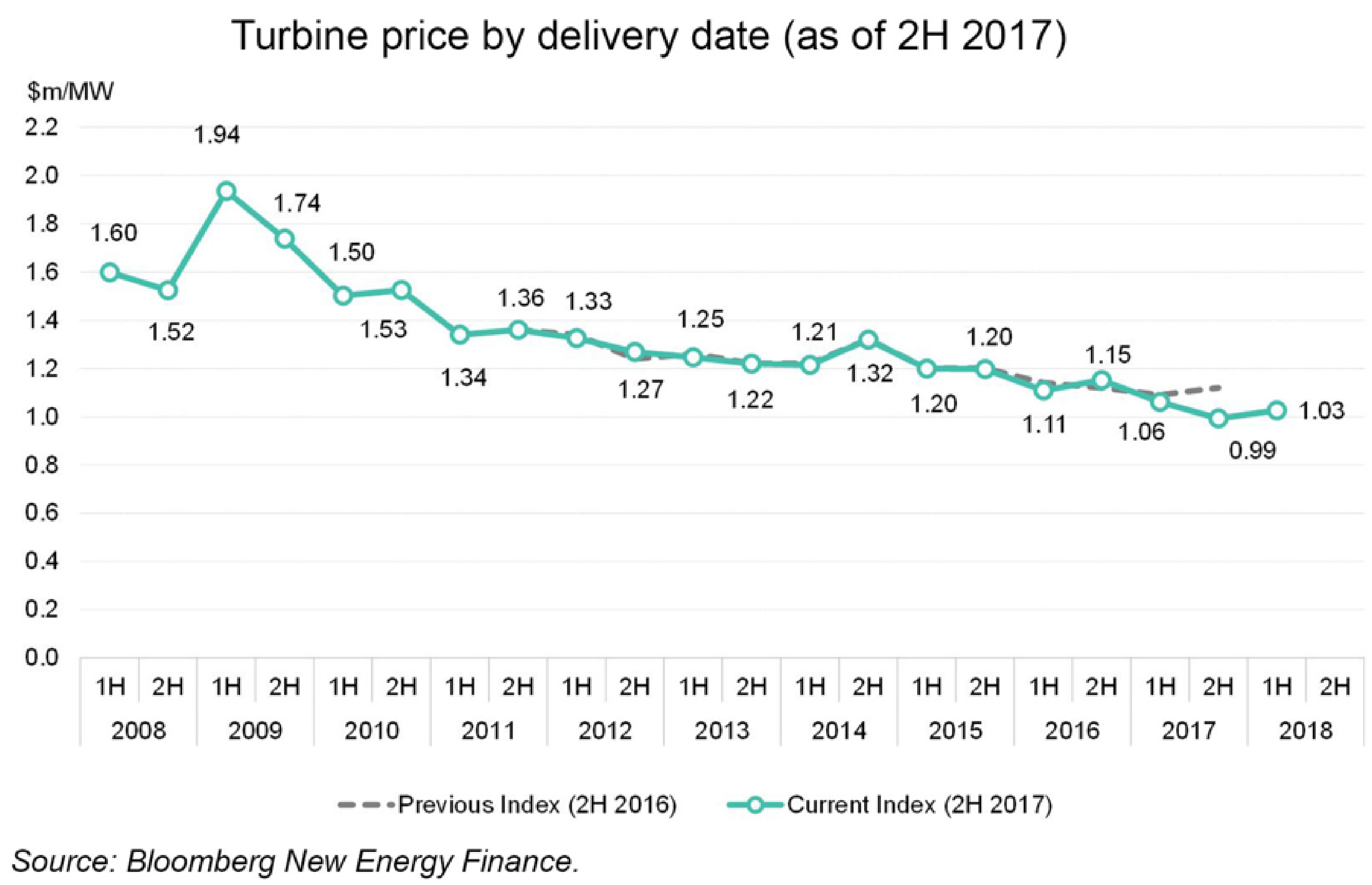


Figure 103: Turbine price by delivery date. (source: BNEF[135])

Figure 104 presents an example of the indicative cost breakdown, in terms of CAPEX, for a large wind turbine. With about 23%, the most significant impact is found for the generator, the power converter and the control systems as well as the tower component. The gearbox, shafts and bearings account for 19%, followed by the blades with about 17%. The remainder (pitch drives, nacelle, hub and yaw drives and yaw bearing) have a minor impact on cost totalling up to 18%. Additionally, gearboxes are generally an important part of the O&M costs, as they require extensive maintenance.

Advanced materials (from electromagnetic, to structural and mechanical) included in all parts of a wind turbine play a very important role in its performance as well as their cost structure.

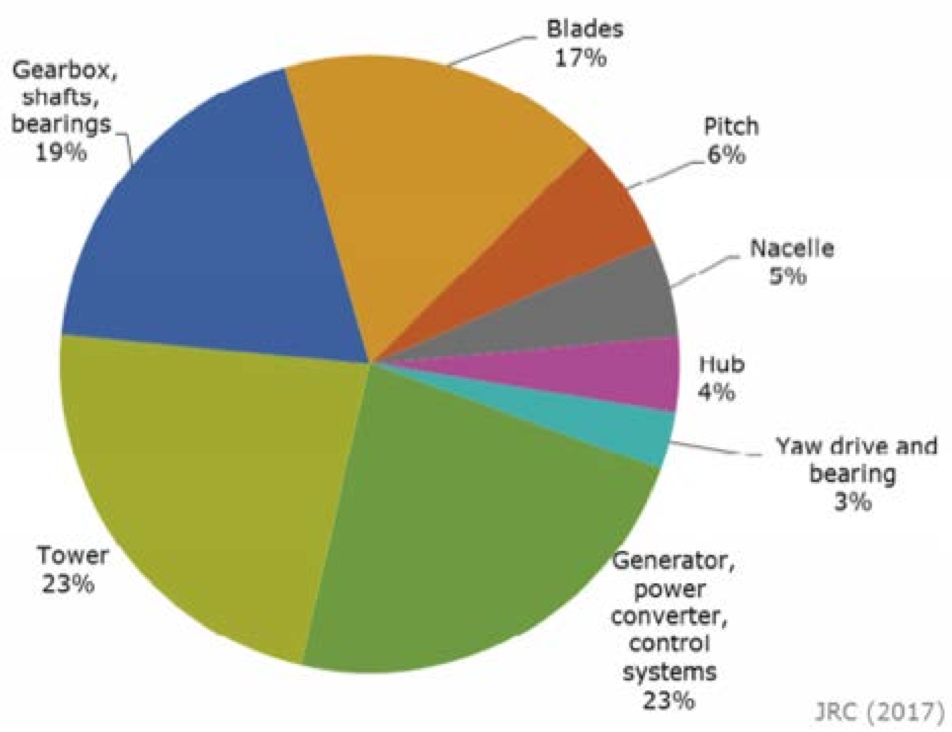


Figure 104: Main components of a wind turbine and their share of the overall turbine CAPEX. (source: Moné et al.[136])

[135] Bloomberg New Energy Finance (BNEF), Wind Turbine Price Index, 2018.

[136] Moné, C., Hand, M., Bolinger, M., Rand, J., Heimiller, D., & Ho, J. (2017). 2015 Cost of Wind Energy Review. National Renewable Energy Laboratory, (February), 113.

 European Landscape

Market and applications

As shown in Figure 105 below, the total installed capacity of wind power in Europe in 2017 accounted for 168.7 GW. 90% of this total (153GW), was represented by onshore, while offshore accounted for the remaining 10% (16GW). According to Wind Europe, this dominance of onshore installations is expected to continue, however, EU offshore market is growing at an increasing pace. Offshore installations grew in 2017 by 101%, compared to 2016.

Offshore wind represents a significant future opportunity: resources are stable, abundant and public acceptance is higher.

"ADVANCED MATERIALS (FROM ELECTROMAGNETIC, TO STRUCTURAL AND MECHANICAL) INCLUDED IN ALL PARTS OF A WIND TURBINE PLAY A VERY IMPORTANT ROLE IN ITS PERFORMANCE AS WELL AS THEIR COST STRUCTURE"

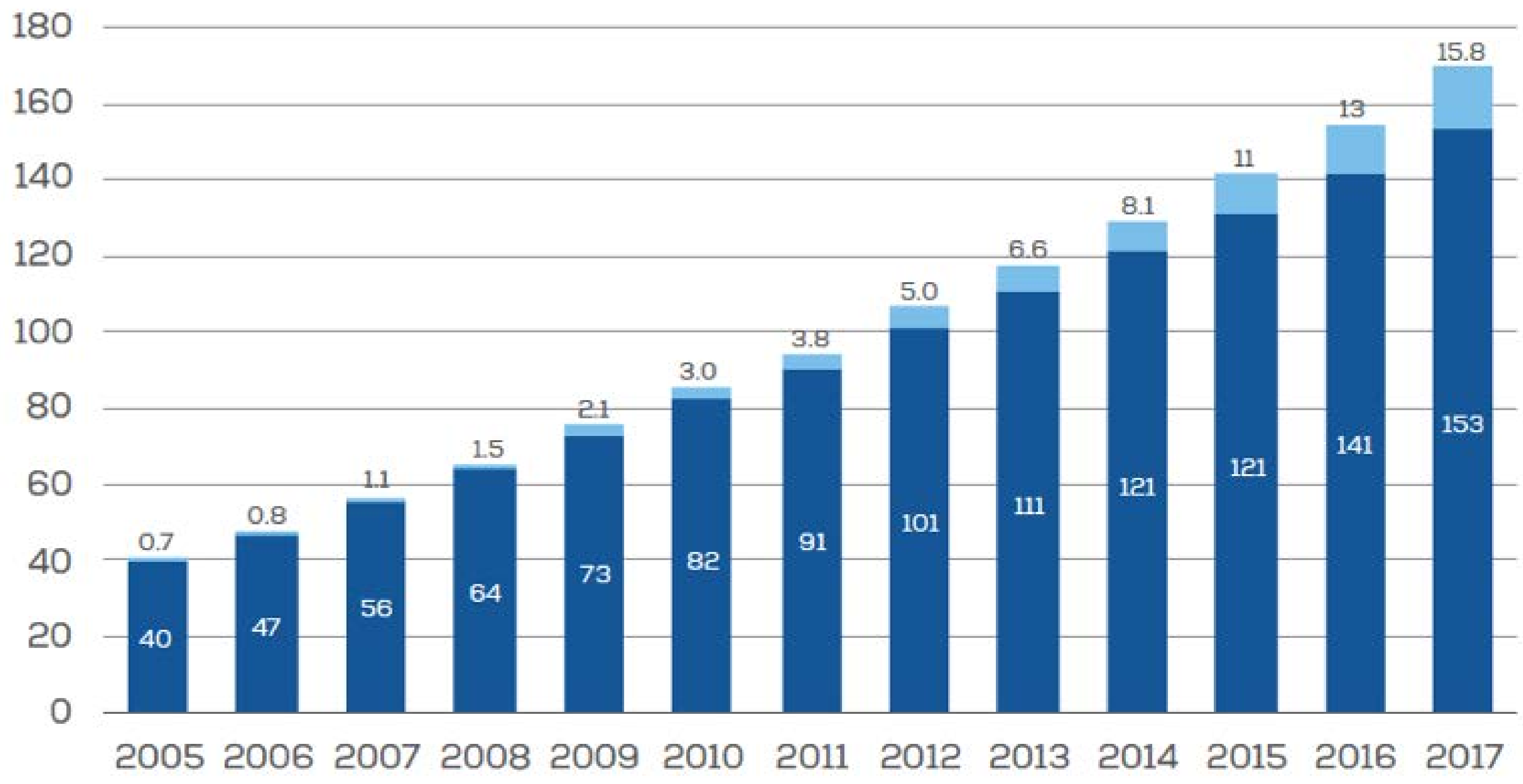


Figure 105: Cumulative installations onshore and offshore in the EU by year (source: WindEurope[137])

[137] Wind Europe, Wind in power 2017, 2018

While in other regions of the world the offshore wind sector has just started to develop, European industries count more than 20 years of experience and on continuous increase in annual capacities (GW) since 2012.

"FORECASTS FOR EUROPE SHOW A SHARE OF WIND POWER IN THE TOTAL ELECTRICITY MIX OF CLOSE TO 30% BY 2030"

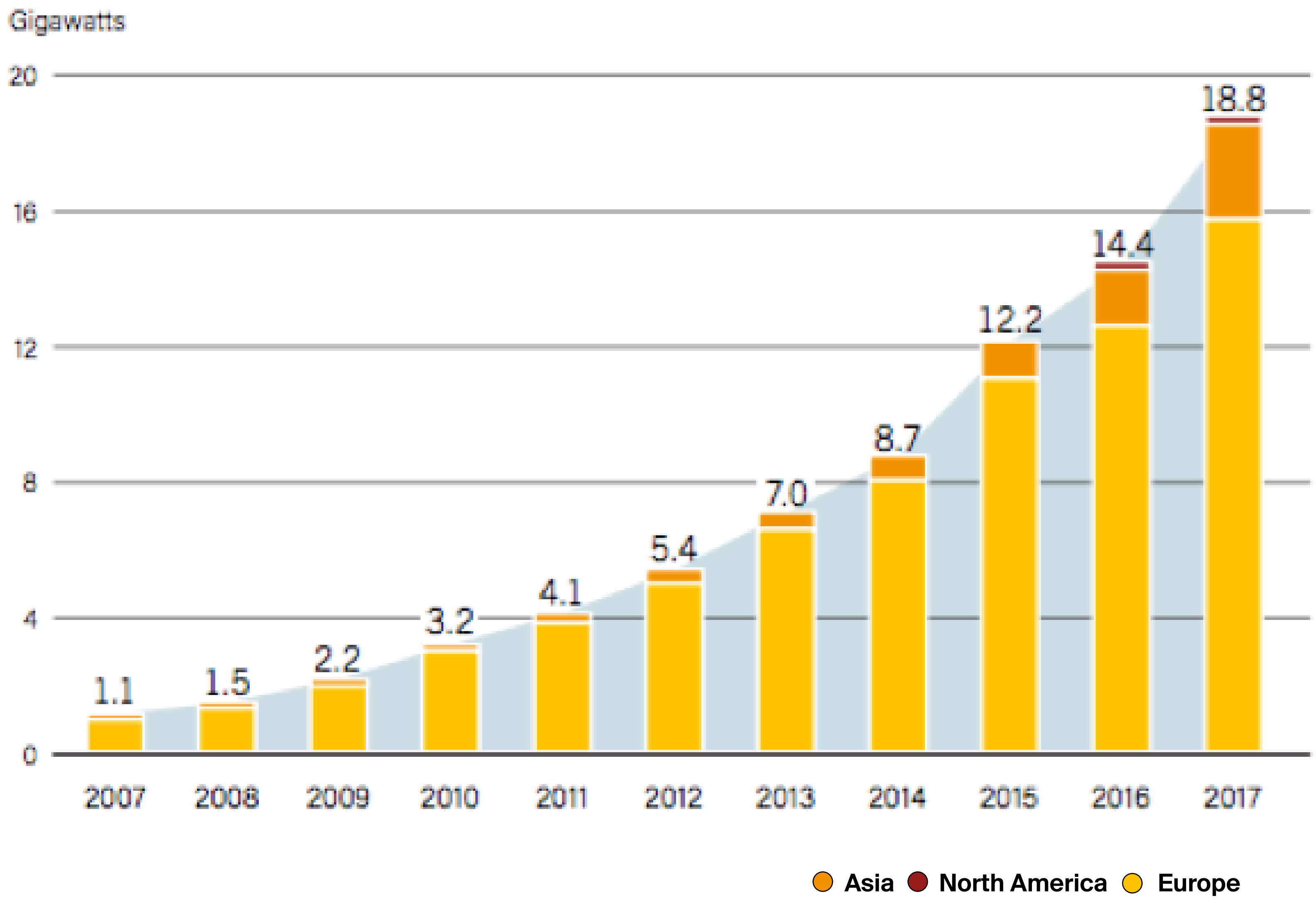


Figure 106: Installed off shore wind power capacity, by region (source: REN21 [138])

[138] REN21, Renewables 2018 Global Status Report, 2018

124 Forecasts for Europe show a share of wind power in the total electricity mix of close to 30% by 2030 (see Figure 107). Denmark would remain the country with the highest share of wind energy in its power mix followed by Ireland and Estonia. Germany, the UK, Spain and France would power respectively 47%, 38%, 34% and 26% of their electricity demand with wind energy.

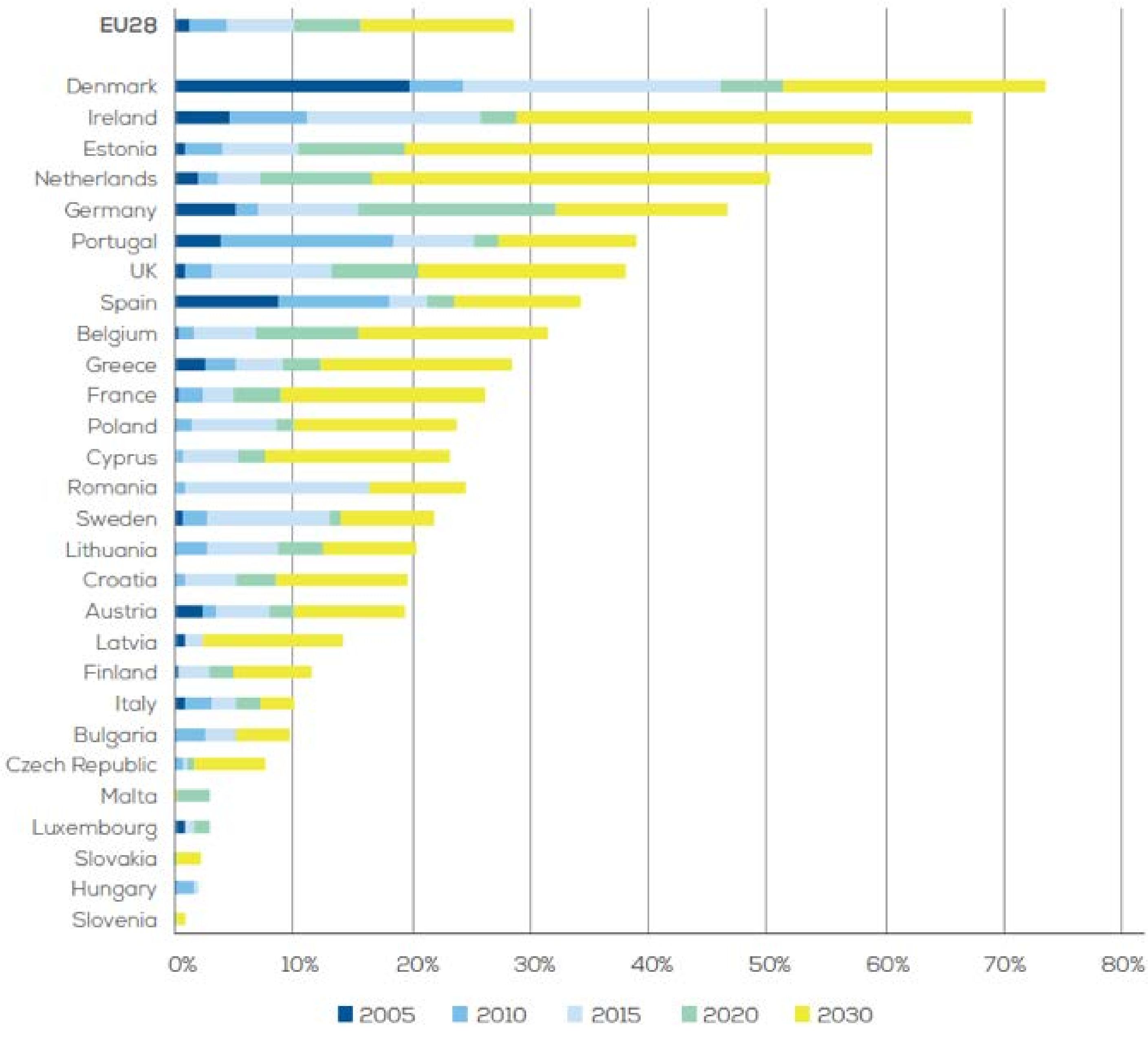


Figure 107: Wind share in annual electricity generation (source: WindEurope[139])

[139] Wind Europe, Wind energy in Europe: Scenarios for 2030, 2017

Value chain and key players

The wind energy value chain includes multiple steps, and presents opportunities for several stakeholders, from material suppliers, to manufacturers, to a multitude of sectors benefitting from the decarbonisation of the energy mix. Table 23 below presents a SWOT analysis for the European wind energy landscape.

Value Chain Step	Strengths	Weaknesses	Opportunities	Threats
Advanced Materials	• Good position in wind academic research and research capacity in industry • Strong knowledge and infrastructure in various recycling technologies • Strong cooperation between industry and academia • Good understanding of materials performance	• Non- secured supply of RE magnet materials • Missing Standards & guidelines • Lack of EU sector-wide initiatives	• Become the dominant player in the recycling of wind turbine modules • Maximize materials performance by close collaboration between materials companies • Creation of cross sector wind/aviation and European wide initiatives to drive accelerated high-tech materials	• Not making full use of the existing expertise in Europe • Large R&D spend by Asian competitors • Large foreign government support of their companies • Lack of appeal of industry towards talented female scientists and engineers • High level of risk aversion to trying new materials
Turbine manufacturing	• Leading players in turbine manufacturing are European	• Materials & design for circular economy to be further developed • Methods for recycling and reuse to be further developed • Sub-suppliers do not possess correct technologies to drive circular economy	• Manufacturing automation • Prefabrication of subcomponents • Increase imperfection tolerance • Establish multi-scale modelling approach	• Slow expected ROI (5-10 years) • Faster lifecycles • Huge R&D competition from China
Integration into Applications	• Global leader in offshore sector • Strong European companies in the downstream part of the value chain (installation, O&M) • Wind energy is the cheapest form of new power generation in EU • Wind energy can deliver the green bilk electricity needed for the energy transition	• Lack of harmonisation of the Member States' policies and regulatory frameworks • Low accessibility for inspection and maintenance • Revenue loss due to downtime • High maintenance cost • Lack of sector wide cooperation and standardisation of big-ticket items	• Strong interest from companies to increase reliability of systems (with the aim of decreasing maintenance costs) • Coordinate wind energy developments with ones in stationary batteries to create robust energy generation and storage systems • Increasing number of policies that accelerate uptake of RES at national or local level • Significant market anticipated in EU • Further expansion of leading role in off-shore	• Optimal usage of offshore needs interconnected grid with high investments • High level of wind penetration needs new materials to deliver utility scale storage • Wind turbine threat to entry is determined by high capital requirements • Pressure from substitute RES, specially PV

Table 23: SWOT analysis of wind energy harvesting technologies for the European landscape (sources: EMIRI community)

"EUROPE IS GLOBAL LEADER IN WIND TURBINE MANUFACTURING AND APPLICATIONS"

 Figure 108 below illustrates the steps of the value chain, along with the main players. European organisations are marked with a star. As can be seen, Europe is global leader in wind turbine manufacturing and applications.

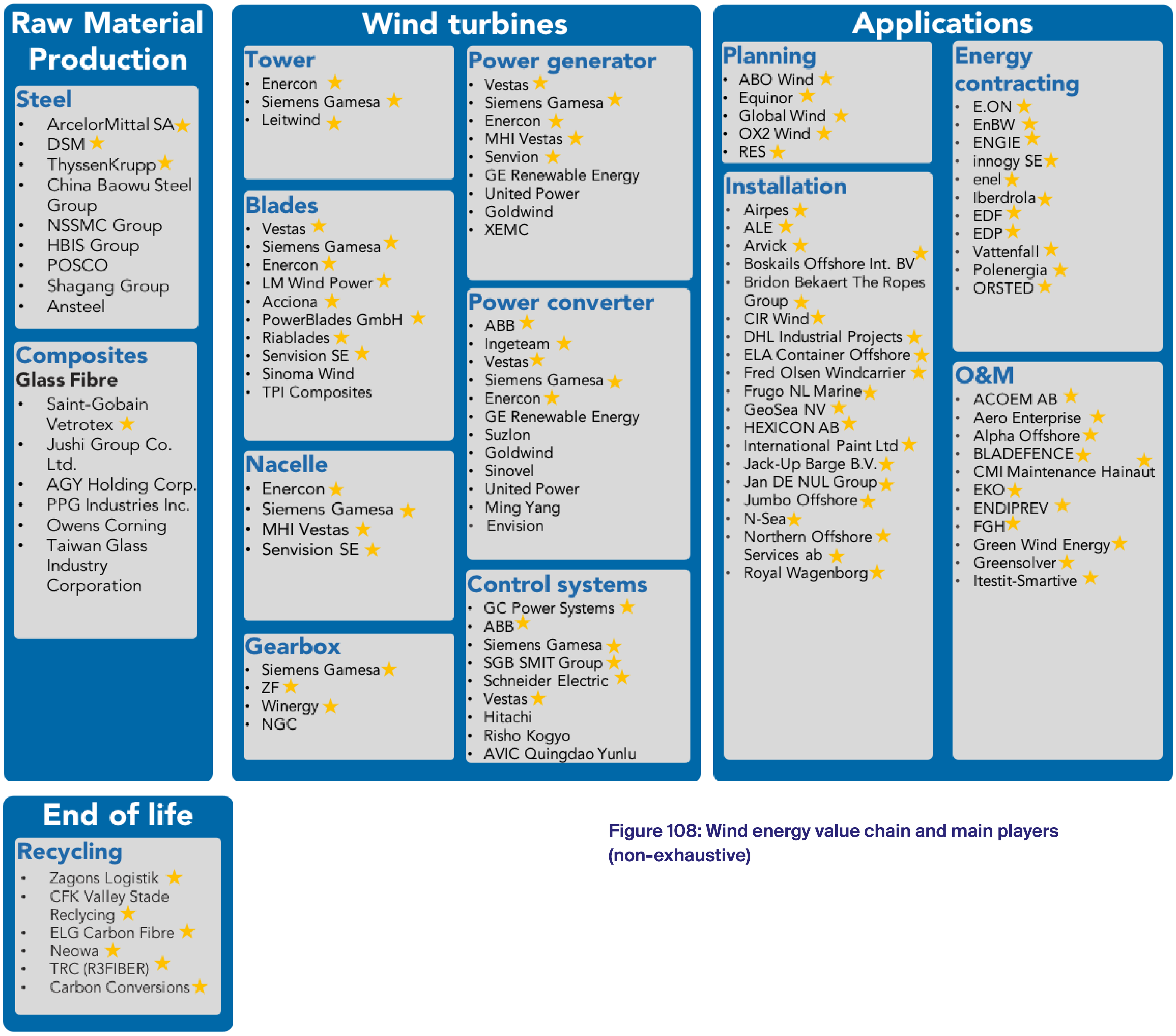


Figure 108: Wind energy value chain and main players (non-exhaustive)

The positioning of the EU can be assessed by considering how European manufacturers rank, where production takes place or where component suppliers are located. As shown in Figure 109, the EU is currently home to four of the top 10 wind energy manufacturers.

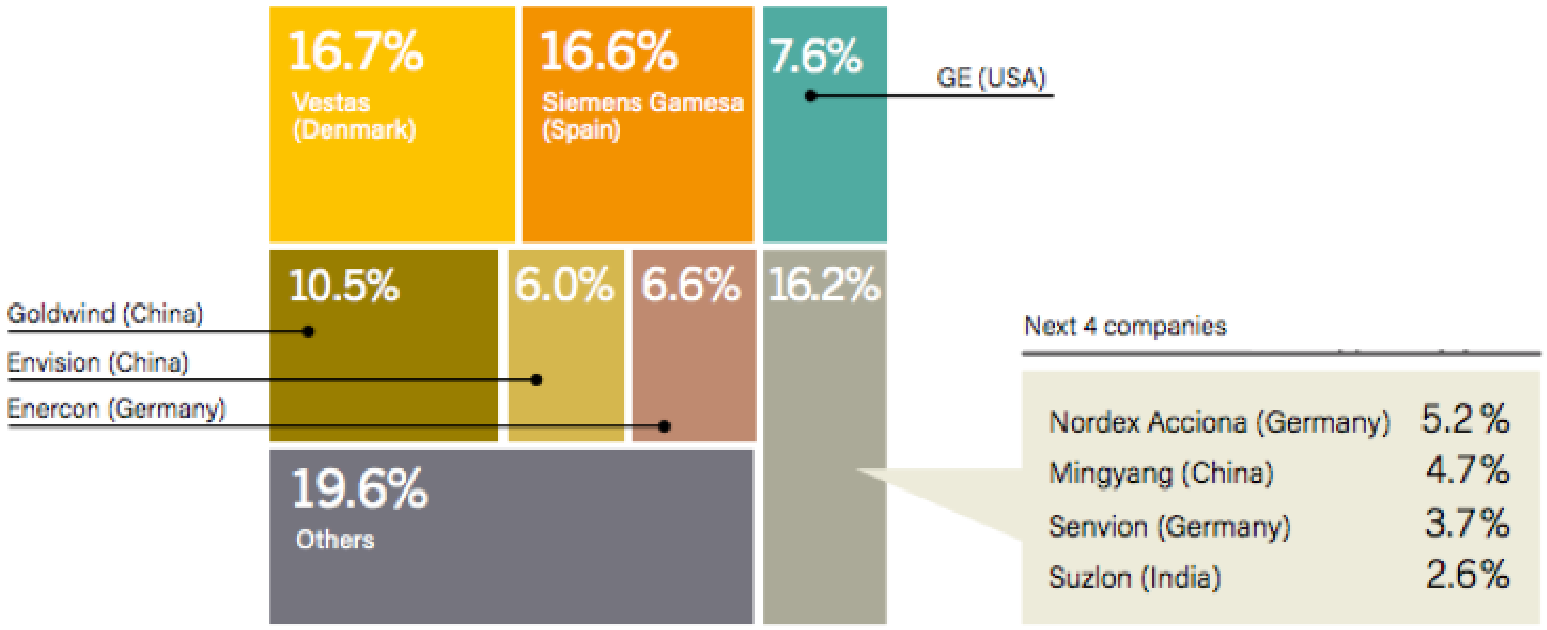


Figure 109: Market Shares of Top 10 Wind Turbine Manufacturers (source: REN21[138])

Current Status/Market Overview

Main trends

This section lists the main trends that drive the growth of the global wind energy market.

Advancements in lightweight materials

Over the last few years, lightweight materials – and particularly FRP – have undergone significant improvements. New material formulations, material combinations, and design – e.g. sandwich blade shell structures with PET foam cores – have enabled increased mechanical performance, such as strength-to-weight and stiffness-to-weight ratios, as well as higher reliability (e.g. better corrosion resistance). The advancements in such materials have allowed the construction of higher and larger wind turbine blades, which are able to harvest more energy from the wind – due to larger rotor diameters, higher towers – and remain operational longer, due to the high reliability of such materials. The next challenge that is currently being tackled is how to ensure that such materials have a minimal impact on the environment, especially after they have reached their end of life.

"ADVANCEMENTS IN MATERIALS HAVE ALLOWED THE CONSTRUCTION OF HIGHER AND LARGER WIND TURBINE BLADES ABLE TO HARVEST MORE ENERGY FROM THE WIND AND REMAIN OPERATIONAL LONGER.THE NEXT CHALLENGE THAT IS CURRENTLY BEING TACKLED IS HOW TO ENSURE THAT SUCH MATERIALS HAVE A MINIMAL IMPACT ON THE ENVIRONMENT, ESPECIALLY AFTER THEY HAVE REACHED THEIR END OF LIFE"

Main challenges

Table 24 below summarises the main materials related challenges that need to be addressed – per technology and application sector – within the next 10-15 years in order to increase Europe's competitiveness.
The challenges were identified by the EMIRI community in workshops that took place throughout 2018.

Challenge	Application	
	On-shore	Off-shore
• Reduce investment, operating and electricity generation costs	●●●●	●●●●●●
• Increase durability of turbines by enhancing the WEC, fatigue limit, corrosion/erosion and vibration resistance of components	●●●●	●●●●●●
• Increase the performance of turbines to achieve high power and lighter turbines	●	●●
• Reduce audible noise of turbines to increase their acceptance	●	●
• Reduce the use of critical raw materials and increase the recyclability of components to lower the environmental impact of turbines	●●●●	●●●●

• Lightweight materials • Advanced coatings/paintings • Advanced drivetrains • Advanced durable blades • Foundations • Cables & moorings

Table 24: Main materials related challenges to be addressed

Proposed R&D topics

Table 25 below summarises the suggested calls to be included in the Horizon Europe framework program, based on the challenges identified above.

Identifier	Call Title	Type
W1	Advanced materials to reduce weight of wind turbines	IA
W2	Advanced materials to reduce erosion and corrosion of structural parts of wind turbines	RIA
W3	Advanced materials to reduce the content of critical raw materials in drivetrain components	RIA
W4	Advanced materials to improve durability of wind turbine blades	RIA
W5	Advanced materials to improve durability of wind turbine drivetrains	RIA
W6	Advanced materials to improve durability of off-shore wind turbine foundations	RIA
W7	Advanced materials to improve durability of cables and mooring of off-shore wind turbines	RIA
W8	Advanced material developments to increase circularity of wind turbines	RIA
W9	Advanced materials and material solution to increase the circularity of wind turbine drivetrains	RIA

Table 25: Suggested materials related calls for wind energy harvesting technologies

Figure 110 below illustrates the importance and urgency of each call.

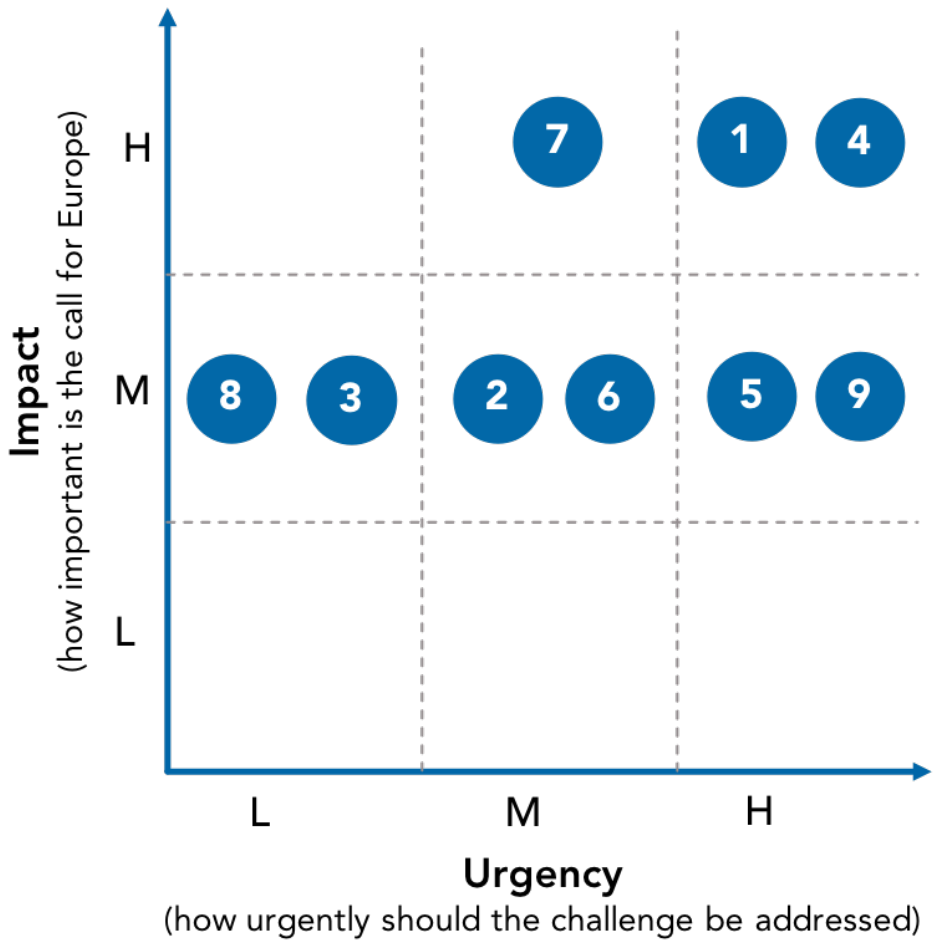


Figure 110: Prioritisation of wind energy harvesting calls

6

BUILDING ENERGY PERFORMANCE

Buildings are responsible for approximately 40% of energy consumption in the EU[140]. Their combined energy demand results from the consumption during use and the building construction sector. The energy consumption in buildings grew steadily from 33 PWh in 2010 to 34.5 PWh in 2016 as a result of increasing floor area growth, which is higher than the energy intensity reduction[141]. The main focus in the long term is to have buildings and districts that become energy neutral, with zero CO2 emissions, behaving smartly through devices that are connected and communicate with each other, effectively responding to energy demands. In fact, the Energy Performance of Buildings Directive (EPBD) requires all new buildings to be nearly zero-energy by 2020[140].In order to achieve this target, all sources of energy consumption and losses must be addressed.

Nowadays, energy efficiency in buildings is delivered through technology, which in most cases relies on advanced materials either by developing new materials or modifying existing ones. These innovative materials contribute to reducing both the embodied energy and manufacturing cost. The paragraphs below describe how advanced materials and their related technologies could address the issues related to energy efficiency in buildings performance for achieving the long-term targets and goals.

Although the embodied CO_2 of structural materials such as concrete is recognized, these are not considered advanced materials and therefore left outside of the scope of the present roadmap.

"THE MAIN FOCUS IN THE LONG TERM IS TO HAVE BUILDINGS AND DISTRICTS THAT BECOME ENERGY NEUTRAL, WITH ZERO CO_2 EMISSIONS, BEHAVING SMARTLYTHROUGH DEVICES THAT ARE CONNECTED AND COMMUNICATE WITH EACH OTHER, EFFECTIVELY RESPONDING TO ENERGY DEMANDS"

[140] European Commission, Energy, 2018
[141] International Energy Agency, Energy Efficiency, 2017
[142] European Environment Agency, Indoor air quality, June 2016

Energy Consumption

People might spend up to 90% of their time indoors, either in the office or at home[142]. The energy consumption in buildings comprises energy used for heating, cooling, lighting, water heating, and consumer products. The type and amount of energy consumed can vary significantly since several factors are involved, including building characteristics, weather, efficiency and type of equipment, among others.

Buildings are formed by several elements. There is no one single component, sub-component or material whose improvement alone can enhance the entire building energy performance. Thus, in order to increase energy efficiency, the different components and related technologies should be addressed as a whole. A mix of measures tailored to specific regions and applications is required to attain the most efficient solution. Considering the building as the entire system, the elements that integrate it can be organized as in the hierarchy shown in Figure 111.

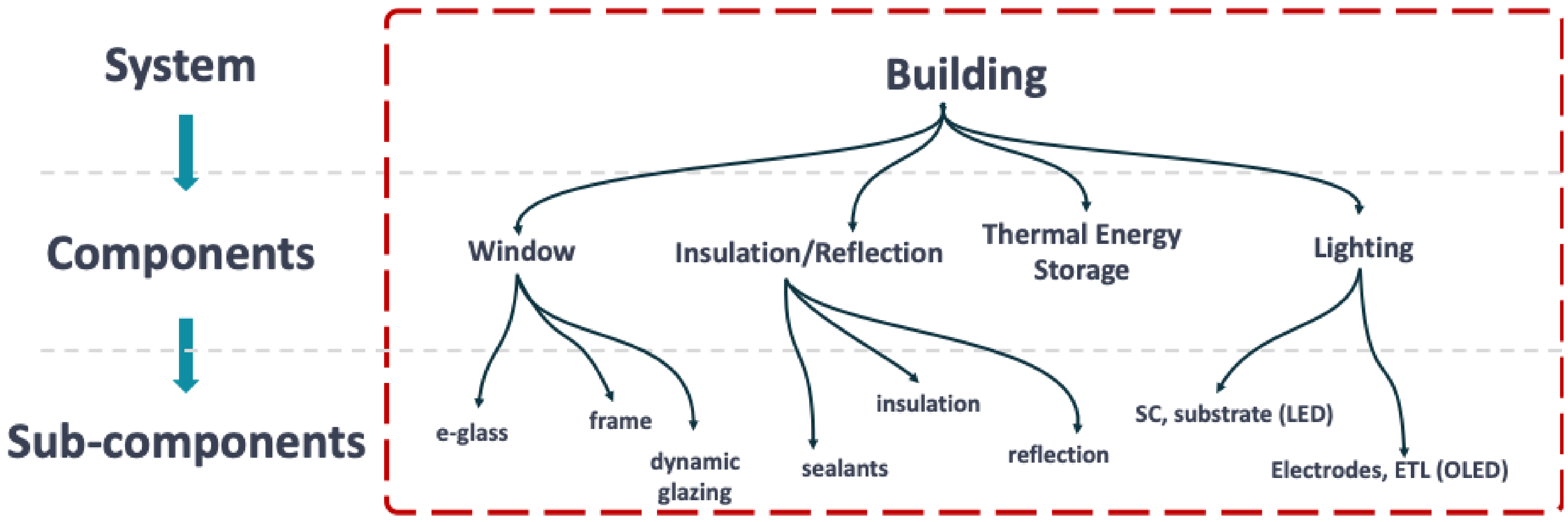


Figure 111: Hierarchy approach used for the elements in buildings (source: Bax & Company).

Assessing the contribution of each envelope component to the system performance over time is a difficult task. **The development of advanced materials and their related technologies should enable the elements of a building to increase energy efficiency as a whole**[6].

Overall, building energy performance may be related to elements integrating the envelope, including windows, façades (for insulation/reflection) and energy management systems (thermal energy storage and lighting). The combination and synergistic integration of both envelope and energy management systems is critical for the transition to sustainable buildings[136].

[142] European Environment Agency, Indoor air quality, June 2016

Envelope – Windows

The envelope of a building is a critical element that impacts 57% of the building thermal loads since it physically separates the exterior and interior environments . It comprises various elements including roofs, doors, and most importantly windows.

Windows must receive a special attention since most of energy loss take place through them, playing an important role in the overall energy flow. Typically, windows should let in as much light as possible, but heat gain needs to be minimised in summer and maximised in winter. Both flows of heat and natural light should be balanced through suitable selection of framing materials, glazing, coatings, spacers between panes of glass and low thermal conductivity inert gases. Figure 112 shows the most common types of windows used nowadays.

As it can be seen, recommendations are clearly towards installing systems with low U-values close to 1 W/m2·K (also known as thermal transmittance, which is the rate of transfer of heat through a structure – heat loss). In addition to its insulation value, the quality of a window is also related to the amount of visible light and infrared radiation than be transmitted across its structure. Both factors are addressed by the following technologies.

"BOTH FLOWS OF HEAT AND NATURAL LIGHT SHOULD BE BALANCED THROUGH SUITABLE SELECTION OF FRAMING MATERIALS"

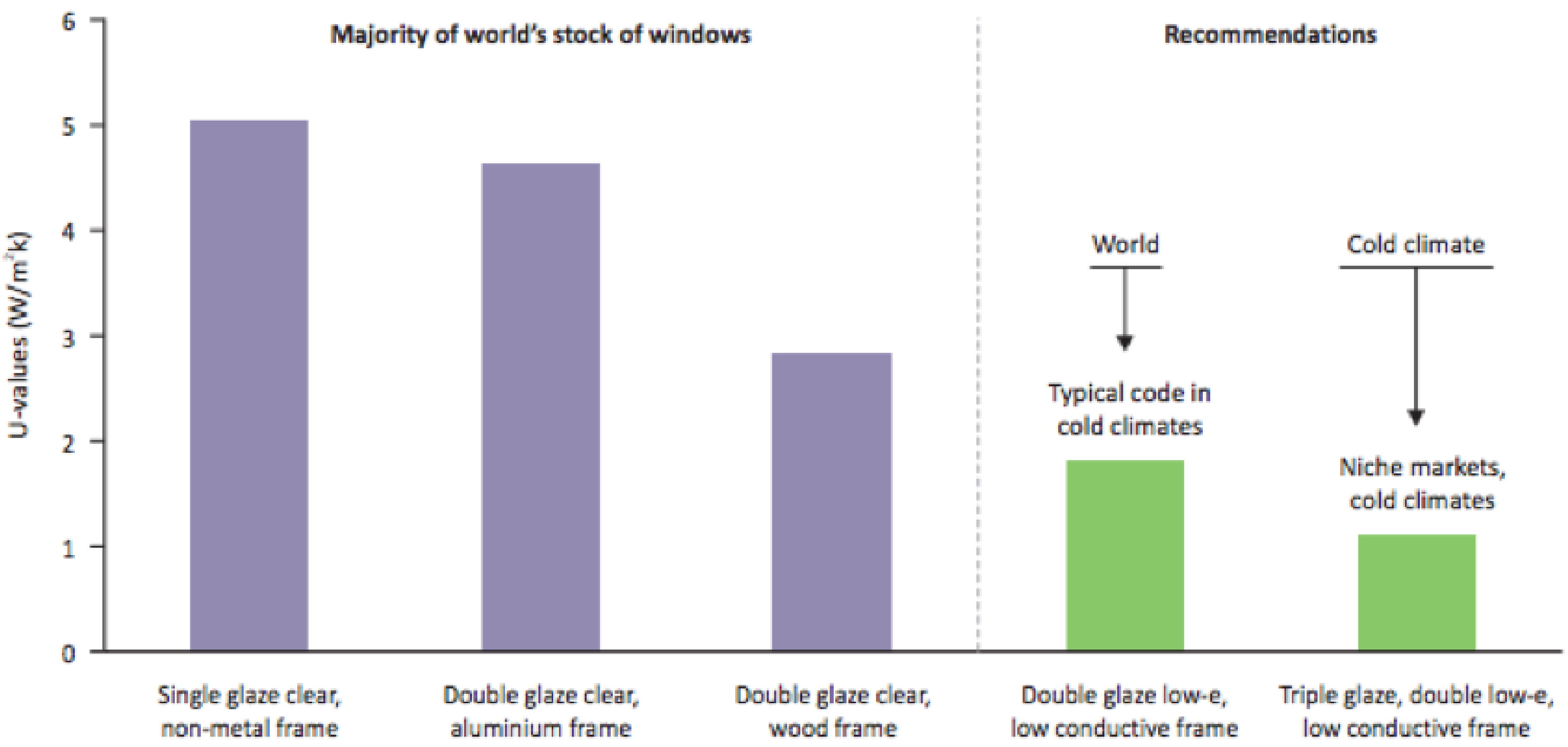


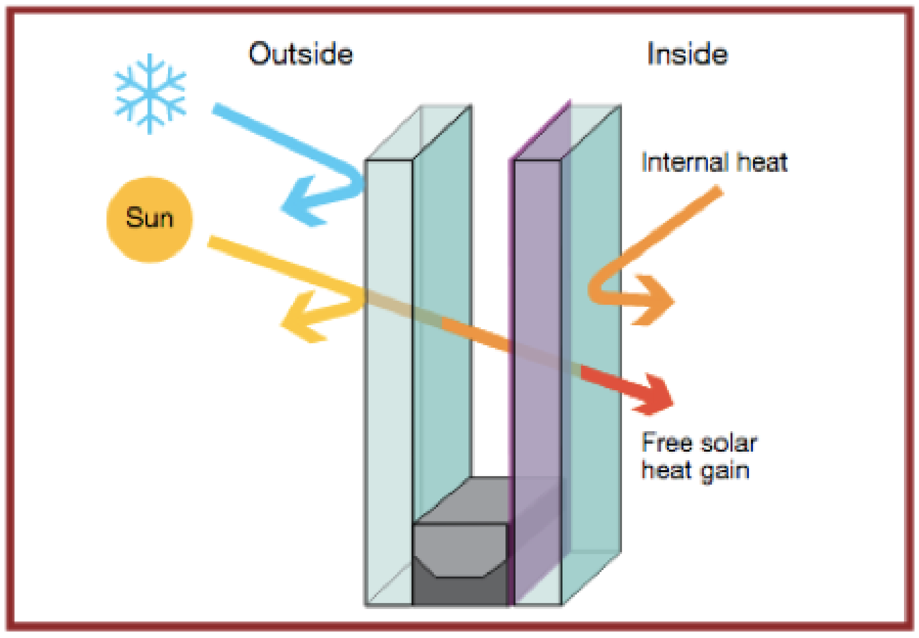
Figure 112. Types of windows available nowadays (source: IEA 2015 [144]).

[144] Marc LaFrance, IEA Building Sector Strategies: Global and Ukraine, March 2015

Low emissivity (low-e) glass

The “emissivity” of a glass refers to the ability of its surface to reflect heat. This type of glass consists of a coating placed over a flexible plastic that is sandwiched between two glass plains (Figure 113) or a triple glazing unit with two coatings (Figure 114).

In order to improve insulation, the space between panels is filled with argon or krypton, which have a low thermal conductivity. This type of window treatment is currently the most widely marketed and installed option. The coating consists of one or more semi-transparent Ag or Al layers that are sandwiched between transmissive dielectric layers (e.g. TiO_2, Ta_2O_5, SnO_2). It allows to minimize the amount of UV/IR light without compromising the amount of visible light. During winter, low-e glass can retain the heat inside the building from the cold outside while doing the opposite in summer. The U-value for this type of windows normally ranges from 0.5 to 1.1 W/m²·K depending on whether double or triple glazing is used as well as the choice of argon/krypton filling.



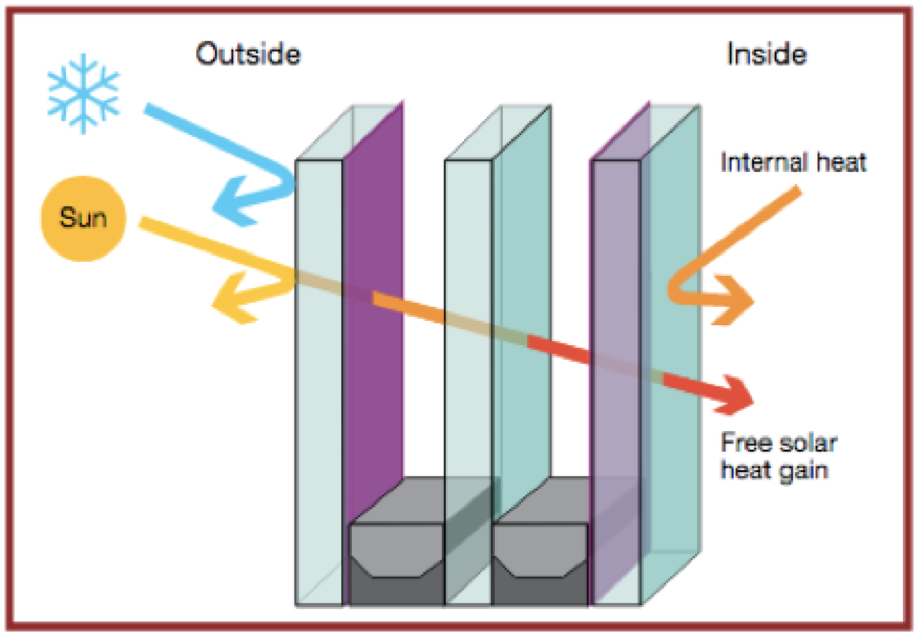


Figure 113: Low-e glass coating in a double-glazing unit (1) and two low-e coatings in a triple-glazing unit (2) (source: Glass for Europe) [145]

[145] Glass for Europe, Low-E Insulating Glass for Energy Efficient Buildings – How policy-makers could save energy and significantly reduce CO2 emissions to meet EU targets for 2020, 2018

Dynamic glazing

Unlike low-e glass, dynamic glazing can be selective, switchable and/or tuneable in order to control the amount of light and heat passing through in optimum conditions. This is made possible by changing the properties according to electrical or user control (active dynamic glazing) or as a response to environmental conditions (passive dynamic glazing).

In the active type, the dynamic glazing can be controlled either manually or automatically by means of an electric stimulus. The main technology is electrochromic (EC), which changes opacity in response to voltage (Figure 114). When switched off, an EC window remains transparent while it gets translucent in mode on. The EC layer is commonly based on different types of tungsten oxide (e.g. WO_3).

Table 26 presents an overview of the different window technologies for energy efficiency in terms of heat loss (U-value).

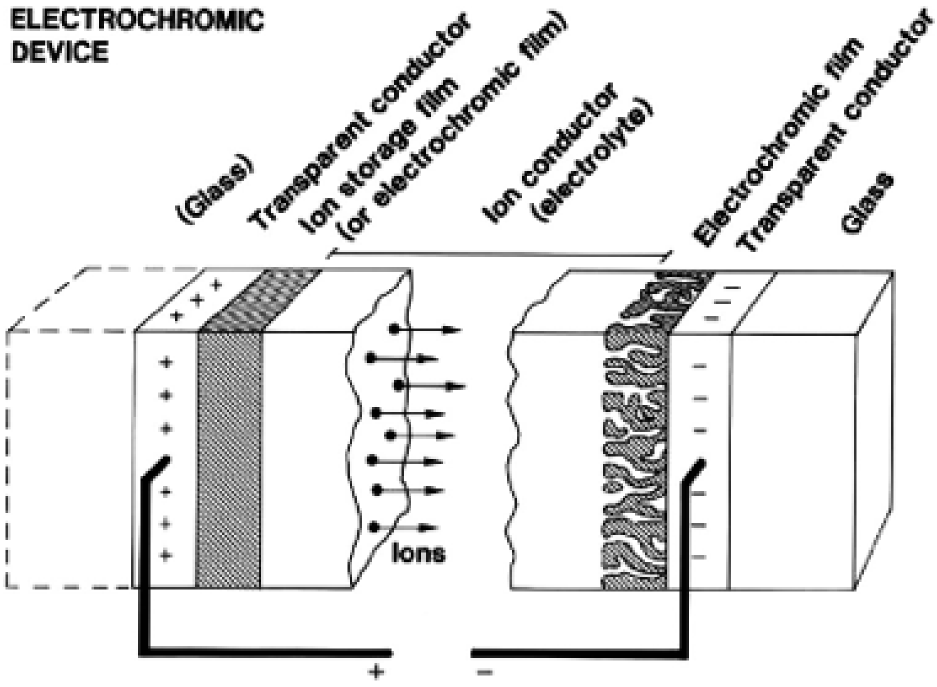


Figure 114. Schematic representation of an EC device (source: Tavares et al., 2014) [146]

Type of technology	Commercial brand	U-value (W/m²·K)
Single glazing (one glass sheet)	N/A (one glass sheet)	5.8 – 6.3
Low-e (double glazing – Air filled)	-	2.7 – 3.2
Low-e (double glazing – Ar filled)	-	2.6 – 2.9
Low-e (triple glazing – Ar)	Pillington energiKare™	0.6 – 0.9
Low-e (triple glazing – Kr)	Pillington energiKare™	0.5 – 0.7
Low-e (triple glazing – Air)	AGC's ENERGY Select™	0.29 – 0.30
Low-e (triple glazing – Ar)	AGC's ENERGY Select™	0.24 – 0.25
EC glazing	N/A	Slightly less than 1
EC glazing (double pane – Ar)	SageGlass®	0.29
EC glazing (triple pane Ar)	SageGlass®	0.14

Table 26: Comparison performance for several technologies for energy efficiency in windows
(source: Ghosgal and Neogi [147] , AGC, SageGlass).

[146] Tavares, P.F., Gaspar, A.R., Martins, A.G., Frontini, F. Evaluation of electrochromic windows impact in the energy performance of buildings in Mediterranean climates. Energy Policy 67, 68-81, 2014
[147] Ghosgal, S., Neogi, S. Advanced Glazing System – Energy Efficiency Approach for Buildings a Review. Energy Procedia 54, 352-358, 2014

Other active technologies are based on polymer dispersed liquid crystal (PDLC) and suspended particle device (SPD). The former consists of liquid crystal (LC) droplets dispersed in a solid polymer matrix while the latter contains dispersed microscopic light-absorbing particles within a film. When moderate voltage is applied in SPD glass, particles align and allow the pass of light Figure 115.

Currently, PDLC devices face challenges related to their high material costs (e.g. for ITO – indium tin oxide used in electrodes). For this type of coatings, other parameters related to light should be considered rather than the U-value, such as transmittance, reflectance, solar heat gaining coefficient (SHGC), among others.

Regarding the passive type of dynamic glazing, it includes the technologies that respond to non-electrical signals such as temperature (thermochromic) or UV light (photochromic). Both responses are given naturally according to environmental conditions and hence are not tuneable. In thermochromic windows, the amount of solar heat is controlled in response to changes in ambient temperature. The most promising material is VO_2. This type of system struggles with their hardly cost-efficient preparation, stability and performance.

As for the photochromic type, it changes its light transmission properties according to the amount of UV light received. It can be inorganic (e.g. oxides of transition metals and silver-based compounds), organic (Spiropyran family compounds) or, a combination of both (hybrid). The synthesis of these materials is difficult. The most promising window technologies for increasing energy efficiency in buildings are low-e glass and EC.

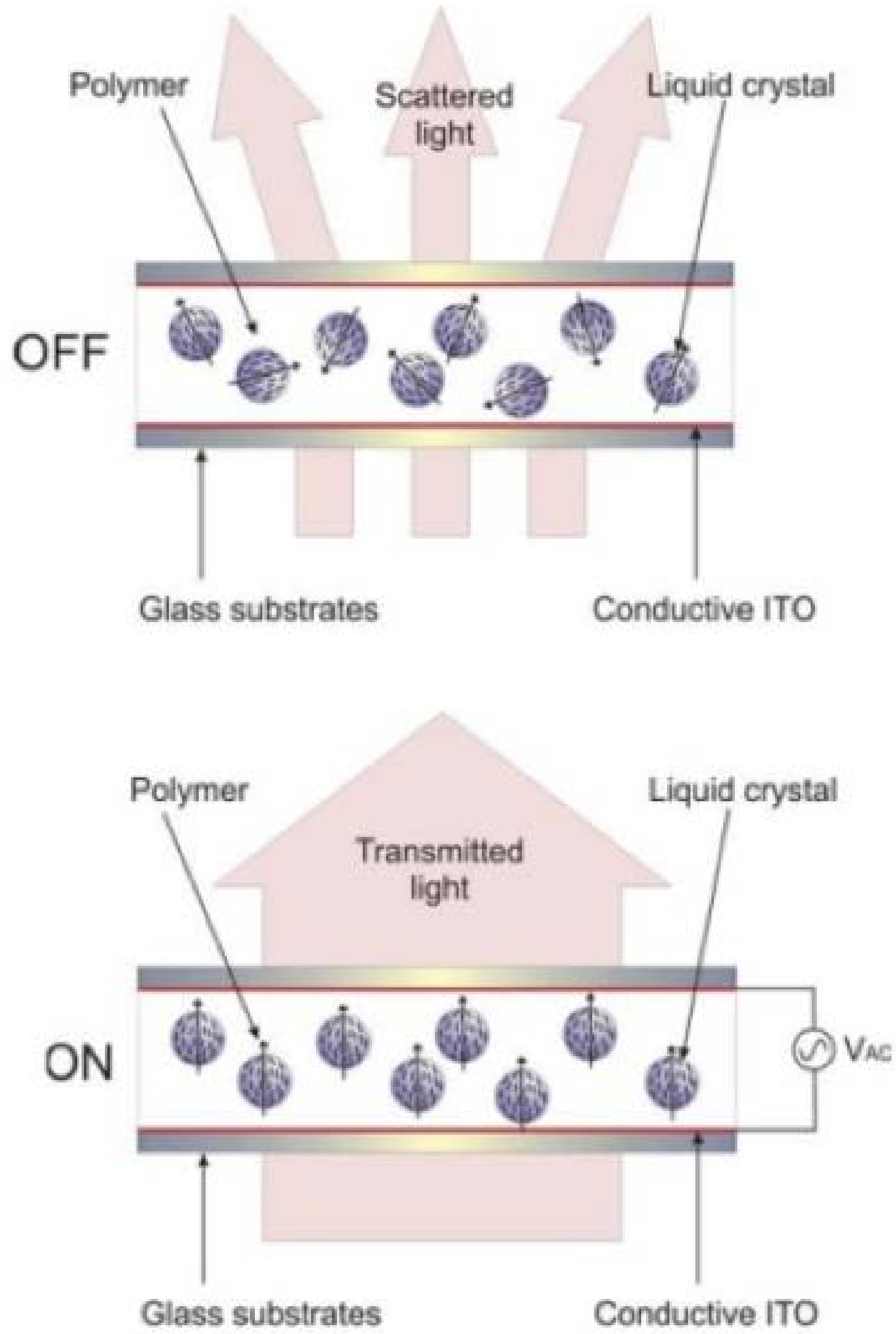


Figure 115: The scattering light phenomena in PDLC coatings (source: University of Cambridge [148]).

[148]Centre of molecular materials for photonics and electronics, Department of Engineering (University of Cambridge), Polymer dispersed liquid crystals (PDLCs)

Envelope – Insulation technologies

The insulation of a building might have significant impacts on its overall efficiency, especially on the external walls forming the envelope. The building's envelope should perform well in terms of airtightness, which focuses on eliminating gaps and cracks in which leakage airflow goes through[149]. A poor airtightness level can lead to moisture issues, excessive heat loss, as well as poor indoor quality that affects health and comfort.

An effective air barrier consists of a system of materials used on different components of the envelope (doors, windows, etc.) using selected accessories, as it is shown in Figure 116.

The level of airtightness is often expressed by the leakage air flow rate through the building at a given pressure (typically 50 Pa) and it is determined by the blower door test method (EN ISO 9972).

The most common insulation materials and the innovative ones are summarised in Figure 117.

Both the quality of materials and the effectiveness of their installation procedure should be high in order to meet insulation and anchoring requirements.

There are several innovation opportunities for improving insulation in envelopes through developing advanced materials for renovation, such as super-insulating materials. In this type of materials, the highest thermal resistance with the thinnest layer is sought [152] .

Energy Management in Buildings

This includes the technologies for improving energy consumption in buildings. The highest share of energy used in buildings accounts for heating and cooling systems (85%)[153] . Lighting accounts for approximately 19% of global electric energy consumption [154].

The development of new advanced materials and improving existing ones hold promising opportunities, as it is described below.

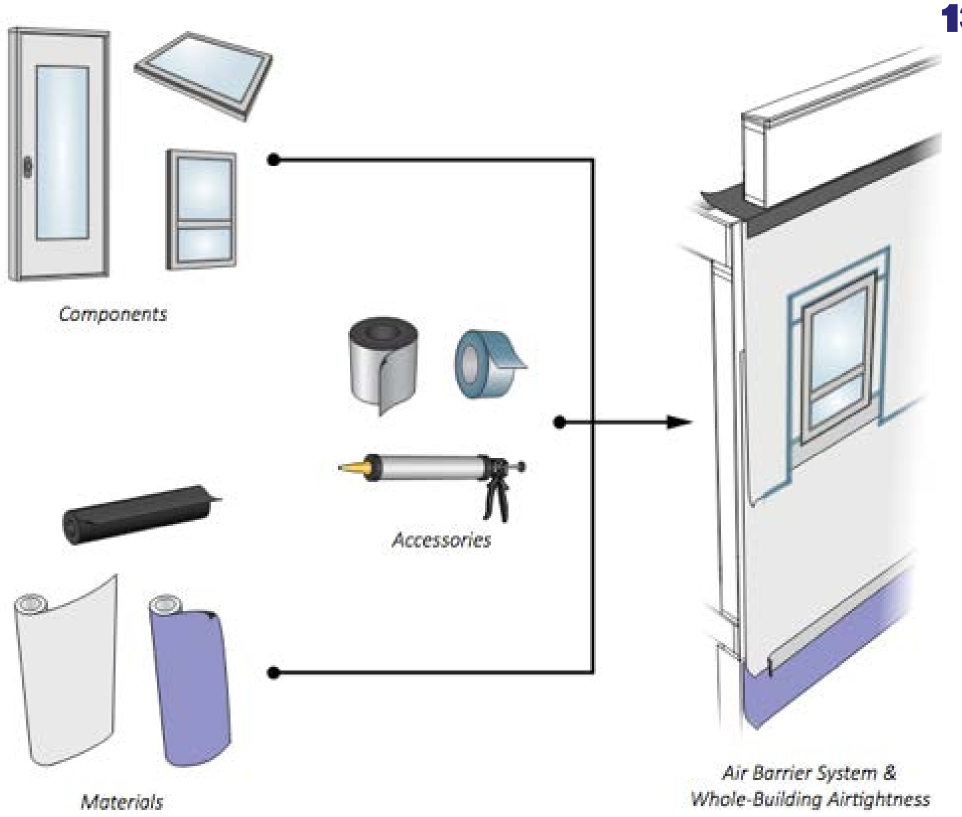


Figure 116: Materials used on components for achieving a good building airtightness (source: BC Housing [150])

Thermal insulation materials

Inorganic mineral derived	Organic fossil fuel derived	Organic plant / animal derived	Innovative materials
• **Stone wool*** **Glass wool*** (fibreglass) • Slag wool • Cellular glass • Aerated glass • Vermiculite • Expanded clay pellets	• **Polyurethane (PU)*** • **Expanded polystyrene (EPS)*** • **Extruded polystyrene (XPS)*** • **Polyisocyanurate (PIR)*** • Phenolic foam	• Woodfibre • Cork • Sheep's wool • Cotton • Hemp • Flax • Compressed straw	• Biopolymers • Nanocoatings • Aerogels • Vacuum insulation panels • Nanocellular foam • Phase change materials • Advanced insulation foams

* The most common types

Figure 117: Most common thermal insulation materials (source: European Commission [151]).

[150] BC Housing, Ilustrated guide – Achieving airtight buildings, September 2017.

[151] Pavel, C.C., Blagoeva, D.T., Competitive landscape of the EU's insulation materials industry for energy-efficient buildings, Luxembourg 2018

[152] BUILD UP: The European Portal for Energy Efficiency in Buildings, OVERVIEW: Super insulating Materials: From mature products to market ready solutions, December 2017

Thermal energy storage (TES)

TES in buildings can play a key role in implementing a smarter and more sustainable use of heating and cooling systems. These technologies consist on stocking thermal energy so that it can be used at a later time, which can improve peak load distribution during the day. It can be grouped in three categories:

Sensible thermal energy storage is the heating or cooling of a material without phase change to store either heating or cooling potential. The most common material is water, although other solids and liquids including glycol, concrete, and rock are also used.

Latent thermal energy storage involves a phase transformation when the material stores and releases heat (phase change materials – PCM).

Thermochemical energy storage (TCM) uses the heat of reaction of a reversible thermochemical process.

A performance comparison for these technologies is shown in Figure 118.

As can be seen, the greatest storage capacity is attained for TCM although at a high temperature range. This type of systems remains largely at an experimental stage [156]. On the other hand, PCMs have transition temperatures suitable for building comfort range while being non-toxic, fire-retardant and aesthetically pleasing when integrated with interior surfaces. These materials can offer high storage capacity and storage efficiencies from 75-90%. In most cases, storage is based on a solid/liquid phase change with energy densities in the order of 100 kWh/m^3. The development of advanced materials for PCMs holds promising advances for the next years. A comparison of several commercial PCM products is shown below.

"THERE ARE SEVERAL INNOVATION OPPORTUNITIES FOR IMPROVING INSULATION IN ENVELOPES THROUGH DEVELOPING ADVANCED MATERIALS FOR RENOVATION, SUCH AS SUPER-INSULATING MATERIALS."

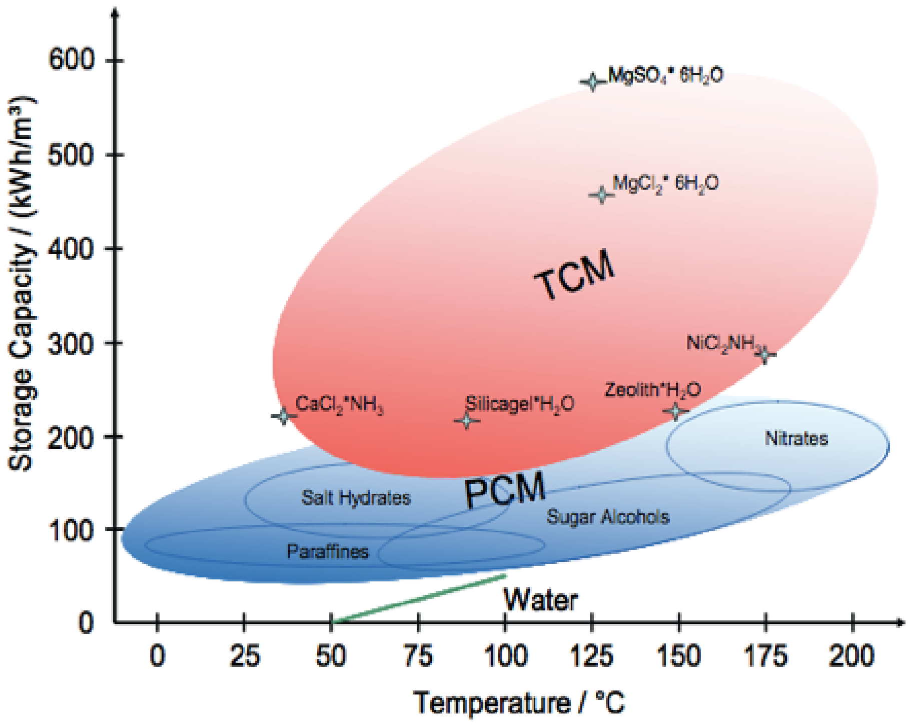


Figure 118: Storage capacity vs. temperature for the different TES technologies (source: IRENA [155]).

[153] Hall, M., Energy Efficiency in Buildings, July 2016

[154] IEA SHC Task: Advanced lighting solutions for retrofitting buildings, Daylight and lighting retrofit to reduce energy use in non-residential buildings: A literature review, Germany 2016

[155] IEA-ETSAP and IRENA, Thermal Energy Storage Technology Brief, January 2013

[156] Joint EASE/EERA recommendations, European energy storage technology development roadmap towards 2030

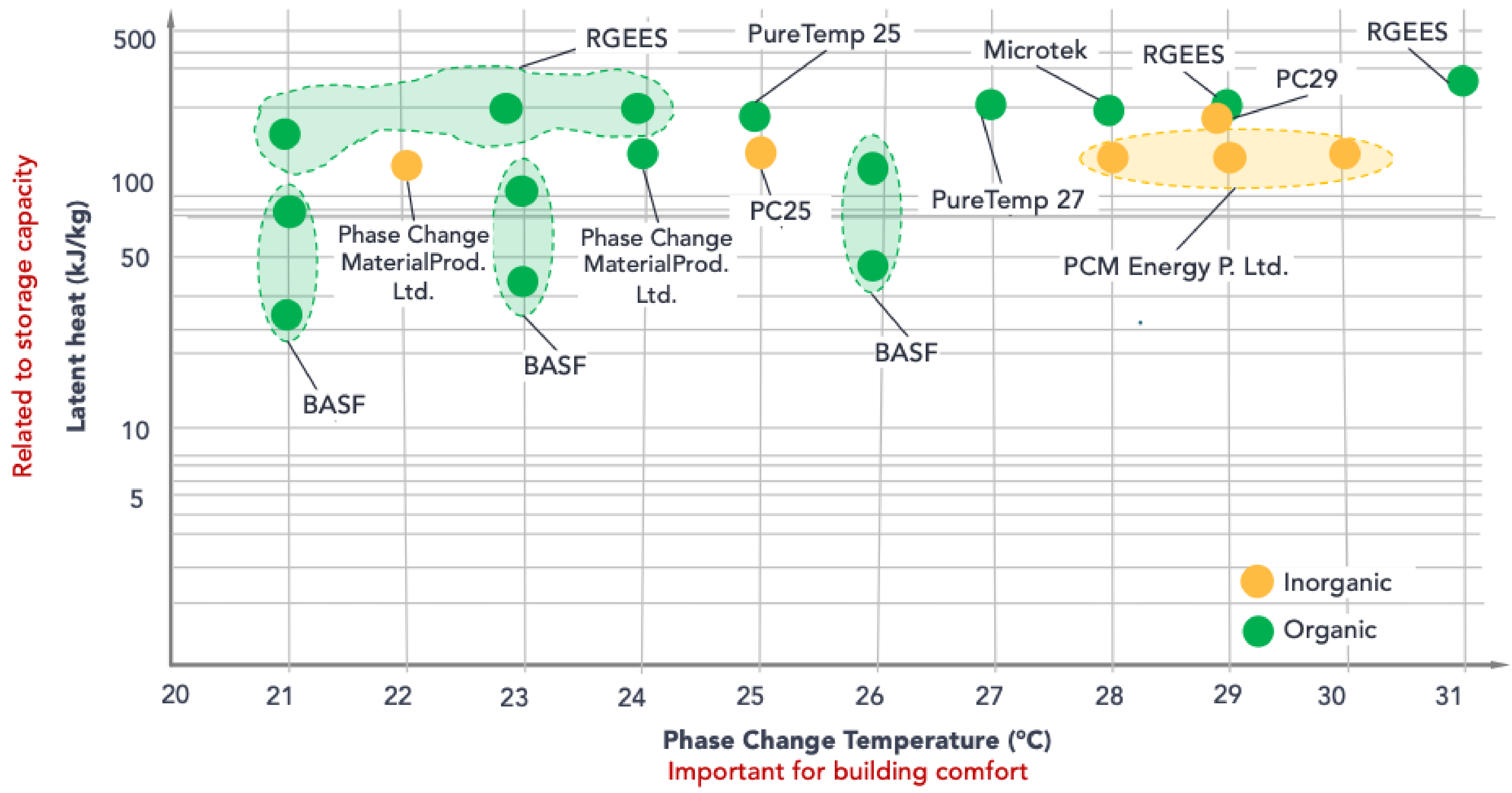


Figure 119: Storage capacity vs. temperature of application for some commercial products (source: SINTEF). [157]

Several options are commercially available for a few years now, with those of organic type being more widespread.

Lighting technologies

Efficient and effective use of lighting can have a great impact on the overall energy and cost saving in both residential and commercial buildings. Besides building design, attractive lighting depends on the performance of lighting technologies, which in turn must adapt to new smart grid concepts. When introduced more than 40 years ago, fluorescent lamps were expected to replace conventional incandescent bulbs since they are about 3 to 5 times more efficient and can last about 10 to 20 times longer. However, their higher costs still hinder their widespread use.

Innovative alternatives for lighting have risen during the last years, with many of them being enabled by the development of advanced materials. While many lighting technologies are commercially available, the technology most likely to dominate the future is the lighting-emitting diode (LED) which can be inorganic (crystalline semiconductor devices) or organic (OLEDs) [158],[159].

[157] Kalnaes, S.E., Jelle, B.P, Phase change materials and products for building applications: A state of the art review and future research opportunities. Energy and Buildings, 2015

[158] Quadrennial technology review – An assessment of energy technologies and research opportunities. Chapter 5: Increasing efficiency of buildings systems and technologies, September 2015

[159] E.F. Schubert, Cambridge University Press, Light-Emitting Diodes, 2006

Lamp type	LED	Incandescent	Halogen	Fluorescent	CFL	Metal halide	HPS	LPS	Mercury vapour
Conversion efficiency (%)	++++	-	-	+	++	+	++	++	+
Average lifespan (hours)	++++	-	-	+	+	++	++	+	+
Power consumption	+	++++	++++	+++	++	+++	+++	+++	+++
Maintenance cost	+	++	++	++	++	++	++	++	++
Efficacy (lm/W)	++++	-	-	+++	++	+++	+++	+++	++
Mercury	No	No	No	Yes	Yes	Yes	Yes (for mercury vapour)	-	-
Lead	No	Yes	Yes	No	No	Yes	Yes	No	Yes

Table 27: Comparison performance for different lighting technologies (source: UNEP [160])

Lighting-emitting diode (LED)

Conventional LEDs are made from a variety of inorganic semiconductor materials, depending on the wavelength and colour of the light emitted. The semiconductor materials form a P-N (positive-negative) junction that converts the flow of electrons into the emission of photons within a specific wavelength. Compared to conventional technologies, LEDs can have high conversion efficiency values as well as increased lifespan (Table 27).

The current major barriers to LED technology are related to cost, colour characteristics and efficacy, which measures how well the visible light is produced. These features could be improved with the development of more advanced LED materials.

Organic LEDs (OLEDs)

OLEDs are solid-state semiconductor devices that are formed by several layers that jointly have 100 to 500 nanometres thickness (Figure 120).

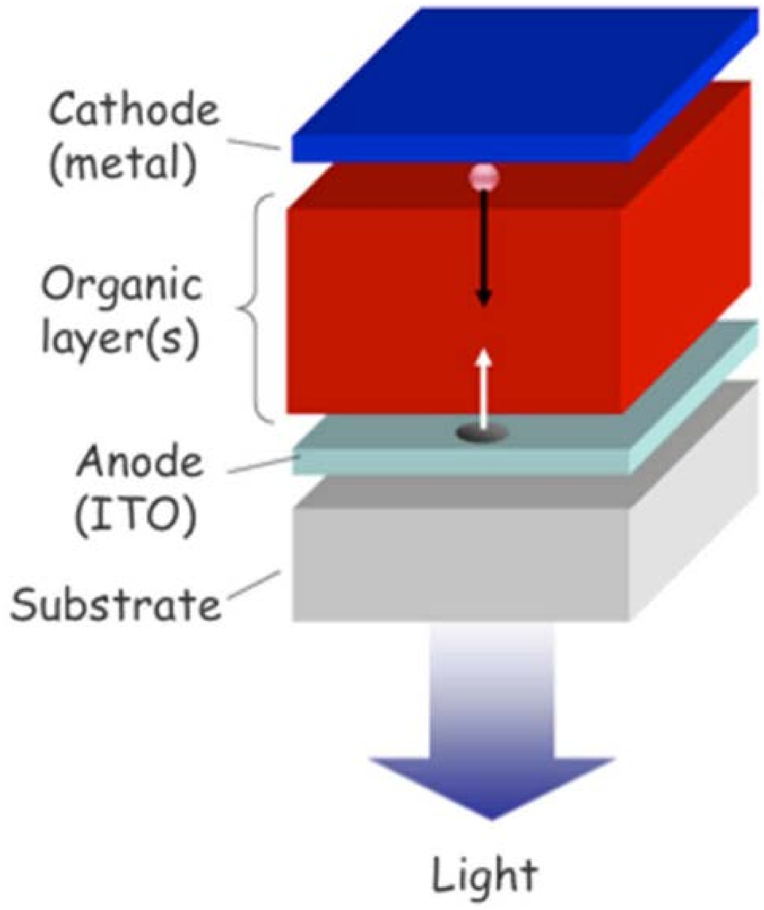


Figure 120: Typical structure of a bottom-emitting OLED (source: European Commission [161]).

[160] Petrichenko, K., UNED DTU Partnership Coppenhagen Centre on Energy Efficiency, Energy Efficiency – Buildings, Lighting & Appliances, in Danida Fellowship Course, 2015
[161] Zissis, G., Bertoldi, P. 2014 Status Report on Organic Light Emitting Diodes (OLED), Luxembourg 2014

The emissive electroluminescent layer is a film or organic compound that emits light in response to an electric current. Current values of efficacy range from 60-125 lm/W and targets for 2020 are expected to reach 168[162] Their flexibility and potentially lower cost are seen as the main advantages over conventional LEDs[163].

The manufacturing of OLED components is still evolving, although some products are already commercially available. The utilization of new materials and further technology development could allow attaining significant improvements in OLED efficiency and operating lifetime.

Cost Structure

Figure 121 shows the average breakdown share values per element for a new house.

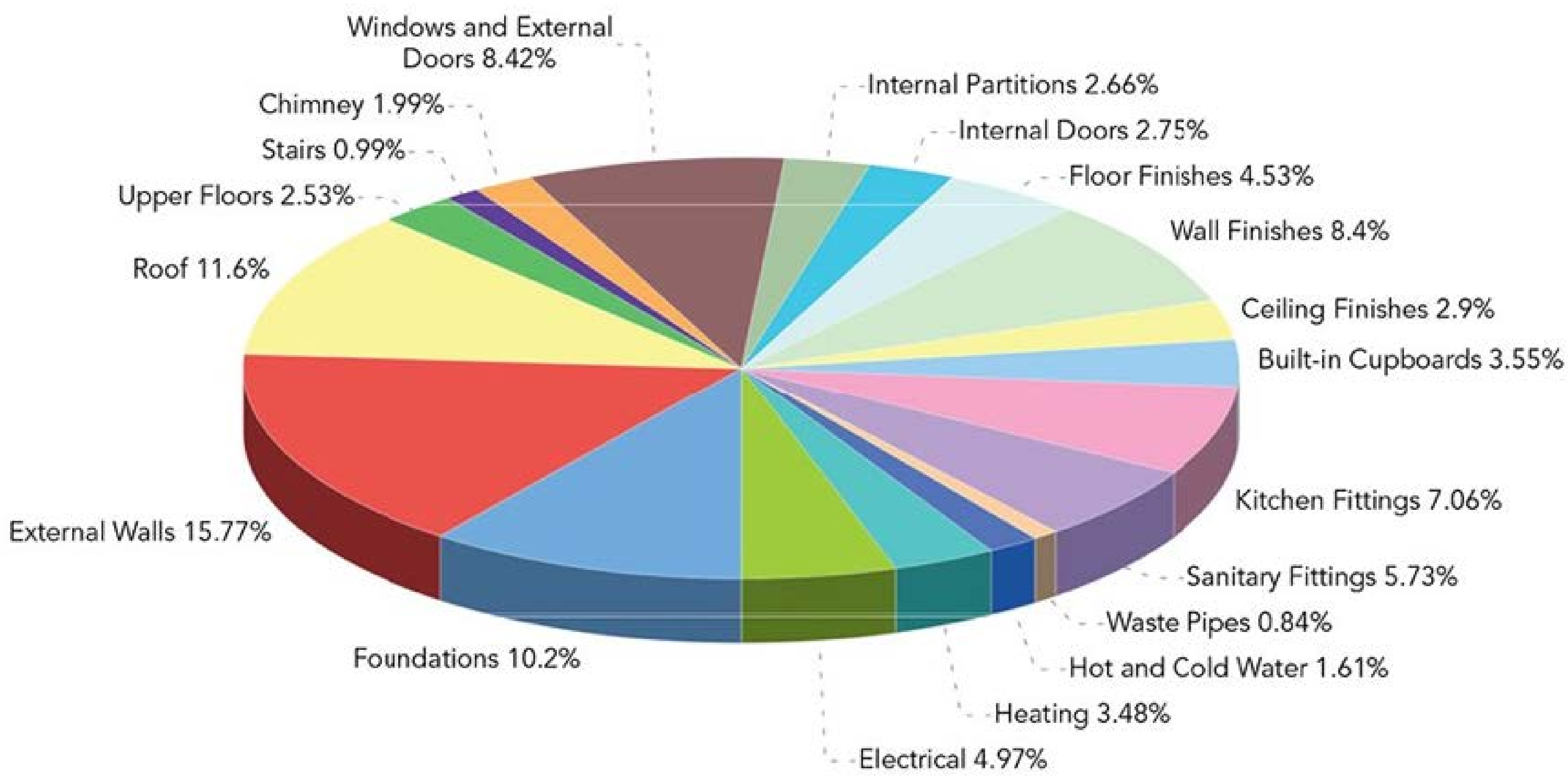


Figure 121: Breakdown costs of an average house (source: Homebuilding & Renovating [164])

[162] Zissis, G., Bertoldi, P. 2014 Status Report on Organic Light Em tting Diodes (OLED), Luxembourg 2014

[163] Y. Karkazi, J. Mater. Environ, Organic light emitting diodes: devices and applications, 2013

[164] Holmes, M., How Much Will Your Project Cost?. Homebuilding & Renovating, 2012

As can be seen, external walls and foundations represent the largest share, with 15.77% and 10.2% respectively. The entire cost of the envelope, including chimneys, external doors and windows, account for 50% of the total costs with the balance going on internal structures, fixtures and finishes. The energy management (electrical & heating) account for approximately 8.45%. Thus, the development of advanced materials for increasing energy efficiency in the elements of the envelope and energy management systems is likely to have a direct impact on almost 60% of the overall budget of a new house (including chimneys and doors).

For new buildings, the added cost for reaching the status of 'zero-emission' buildings normally do not exceed the cost by more than 8% . For existing buildings, the costs of deep refurbishment for increasing energy efficiency can be up to €1,000/m².[15]

For both new and refurbished buildings, the cost-to-benefit ratio depends on local conditions and energy savings (kWh/m² saved per year). Considering an average energy consumption for space heating and cooling of about 140 kWh/m² and possible heating/cooling cost savings of 40%, this would amount to some 56 kWh/m². With average electricity cost of about €0.17 per kWh and gas of about €0.06 per kWh, a typical gas heated 100 m² apartment would save around €336 per year.

"THE DEVELOPMENT OF ADVANCED MATERIALS FOR INCREASING ENERGY EFFICIENCY IN THE ELEMENTS OF THE ENVELOPE AND ENERGY MANAGEMENT SYSTEMS IS LIKELY TO HAVE A DIRECT IMPACT ON ALMOST 60% OF THE OVERALL BUDGET OF A NEW HOUSE"

Within building elements, windows manufactured with low-e coatings typically cost about 10% to 15% more than regular windows, but they reduce energy loss by as much as 30% to 50%[166].

In general, the cost of a PCM system for TES ranges between €10-50 per kWh. The cost of micro-encapsulated PCMs systems can be even higher, despite avoiding the use of heat exchangers. For example, the cost of complete plaster board with micro-encapsulated paraffin to be used as gypsum boards includes the price of paraffin (about €5/kg) and the micro-encapsulated material (€13/kg). For a complete TES system, the cost of containers, heat exchangers and other components can be also significant, for which the overall cost-benefit depends to a large extend on the specific application and operation needs, as it is summarised in Table 28[155].

	Cycles per year	5-year energy savings (kWh)	5-year economic savings (€)	Investment cost (€/kWh)
Seasonal storage	1	500	25	0.25
Daily storage	300	150,000	7500	75
Short-term storage (3 cycles/day)	900	450,000	22,500	225
Buffer storage (10 cycles/day)	3,000	1,500,000	75,000	750

Table 28: Economic viability of TES Systems as a Function of the Number of Storage Cycles per year (source: IRENA).

PCM systems are economically viable for applications that involve a high number of cycles.
For various LED solutions, the average breakdown cost is shown in Figure 122.

[165] Bax, L., Cruxent, J., Komornicki, J., European Commission, Advanced Materials for Energy Efficient Buildings. Innovative chemistry for Energy efficiency of buildings in smart cities, 2015

[166] Energy Department of America, Window Types and Technologies

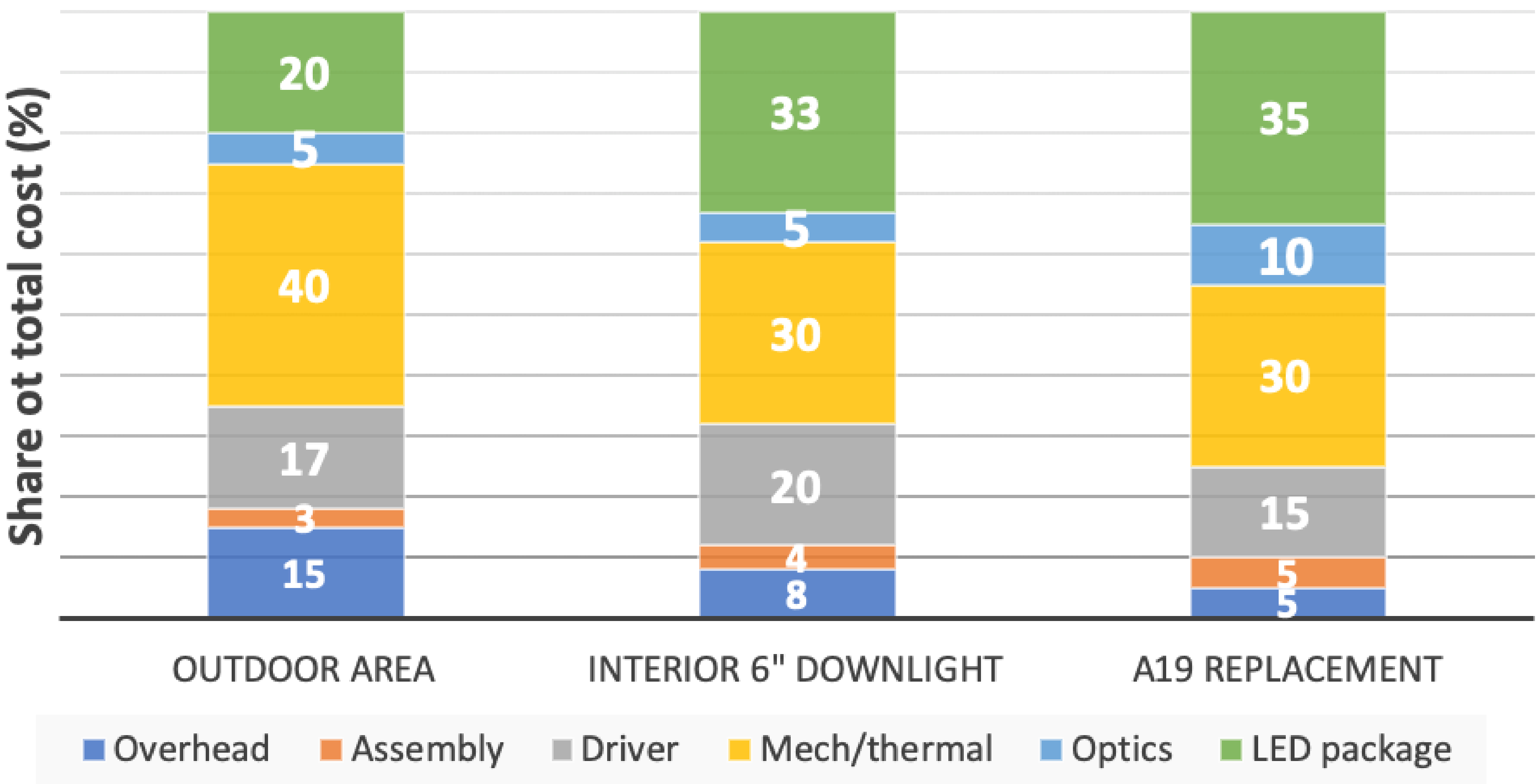


Figure 122: Cost breakdown for various LED solutions (source: Adapted from CREE [167]).

The share cost of the LED package accounts for 20% to 35% of the total system cost (which includes overhead, assembly, driver, optics, and mechanical and thermal equipment).

European Landscape

The European construction sector accounts for 9% of the GDP of the EU . It comprises 3.4 million enterprises and employs 18 million workers. This market is set to grow at 2.9% CAGR in 2019[169].

The substantial growth in the construction sector increases the demand for related products and materials, a market that is forecasted to grow at CAGR of 5.7% until 2023, reaching €109,000 million[170].

In Europe, the market is unevenly distributed among regions, since the sector involves a large number of highly specialized skills. It is a highly regulated sector, with several European regulations and policy strategies impacting their industry (Figure 123[171]).

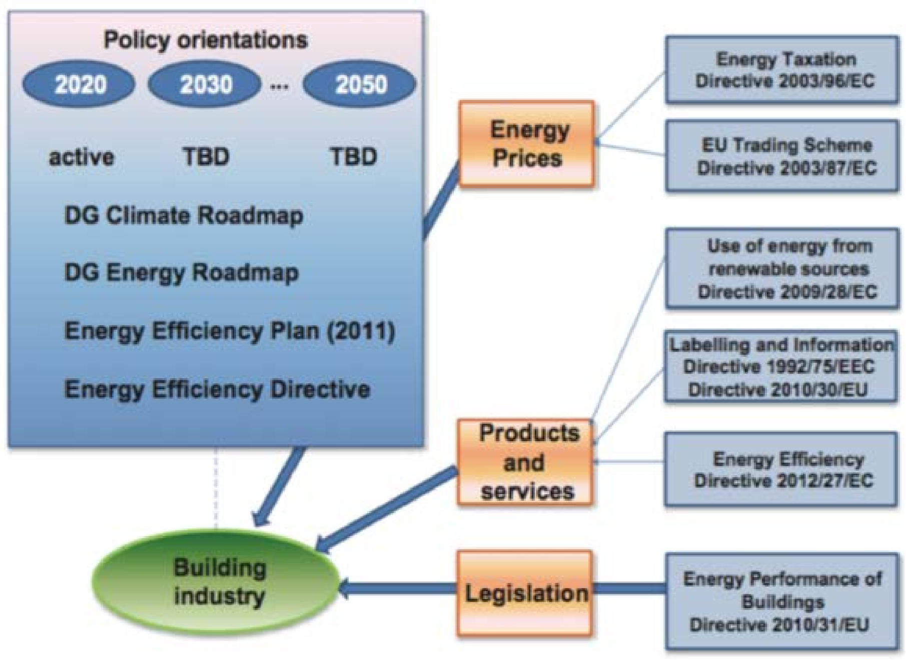


Figure 123: European regulations and policy strategies impacting the building industry (source: European Commission[171]).

[167] Haugaard, E., Cree Lighting, Advanced Materials for LED Lighting, January 2015

[168] EBC Annual report, 2018

[169] Bim News, The Future of Construction: An European Overview, February 2018

[170] Europe Construction Products Market by Product Type and End User - Opportunity Analysis and Industry Forecast, 2013-2023. Allied Analytics LLP, 2018

[171] Directorate-General for Research & Innovation - European Commission, Energy efficient buildings – multi annual roadmap for the contractual PPP under Horizon 2020 – European 2013

The construction of new buildings is already undertaking many of the technologies recognized for increasing energy efficiency in buildings, especially, in many European countries, the public administration buildings. Tackling the refurbishment of existing buildings (including historic buildings) remain a big challenge though. In this field Europe is, however, a leader in innovation for deep renovation of buildings and has the potential to developing an export market on these new techniques (e.g. prefabricated systems) [172].

The European market for building energy-efficient products and services is estimated to increase to €80 billion by 2023[173]. This is the largest share of investment worldwide (30%)[174]. The major investment accounts for building envelopes, appliances and lighting, with the latter having the greatest increase in 2016 since switching from incandescent and halogen lighting to compact fluorescent lamps (CFLs) and light-emitting diodes (LEDs) continues to grow.

Thermal Storage has been utilised effectively for many decades in Europe such as the Underground Thermal Energy Storage (UTES) in the Netherlands, Sweden and Germany[156].For latent heat TES, there are ongoing research programs in Belgium, led by the EnergyVille research partners, which focuses on material improvements. In Germany, Fraunhofer ISE has two research projects concentrated on Phase Change Materials[156].

Focusing on thermal insulation materials, the global market size for building applications was estimated to about €20 billion in 2015 and is projected to increase by a CAGR of 4.5% by 2027, reaching €33 billion[173]. Europe is the thermal insulation materials largest market, which is in average is expected to grow at a rate of 2.8% per year until 2025. Figure 124 shows the forecast in the EU for the thermal insulation market.

"THE CONSTRUCTION OF NEW BUILDINGS IS ALREADY UNDERTAKING MANY OF THE TECHNOLOGIES RECOGNIZED FOR INCREASING ENERGY EFFICIENCY IN BUILDINGS. TACKLING THE REFURBISHMENT OF EXISTING BUILDINGS (INCLUDING HISTORIC BUILDINGS) REMAIN A BIG CHALLENGE THOUGH. EUROPE IS, HOWEVER, A LEADER IN INNOVATION FOR DEEP RENOVATION OF BUILDINGS AND HAS THE POTENTIAL TO DEVELOP AN EXPORT MARKET ON THESE NEW TECHNIQUES"

[172] Pavel, C.C., Blagoeva, D.T., Competitive landscape of the EU's insulation materials industry for energy-efficient buildings, Luxembourg 2018

[173] Ulterino, M., Bloom, E., Navian Research, Energy Efficient Buildings: Europe, Energy Efficient HVAC, Lighting, Insulation and Glazing, Building Controls and Energy Service Companies: Market Analysis and Forecasts. Navian Research 2014

[174] International Energy Agency, Energy Efficiency 2017

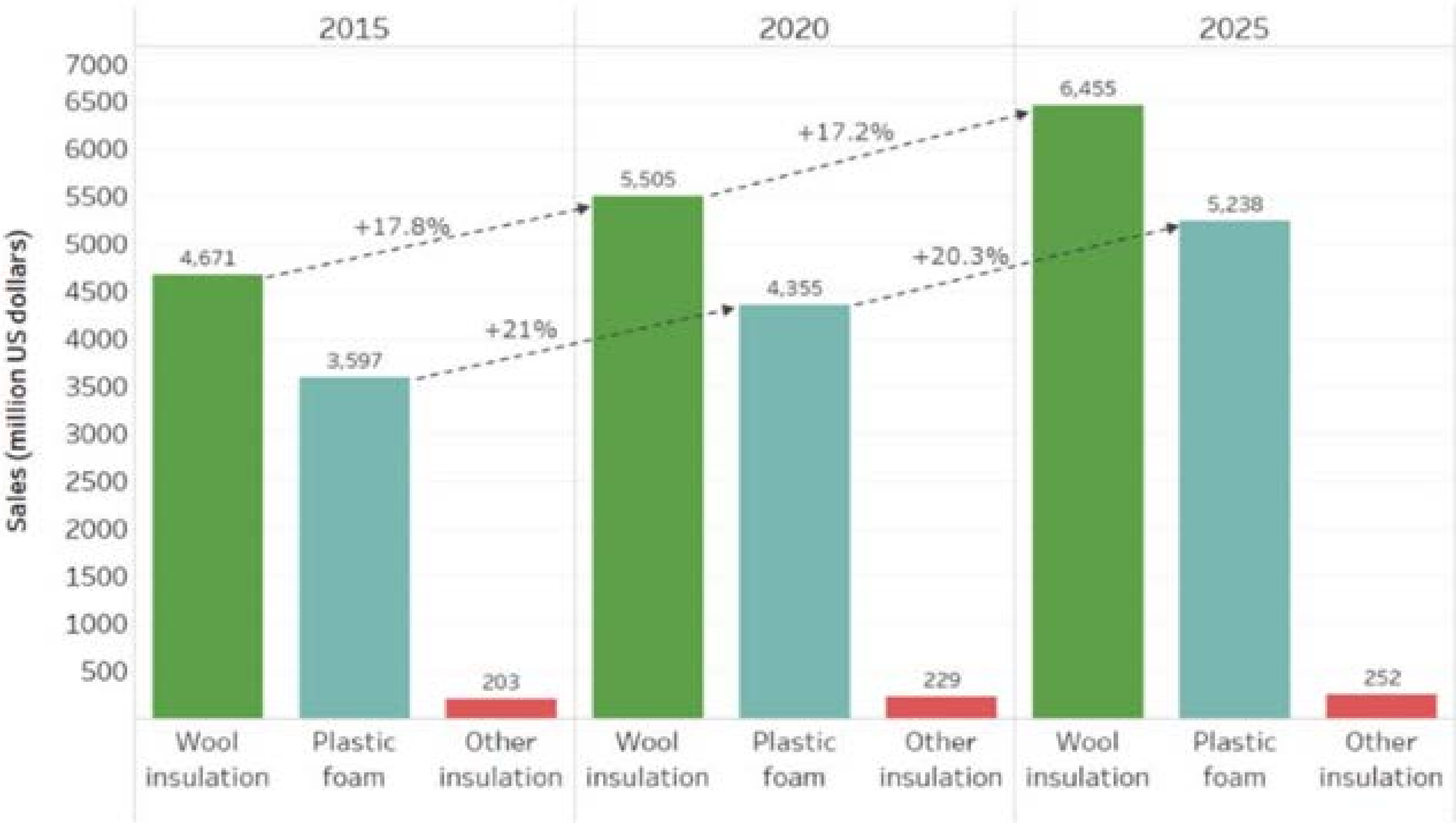


Figure 124: Thermal insulation market in EU in 2015 and forecast for 2020 and 2025 (source: European Commission)

Plastic foam materials (EPS, PU/PIR and XPS) accounting for 42% of the thermal insulation market in 2015 are estimated to grow by 46% by 2025, with Germany, France and Poland leading the market.

Value chain and key players

The construction sector encompasses activities along the whole building value chain, from design to end-of-life stages and including architects and engineering services, manufacturers of construction materials and technologies, onsite construction companies, property developers and facilities managers, energy companies as well as end-users[171] (Figure 125). Nowadays, the building construction chain is driven by a strong push from regulation on the refurbishment of the existing stock of buildings.

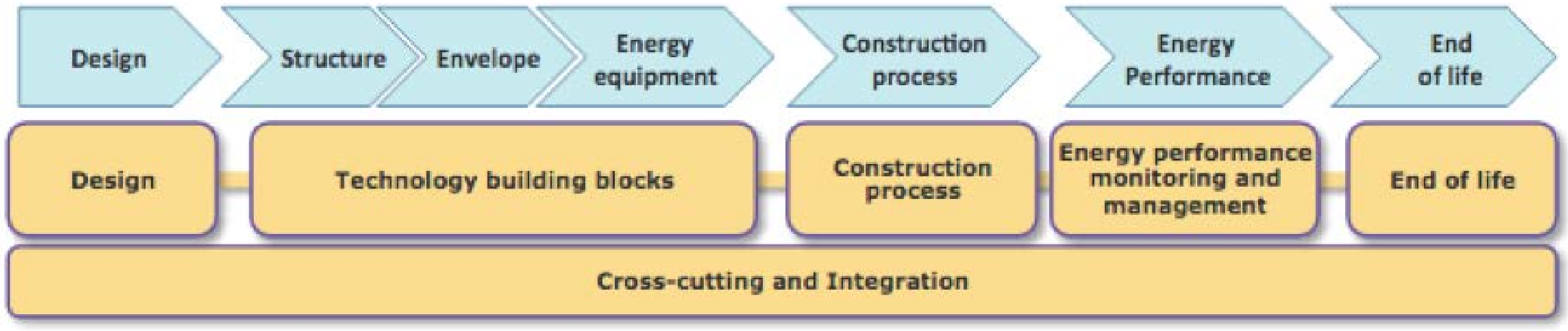


Figure 125: Building construction value chain (source: ECTP[175])

The implementation of the 2050 decarbonisation goals set by the EU involves challenges for the building industry and its entire value chain. The systemic integration of the elements forming the structure, envelope, and energy management equipment covers the whole building value chain and all its actors, including different companies, professions and authorities.

Within the value chain of the building thermal insulation materials, a multi-level network is comprised of raw materials suppliers, manufacturers of finished products and distributors to end-users, such as construction companies (Figure 126).

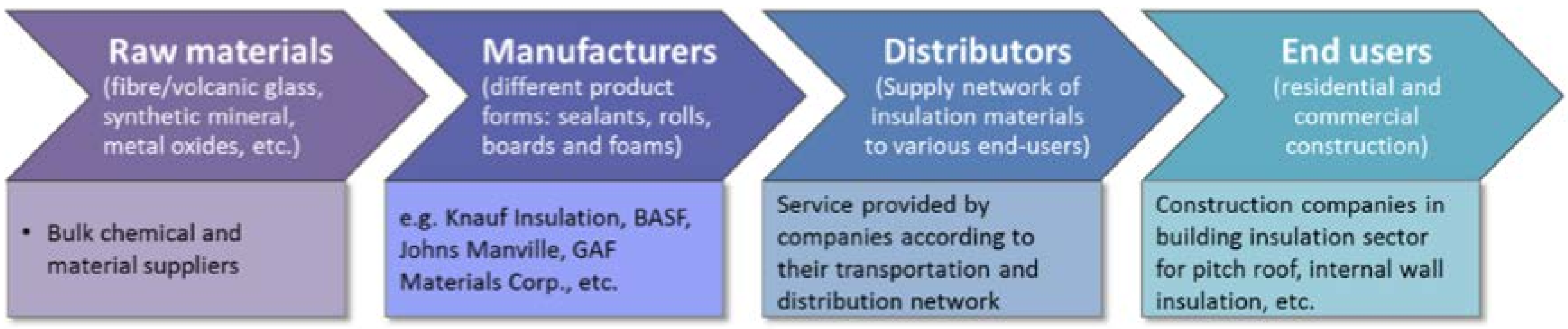


Figure 126. Supply chain of thermal insulation materials used in building applications (source: European Commission[176])

[176] Pavel, C.C., Blagoeva, D.T., Competitive landscape of the EU's insulation materials industry for energy-efficient buildings, Luxembourg 2018

The raw materials determine the final properties of insulation products (e.g. water resistance, temperature range, durability, compressive strength). Table 29 below presents a SWOT analysis for the European building energy products.

Technology	Strengths	Weaknesses	Opportunities	Threats
Dynamic Windows	• Strong background in advanced materials. • High demand in infrastructure projects and buildings. • Innovation is also driven by the automotive sector. • High degree of recyclability • Several large EU-based companies are competitive at global scale. • Skilled labour force.	• Capital intensive market. • High entry barriers for new companies due to high start-up costs, economies of scale, and tied distribution channels that may hinder innovation. • In some sub-sectors, the line of products is very diverse, making it difficult to obtain high sufficient volume in production to secure profit margins.	• Bright future of innovation through R&D. • Increased acceptance of Green Building concept. • Opening of new markets increase export potential. • Liberalization of the EU energy markets and switching to renewable energy.	• Demand slowdown for related industry (e.g. real estate). • Interest rate risk as the industry is capital intensive • Threat from substitute products like conventional materials because of lower costs. • Cheap imports from outside countries. • Environmental regulations exclusively in the EU. • Trade restrictions to non-EU markets, e.g., the USA, Turkey, Saudi Arabia.
Insulation products	• Supply and distribution network capturing large market share. • Established technical expertise. • Strategic growth initiatives. • High degree of R&D and innovation. • Large product portfolio.	• Frequent environmental regulation changes. • Working capital required.	• New product developments. • Opportunities for acquisition to strengthen existing business. • Exports to the growing market demand in Asia-Pacific.	• Governmental compliance cost affecting the profit margins. • Volatility in energy and raw materials prices. • Increasing global competition can lead to loss of market share.
Thermal Energy Storage	• Large demonstration projects with positive results prove the effectiveness of methods available.	• No significant comfort improvement on cloudy days for solar TES. • The current systems require integration with indoor air temperature control strategies.	• The transition temperatures of PCM can be chosen freely over a wide range of values and thus a relatively high degree of tuning is assured to suit different conditions.	• Few commercial PCM glazing on the market, and limited quantification of their real advantages in terms of energy efficiency and indoor environmental comfort.
	• Large expertise background in advanced materials to support innovation. • Several hubs in Europe are consolidated as reference in the matter. • Systems are effective in both winter and summer.	• There are only a few specialists on the market that are familiar with designing and producing complete latent storage systems. • The technology of latent heat storage is perceived as a subject of R&D. • Many PCMs are aggressive to the housing material. • TCM storage is still in the laboratory stage.	• Integration of PCM into the building final products (e.g. plaster and concrete containing microencapsulated PCM). • Integration into the acclimatization system of a building (in pipes and ducts, in the compression system, etc.) • Energy density and reliability are topics to be further improved. • Envelope thickness reduction. • Available use in retrofitting projects for existing buildings.	• The integration of PCM in building products might increase final price. • Potential competitions from other technologies (thermochromic window, electrochromic glass, window with semi-conductor solar cells and low-e films).
LED/OLED technologies	• Rising investments in infrastructure and new installations. • Several EU governments have launched “smart cities” initiatives. • Rising implementation due to modern and stylish designs. • Enabling of wireless lighting control systems. • Reduced electricity bill. • Long lifespan.	• Lack of awareness of the different kinds of technologies. • Higher entry costs than conventional solutions. • Some degree of incompatibility with traditional switching boards due to changes in circuitry design. • OLED manufacturing is still expensive and not cost-effective.	• Increasing demand for energy efficient lighting solutions. • Strong development of healthcare facilities providing comfort and security. • Rapid urbanization. • OLED industry can leverage the expertise from the display industry. • Market driven by increasing smartphones use.	• Traditional bulbs dominate the lighting industry. • Despite the above, plenty of competitors of smart lighting solutions already exist. • Smart lighting might be perceived as more complex systems than the widely and largely known regular lightbulbs.

Table 29: SWOT analysis of main technologies for increasing BEP at European scale (sources: European Commission[176],; EERE-EASE[156]; Global Market Insights[177] ; PESTLE [178])

[177] Global Market Insights Europe LED lighting Market Growth Industry Share Forecast 2018-2024, 2019

[178] Frue, K., PESTLE ANALYSIS, SWOT Analysis of LED Smart Lights: Fighting the traditional light bulb industry, 2018

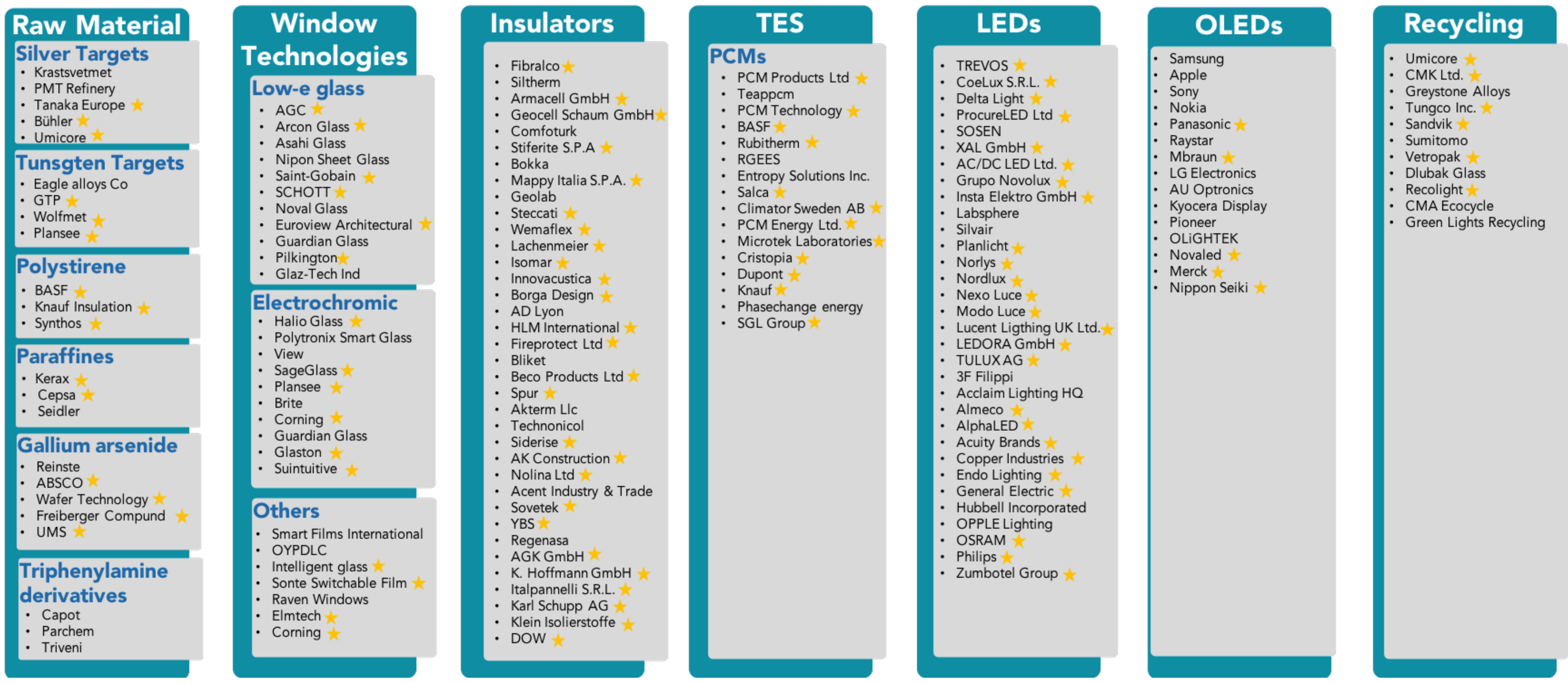


Figure 127 above illustrates the steps of the value chain for increasing efficiency in building energy performance, along with the main players. European organisations are marked with a star.

A large amount of companies working on developing insulation materials are located in Europe.

Figure 127: Value chain and main players for increasing efficiency in building energy performance (non-exhaustive) (adapted by Bax & Company, sources: online web search)

Current Status/Market Overview

Main trends

About 36% of the EU's total GHG emissions can be attributed to the large share of energy consumed in buildings. Among the different energy consumption sources in buildings

Figure 128, space heating accounts for the largest share in energy consumption due to the fact that 75% of the EU's building stock is still energy inefficient.

> "THE RELATED GHG EMISSIONS PER YEAR DECREASED FROM 9.5 GTEQ IN 2013 TO 9.0 GTEQ IN 2016 DESPITE THE INCREASE IN THE FINAL ENERGY CONSUMPTION

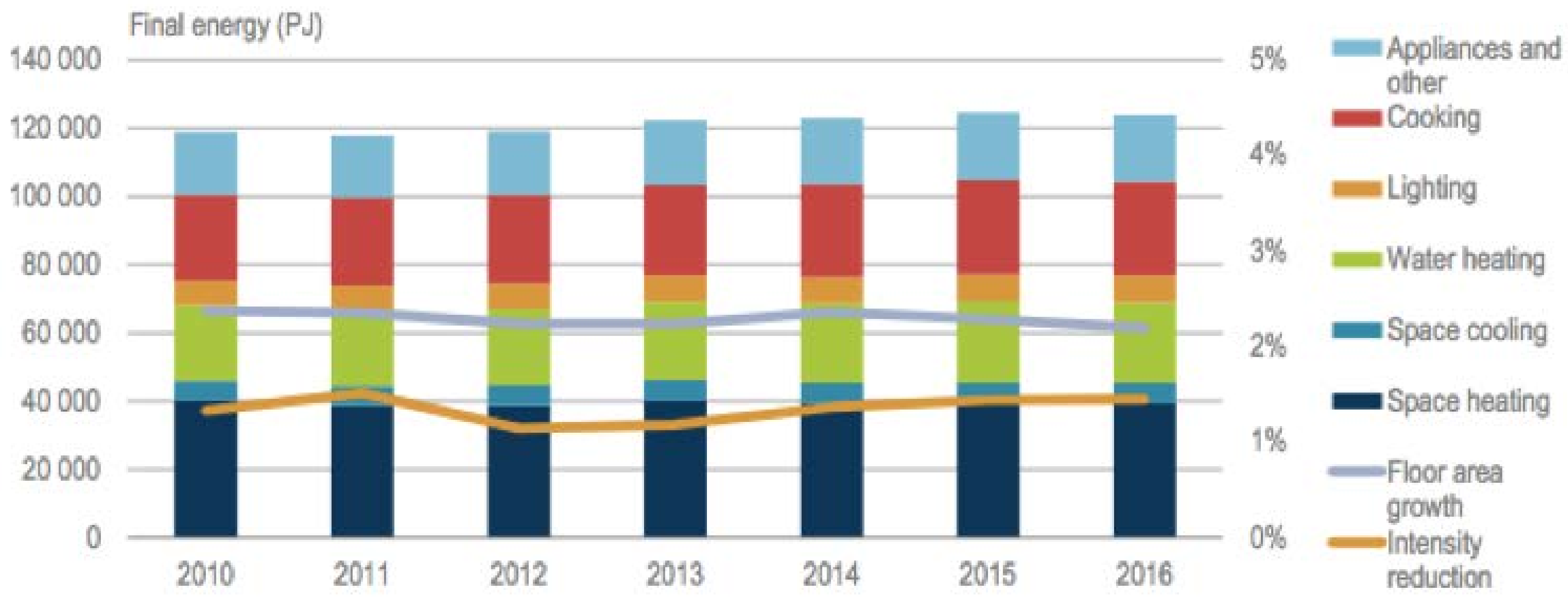


Figure 128: Building sector energy consumption (source: IEA)

The related GHG emissions per year decreased from 9.5 Gteq in 2013 to 9.0 Gteq in 2016 despite the increase in the final energy consumption. Per type of building, the average energy intensity (kWh/m²) in hotels remained the highest, followed closely by office buildings.

Figure 129: Average energy intensities by property type (source: European Commission – BUILD UP) [179].

[179] BUILD UP, European Commission, European Real Estate sector achieves a 5.6% reduction GHG emissions in 2018, 2018

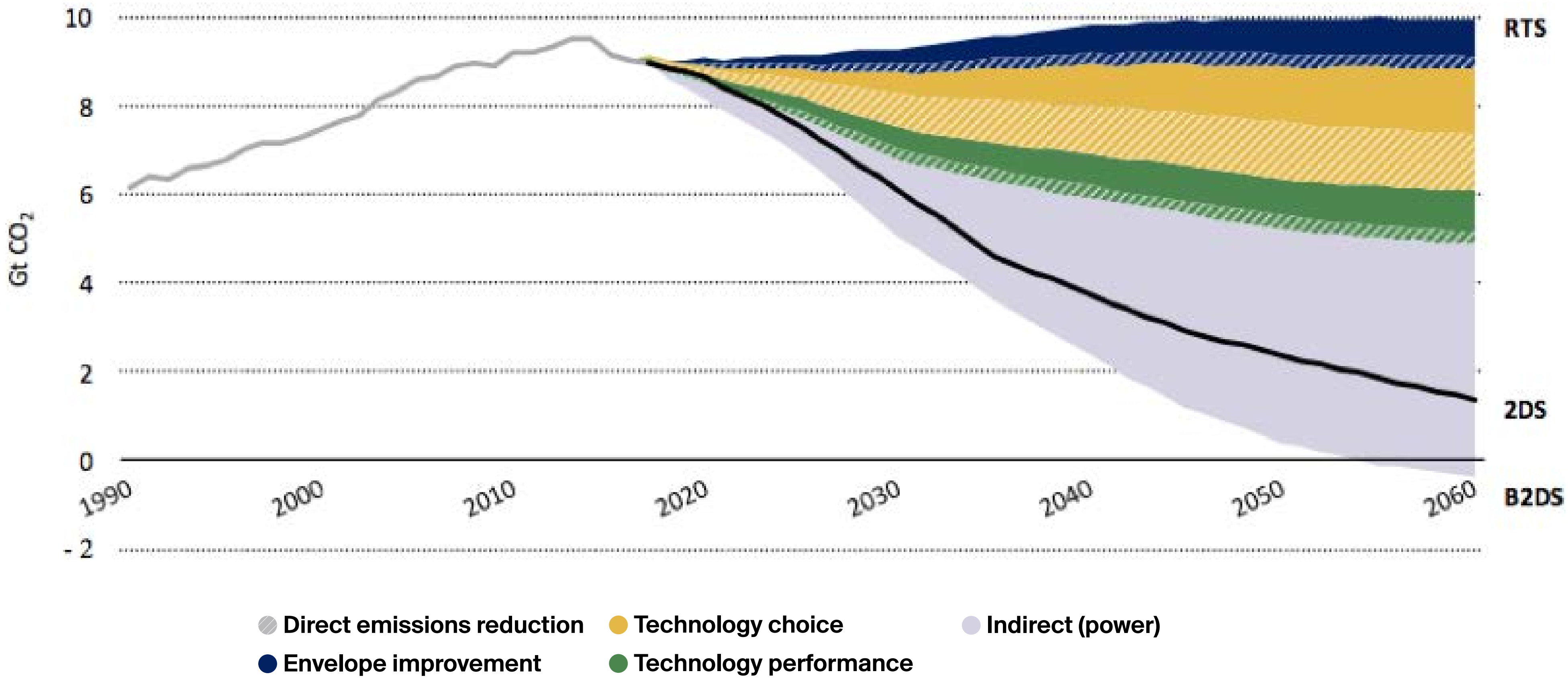


Figure 130: Global building sector emissions saving potential to 2050 (source: UN[180])

Energy efficiency in the building sector holds the greatest potential for reducing CO2 emissions (Gt) at the long term, as it is shown in Figure 130 for different decarbonisation scenarios pathways (RTS – Reference Technology Scenario, 2DS - 2°C Scenario, B2DS – Beyond 2°C Scenario).

"Direct emissions reduction" represents a decrease in emissions from reductions in direct fossil fuel consumption in the buildings sector. "Envelope improvements" include measures that improve the energy intensity of the building envelope. "Technology choice" represents shifts to more efficient technologies (e.g. LEDs). "Technology performance" represents energy technology efficiency improvements (e.g. higher operational performance for heat pumps). "Indirect (power)" emissions reduction is from improved carbon intensities of power generation, where negative emissions are from carbon capture and storage (CCS) technologies. It is also regarded to deliver an increase in economic activity as well as health cost savings (Figure 131).

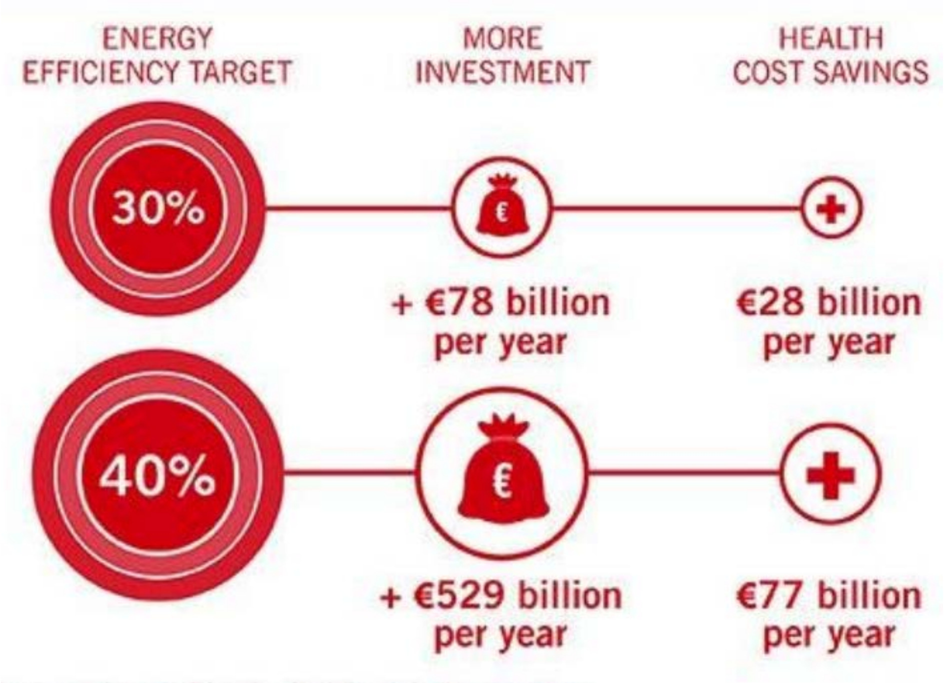


Figure 131: Effect of energy efficiency over economic investments and health cost savings (source: Deutsche Umwelthilfe [181])

During the last years, increasing building energy efficiency has also been related to the monitoring and control of mechanical and electrical equipment by means of software-based platforms, typically known as building management systems (BMS). This type of systems allows for responding to energy demand changes very effectively and also to be managed, controlled and automated in a remote way. BMS comprises devices for lighting, appliances and home automation (Figure 132).

Figure 132: Scope of BMS for increasing energy efficiency (source: European Commission[182]).

By means of these automated systems, which are enabled by advanced materials improvements, EU energy consumption can be reduced by 5-6%[182], especially for lighting and HVAC devices (Figure 133).

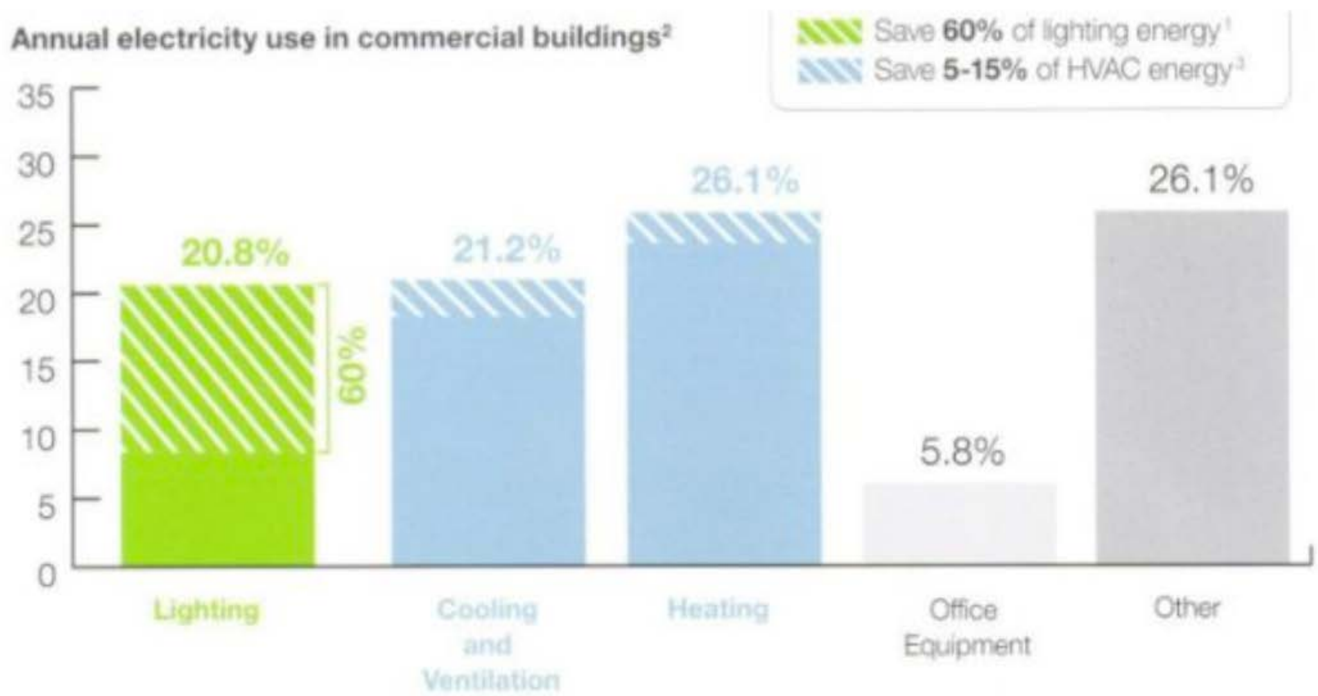


Figure 133: Expected savings in energy demand by means of BMS (source European Commission[182]).

[181] Brandmeyer, P., Environmental Action Germany, Energy efficient buildings are key to shaping our future – Is industry ready to takle the challenges? Poland 2017

[182] Directorate-General Internal Market, Industry, Entrepreneurship and SMEs; Directorate F: Innovation and Advanced Manufaturing, European Commission, Smart Building: Energy efficiency application, 2017

Main challenges

Table 30 below summarises the main materials related challenges that need to be addressed for increasing energy efficiency in buildings within the next 10-15 years in order to increase Europe's competitiveness. The challenges were identified by the EMIRI community in workshops that took place throughout 2018.

Challenge	Application
• Reduce costs of the system by developing new advanced materials and components	●●● (TES, Lighting, Windows)
• Improve performance by enhancing systems efficiency and capacity	●●● (TES, Lighting, Windows)
• Increase efficacy	● (Lighting)
• Enhance durability of components and system	●●● (TES, Lighting, Windows)
• Reduce switch speed and responsivity of systems	● (Windows)
• Increase applicability for larger range spectrums and improve thermal conductivity	● (Windows)
• Increase sustainability aspects related to recyclability	●● (TES, Lighting)
• Improve integration to frames, routing of cables and uniformity of defects between batches	● (Windows)

• TES • Lighting • Windows

Table 30: Main materials related challenges to be addressed.

Proposed R&D topics

Table 31 below summarises the suggested calls to be included in the Horizon Europe framework program, based on the challenges identified above.

Identifier	Call Title	Type
BE1	Development of advanced materials for thermal energy storage for district heating and cooling applications	RIA
BE2	Advanced materials for lighting technologies (LEDs)	IA
BE3	Advanced materials for coating on glass	RIA
BE4	Advanced materials for EC active dynamic glazing	RIA
BE5	Advanced materials for insulation of buildings	IA
BE6	Advanced materials for lighting technologies (OLEDs)	RIA

Table 31: Suggested materials related calls for building energy performance

Figure 134 below illustrates the importance and urgency of each call.

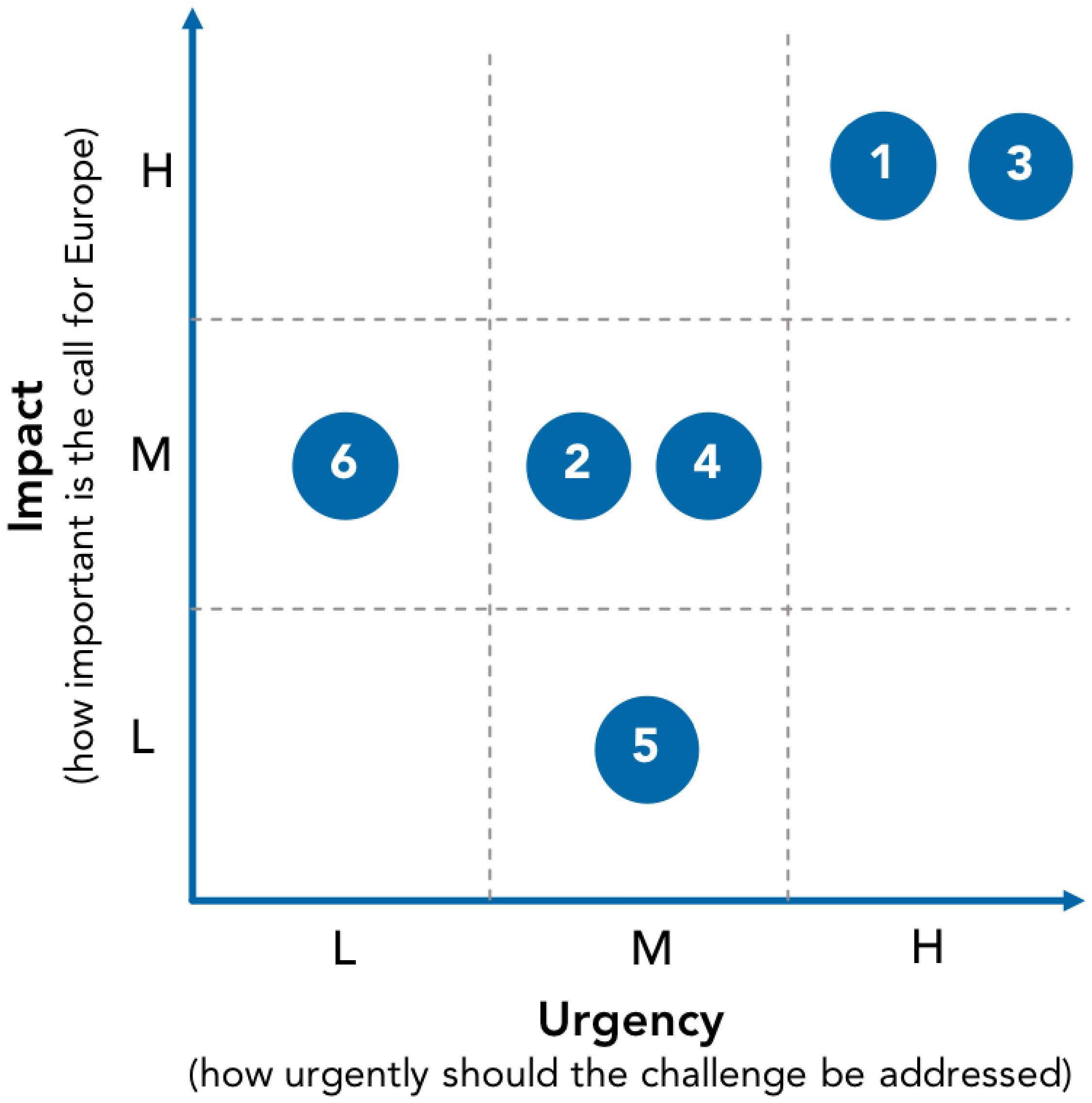


Figure 134: Prioritisation of building energy performance calls

7

LIGHTWEIGHT TECHNOLOGIES FOR MOBILITY

7. Lightweight Technologies for Mobility

Improving the energy efficiency of transportation vehicles has been increasing in importance in the agendas of governments and industries alike to tackle the issue of transportation emissions, which have increased by 71% from 1990 to 2016, reaching a total of 8Gt of CO_2, representing 25% of global CO_2 emissions[183]. This does not only present a challenge to be tackled, but a business opportunity as well. The market for lightweight materials is estimated to exceed 115 billion euros in 2019[184], and continue growing with a CAGR of 5-10%. This market is primarily driven by the large volume of automotive applications – claiming close to 90% of the total lightweight materials market – followed by aerospace/aviation.

"THE MARKET FOR LIGHTWEIGHT MATERIALS IS ESTIMATED TO EXCEED 115 BILLION EUROS IN 2019, AND CONTINUE GROWING WITH A CAGR OF 5-10%"

Technology Overview

Advanced materials are essential for improving fuel economy while maintaining safety and performance in transport applications. Advanced lightweight materials such as high-strength steels, aluminium and composites has been the subject of extensive research over the last few years, exhibiting weight reductions of >30% in the automotive industry, at a cost of ~€3/kg saved[185] Emerging material and manufacturing technologies have given rise to additional material solutions with significant light-weighting reduction, such as polymers, ceramics, and glass.

Such advanced materials are essentially a combination – through a specific manufacturing process – of different elements into a single material, which has significantly improved properties compared to the original raw materials. In the case of metals, the performance of steel and aluminium alloys is defined by their alloying elements as well as the process parameters, in the case of FRP by the type, orientation, and content of the reinforcement, in polymers by the material (molecular) design as well as process parameters, etc. As individual materials are reaching their performance limits – at least for the acceptable cost ranges – multi-material solutions that combine the advantages of

[183] International Energy Agency, CO2 emissions statistics, 2018
[184] Allied Market Research, Lightweight materials market by type and application, September 2016
[185] ALLIANCE H2020 project, 2016 - 2019

Grade (SAE designation)	Type	Main applications
1xxx	Carbon steels	Forging grades, rail steels, spring steels, pre-stressed concrete, wire rope, tire reinforcement, wear resistant steels and high strength bars
2xxx	Nickel steels	Plating for metal protection, producing alloys such as stainless steel, armour plating, boat propeller shafts and turbine blades, batteries, heavy forgings, highly stressed screws, bolds and nuts
3xxx	Nickel-chromium steels	Electric heating elements, resisting to oxidation at high temperatures, bridgewire in explosives, household appliances...
4xxx	Molybdenium steels	Chemical processing plants, marine applications and automotive exhaust systems
5xxx	Chromium steels	Aircraft industry, combined with lighter metals, food processing equipment and decoration in automobiles
6xxx	Chromium-vanadium steels	Steel tools, cutting tools
7xxx	Tungsten steels	Filament in incandescent light bulbs, household applications
8xxx	Nickel-chromium-vanadium steels	Steel tools
9xxx	Silicon-manganese steels	Used for steel compound deoxidizer, desulfurization agent and alloy agent

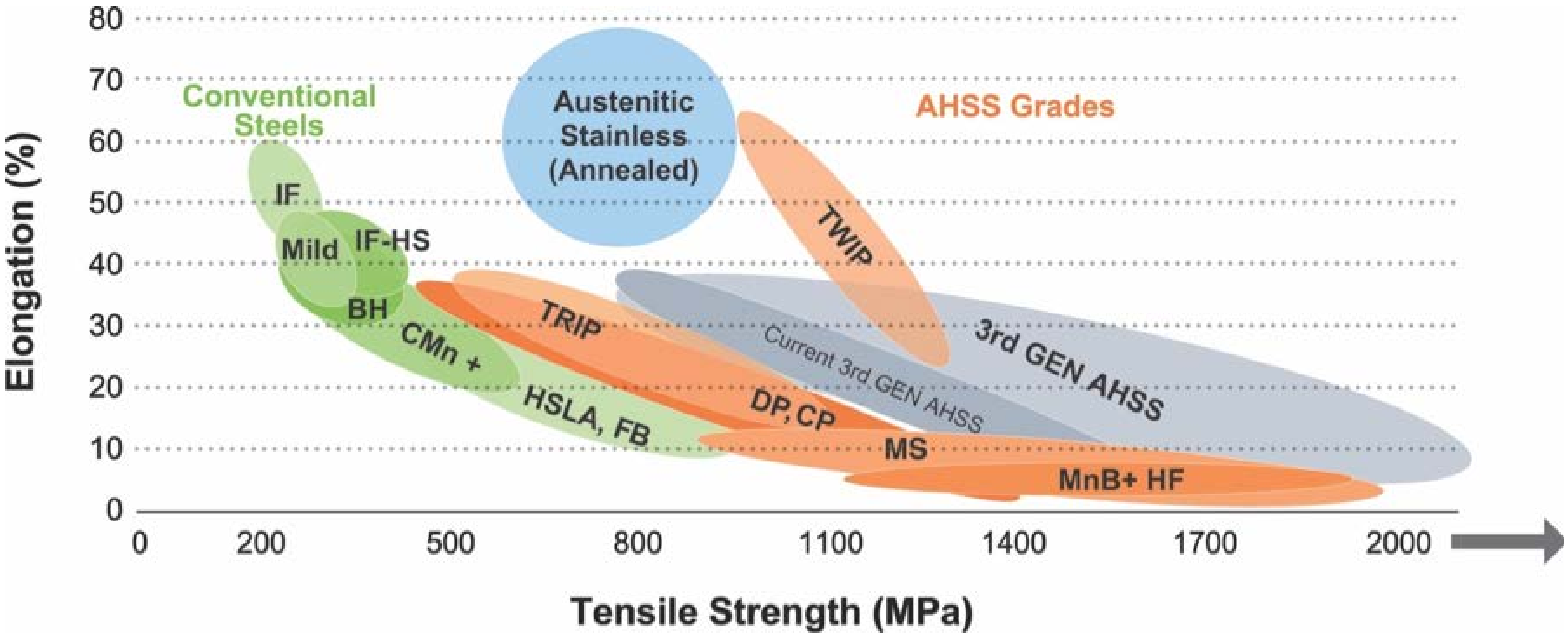
Table 32: Steel grades and their main applications

various mono-materials into one application have been gaining attention.

Steel Alloys

Steel is an alloy of mainly iron, carbon, and in cases, other elements. It has been the main material of choice for several transportation applications, as it combines a wide range of yield strength, high elastic modulus, is adaptable to corrective rework, and is relatively low cost.

The main differentiation between different types of steel is their alloying elements, as well as their manufacturing parameters, which create different steel grades, with varying properties, suitable for one type of application or another. Steel alloys are classified using a four digit code system where the first digit indicates the main alloying elements, the second the top grade elements, and the last two the carbon content by weight (in percentage). An overview of the main steel grades is provided Table 32 above.



Over the years, steel alloying elements and process parameters have evolved to accommodate increasing demands. AHSS offer weight reduction of up to 25% compared to conventional steel grades, at costs lower than €2/kg saved[186]. Figure 135 illustrates a comparison of two of the main steel parameters – elongation, related to formability; and tensile strength, related to crash performance – for low and high-strength steels.

Methods for manufacturing steel have evolved significantly since the beginning of industrial production in the late 19th century. Modern methods, however, are still based on the same premise as the original Bessemer Process, which uses oxygen to lower the carbon content in iron. The manufacturing process to obtain steel is displayed in Figure 136.

Figure 135: Steel strength ductility diagram (source: WorldAutoSteel)

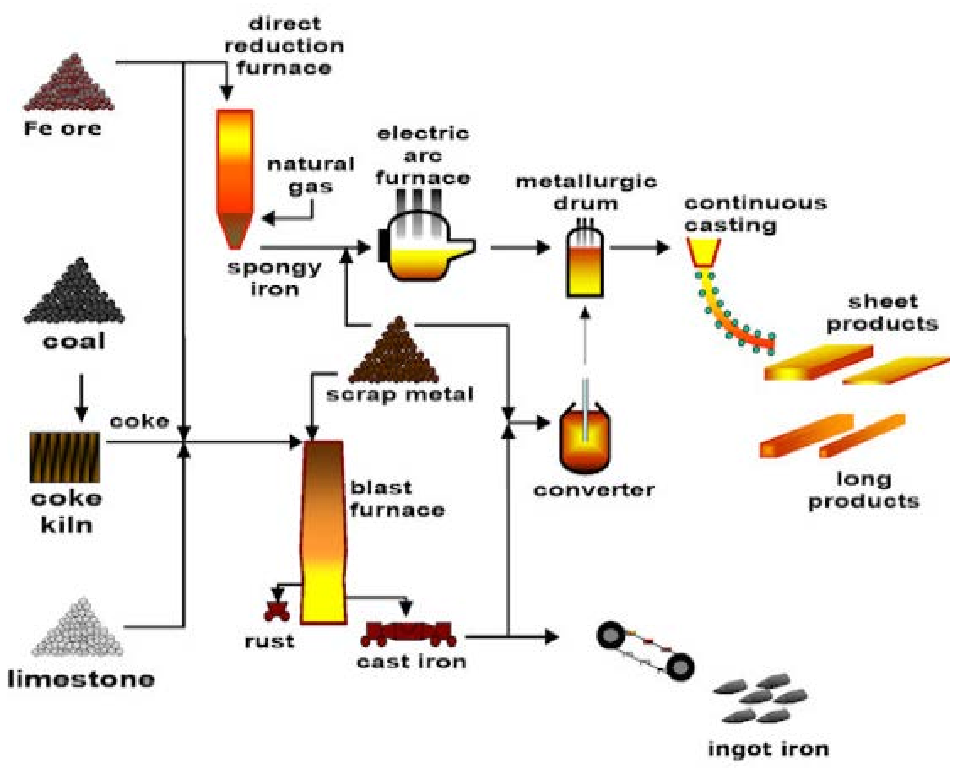


Figure 136: Manufacturing process to obtain steel (source: Steel Feel [188])

[186] Cambridge Core, Advanced lightweight materials and manu facturing processes for automotive applications, December 2015
[187] Steel Feel- From Steel to Manufacturing, What is steel making process: briefly explain, June 2016

Grade (IADS designation)	Type	Main applications
1xxx	Pure aluminium (>99%)	Work-hardened, pressurised vessels, chemical tanks, high corrosion resistance and high thermal and electrical conductivity applications
2xxx	Copper aluminium	Precipitation-hardened, aerospace alloys, military applications, armour plates, wires, rods, bars, extrusions, tubes and forgings
3xxx	Manganese aluminium	Work-hardened, building façade elements, electronics, automotive, electronic components, home appliances
4xxx	Silicon aluminium	Work-hardened components, filler material for welding and brazing
5xxx	Magnesium aluminium	Work-hardened, marine applications, electrical conductors, transportation components
6xxx	Magnesium-silicon aluminium	Precipitation-hardened, welding fabrication, structural components, storage tanks, furniture and automotive body panels
7xxx	Zinc aluminium	Precipitation-hardened, aircraft structures
8xxx	Other elements-aluminium	Thinner gauge applications, transportation applications, wires for electrical purposes

Table 33: Aluminium wrought alloy grades and their main applications

Aluminium Alloys

Aluminium is a non-magnetic, ductile metal that belongs in the boron elements group. It is the world's most abundant metal and is the third most common element comprising 8% of the earth's crust. Compared to steel, aluminium alloys typically have lower density, better thermal and electrical conductivity, lower strength to weight ratio, and are more ductile. Typical alloying elements are copper, magnesium, silicon, manganese, zinc, and tin. Aluminium alloys are divided in wrought and casting alloys. Wrought alloys, means "worked" (rolled, forged, extruded products) meanwhile casting alloys are specifically designed to be cast at near net shape but not worked. The majority of aluminium is used for wrought alloys which have, in general, higher ductility and strength in comparison to cast alloys. However, thanks to their near net shape and their cost advantage aluminium cast products are still dominant in automotive applications.

Due to its low density and high ductility, aluminium alloys are often used in transportation applications. Similarly to steel, the combination of alloying elements and process parameters generates different aluminium grades designated by a four digit code applicable for wrought alloys and three digits code for cast alloys. The first digit indicates the main alloying elements, the second the variation of the alloy, and the last one or two the specific alloy in the series. An overview is presented in Table 33 above.

"AHSS OFFER WEIGHT REDUCTION OF UP TO 25% COMPARED TO CONVENTIONAL STEEL GRADES, AT COSTS LOWER THAN€2/KG SAVED"

"ALUMINIUM IS THE WORLD'S MOST ABUNDANT METAL AND IS THE THIRD MOST COMMON ELEMENT COMPRISING 8% OF THE EARTH CRUST"

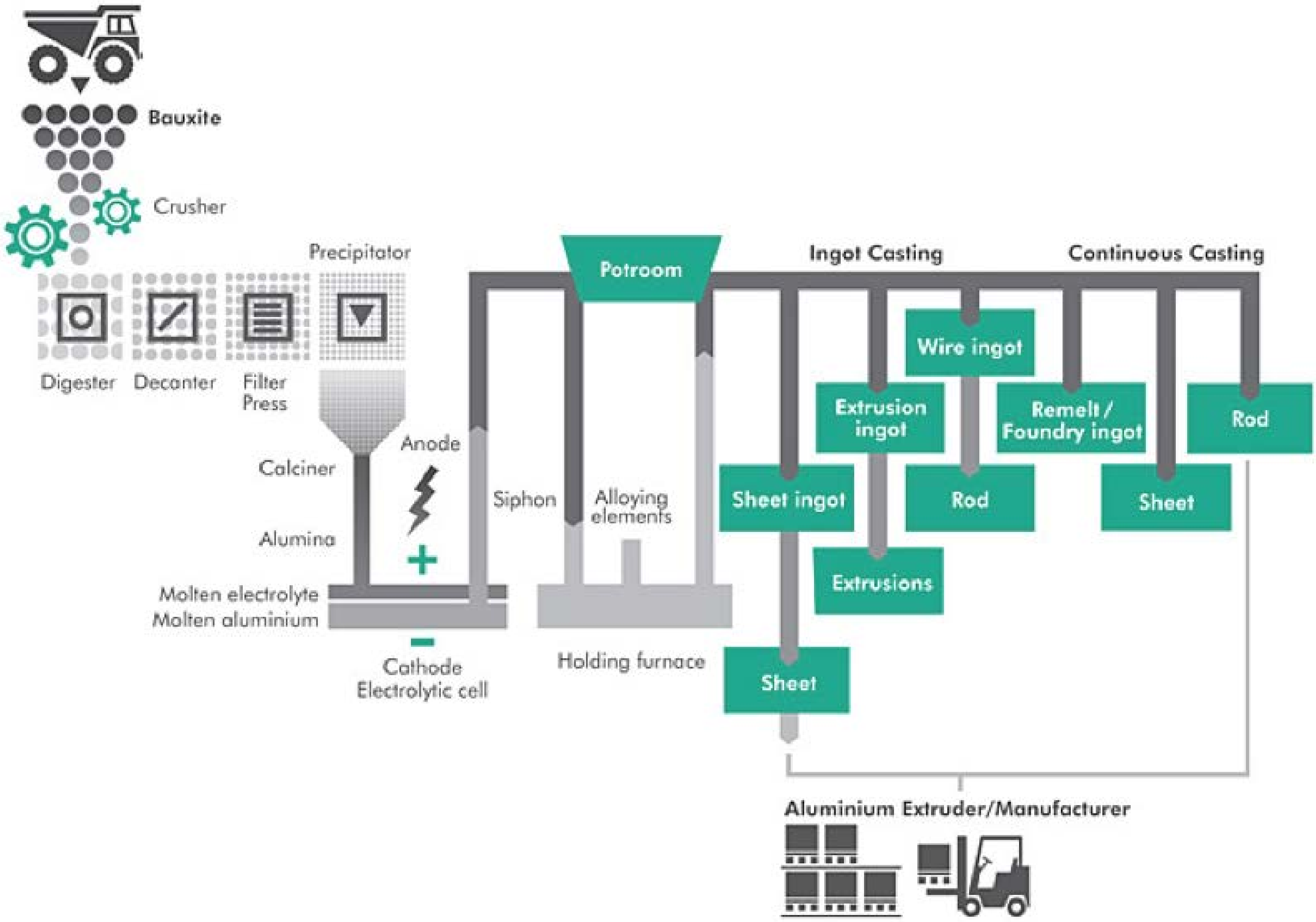


Figure 137: Manufacturing process for aluminium (source: Capral Aluminium)

Aluminium manufacture is accomplished in three main phases. The Bayer process is used to refine the bauxite ore to obtain aluminium oxide, and subsequently the Hall-Héroult process of smelting the aluminium oxide to release pure aluminium. Then, ingot casting or continuous casting products are manufactured followed by further down-stream processing (e.g. rolling, extrusion, drawing). The full process is illustrated in Figure 137.

Magnesium Alloys

Magnesium is the lightest of the structural metals with a density of 1.74 g/cm3 in its solid state. 2.4 percent of Earth's crust are constituted by magnesium and with that it is the eighth most abundant element in nature. Magnesium is highly reactive, therefore, it occurs only in a wide variety of compounds (e.g. seawater, brines, and rocks). Common alloying elements are aluminium, zinc, zirconium, manganese, tin and thorium. The elements introduce different properties such as achieving required strengths for structural applications, promoting precipitation hardening and improving corrosion resistance and castability. Among the common metals the machinability of magnesium is considered to be the best.

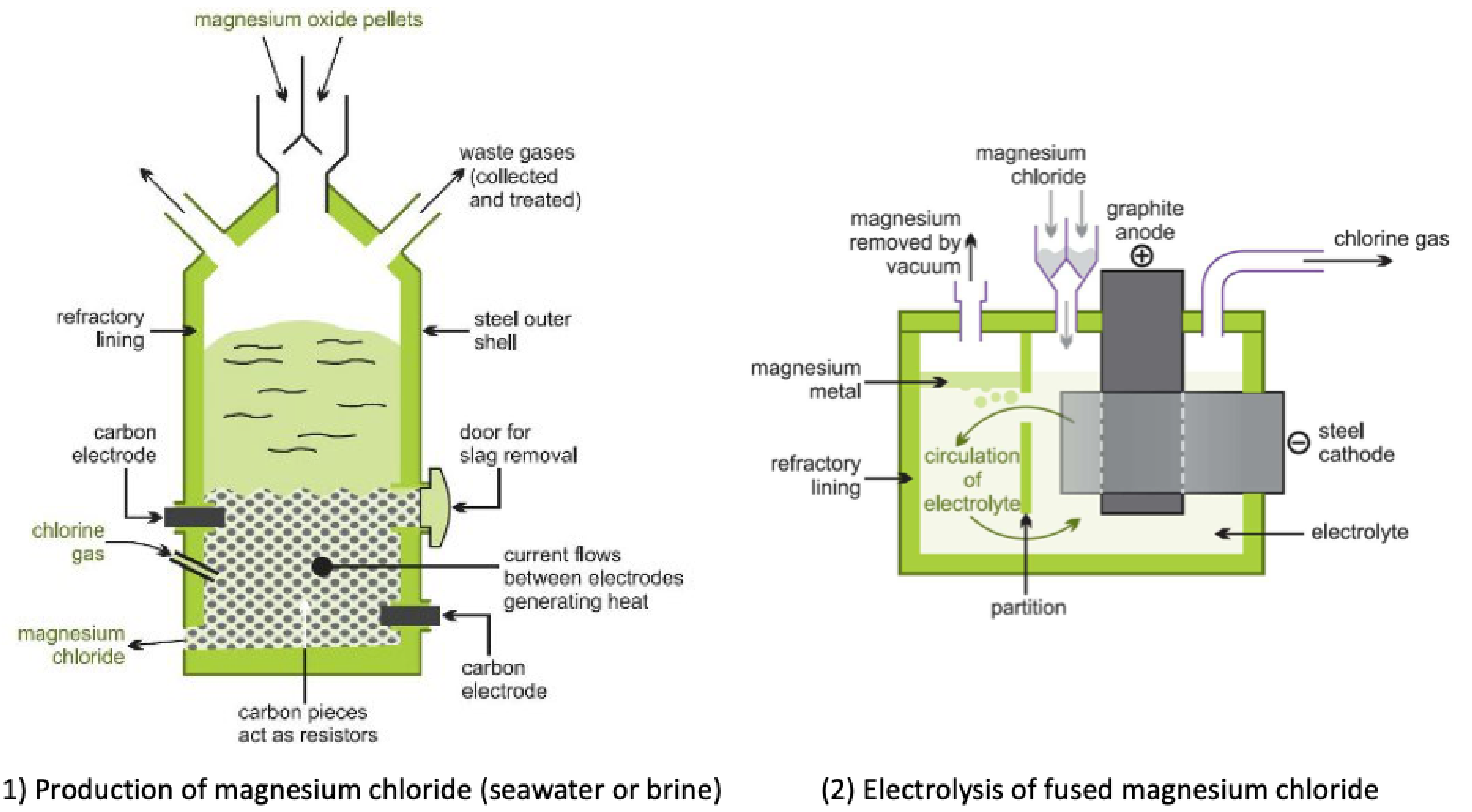


Figure 138: The two phases of electrolysis of magnesium chloride (source: University of York Centre for Industry Education Collaboration)

The heat content and viscosity in the molten state are low which eases the manufacturing. Motivated by properties such as light weight, high strength, high damping capacity, heat resistance, and close dimensional tolerance, both cast and wrought magnesium alloys are used in structural parts in automotive vehicles as well as in aircrafts, rockets and satellites.

Dolomite and magnesite are the most common ore minerals containing magnesium and both are mined and concentrated by conventional methods. Furthermore, magnesium is found in natural brines and seawater. Therefore, manufacture of magnesium knows two methods; thermal reduction of magnesium oxide (mainly China) or electrolysis of magnesium chloride (preferred process outside China). Figure 138 shows the two phases of the electrolysis process. Subsequent processing steps are similar to the approach used for aluminium. Alloys are either worked or cast. Die-casting is the most popular process with two types of systems available to inject the molten metal into the die (cold and hot chamber). To improve material properties or the process itself several enhancements have been developed (e.g. use of vacuum, slow filling).

162 Fibre Reinforced Polymers

Polymer composites consist of a combination of a polymer matrix (resin, either thermoset or thermoplastic) and a reinforcing agent, mainly fibres (usually carbon, glass, aramid or natural fibres). In addition, FRP composites may contain fillers, modifiers and additives that modify the properties and improve the performance of the composite material, or give additional functionalities (e.g. fire-retardancy).

FRP composites are unlike steel, aluminium and magnesium anisotropic materials. While isotropic materials present uniform and identical properties in all directions, FRP are directionally dependent, meaning that the best mechanical properties are in the direction of the fibre placement. In many structures and components, different stresses and loads occur for different directions. FRP allow a more efficient structural design, as fibres can be placed in the direction(s) where the main load(s) occur. Other benefits include a high weight reduction potential due to a high strength-to-weight ratio, corrosion and weather resistance, long-term durability, low maintenance and dimensional stability.

FRPs can be subdivided by their matrix material which consist of either a thermoset or a thermoplastic polymer. Thermosets are cured into a solid form after applying heat or activation through a curing agent. The curing process is irreversible since the polymer is three-dimensionally crosslinked leading to limited EoL options. Thermoset composites are currently cheaper and easier to produce due to the easy handling of the resin. On the other hand, their short life and long cycle times are among the main challenges for thermosets. Thermoplastics consist of molecular chains that are linked through intermolecular forces. These linkages can be reversed by applying heat. Therefore, thermoplastic materials can be moulded, melted, and remoulded again while retaining the physical properties. Thermoplastics used in matrices for composites are, tougher and less brittle than thermosets. Their intitially higher costs compared to thermosets due to energy-intensive processes given the high temperatures and pressures required to melt the thermoplastic and impregnate the fibres with the matrix are nowadays decreasing due to reduced matrix material manufacturing costs.

While thermoplastic composites are usually found in the automotive industry in door panels and interior parts, thermoset composites are typically used in structural applications such as wind turbine blades or aircraft wings where high-performance material properties such as high strength and very good fatigue strength are required.

The exact composition of FRP can be tailored to the intended application and its requirements. Both the type and quantity of the constituent materials as well as the manufacturing process utilised will affect the properties of the final composite. Overall, the most relevant factors to consider for the design of composites include the fibre (type, volume and orientation), type of resin, service conditions, the cost of the final product, the manufacturing process and the volume of production. Carbon FRP (CFRP) are typically used in applications where weight and structural integrity are crucial (e.g. aerospace, high value automotive structural parts). Glass FRP (GFRP) are used in semi-structural applications where weight is less important (shipping, wind turbines, automotive interior parts). Aramid FRP are typically used in defence applications (bullet proof vests and helmets). Natural fibres are for the moment mainly used in non-structural and semi-structural applications (e.g. automotive interior parts) because of the inhomogeneity of current biologically sourced feedstock. Ongoing developments which improve the sourcing homogeneity, the process standardization towards industrial requirements in behaviour as well as in as well as their properties are enabling them to be used in higher value applications.

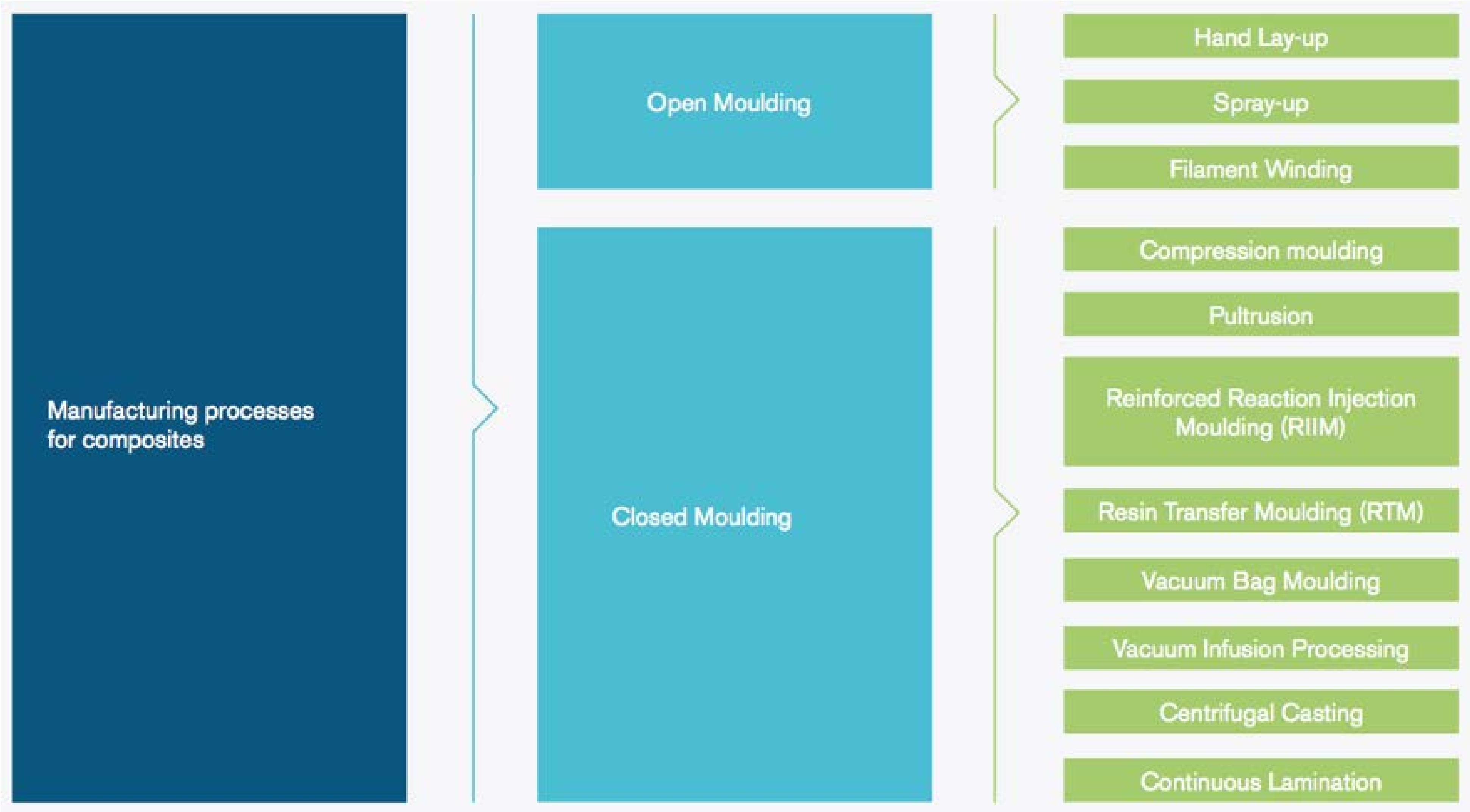


Figure 139: FRP manufacturing processes (source: Cefic/SusChem, Bax & Company [188])

Manufacturing of FRP involves several steps. Following the manufacturing of fibres from a precursor material (polyacrylonitrile for CF, silica sand for GF, polyamide for AF, hemp, flax, jute, or others for NF), such fibres are combined into the reinforcement. The type of reinforcement can vary according to the needs of the application, from fleece (unstructured non-woven short or long fibres), to unidirectional (long fibres in layers of same orientation), to woven fabrics. The reinforcement is subsequently combined with the matrix using a mould, into the FRP component. Such manufacturing processes are divided in two main categories; open mould, and closed mould processes. Open mould processes give the ability to create very large parts, but are manually intensive, while closed mould processes have size restrictions, but can be automated, and provide consistent quality. Most widely used open mould process is hand lay-up – which is also the most commonly used among all processes – while commonly used closed mould processes are compression moulding, pultrusion, and Resin Transfer Moulding. Figure 139 provides an overview of FRP manufacturing processes.

[188] SusChem, Polymer composites for automotive sustainability, January 2016

Ceramics

A ceramic is an inorganic non-metallic solid made up of either metal or non-metal compounds that have been shaped and then hardened by heating to high temperatures. In general, they are hard, corrosion-resistant and brittle. The most important general property of ceramics is that they're refractory. Other properties of ceramics are their considerable durability, low electrical and thermal conductivity, chemical inertness and high melting points. Most ceramics are also nonmagnetic materials.

Nonetheless, ceramics tend to be weak in tension, but strong in compression. For a metal, the compressive strength is near that of the tensile strength, while for a ceramic, the compressive strength may be ten times the tensile strength.

Due to their low thermal conductivity, technical ceramics are typically used in applications with high operating temperatures (coatings of ICE cylinders, coatings for jet aircraft turbine blades). Recent advancements in materials and manufacturing technologies enable manufacturing of composite ceramics (e.g. ceramics reinforced with ceramic fibres), which provide additional properties and have the potential of enabling additional applications.

Ceramics are typically produced by applying heat upon processed clays and other natural raw materials to form a rigid product. Ceramic products that use naturally occurring rocks and minerals as a starting material must undergo special processing in order to control purity, particle size, particle size distribution, and heterogeneity. These attributes play a big role in the final properties of the finished ceramic. Chemically prepared powders also are used as starting materials for some ceramic products. These synthetic materials can be controlled to produce powders with precise chemical compositions and particle size. A general manufacturing process to obtain ceramics is illustrated in Figure 140.

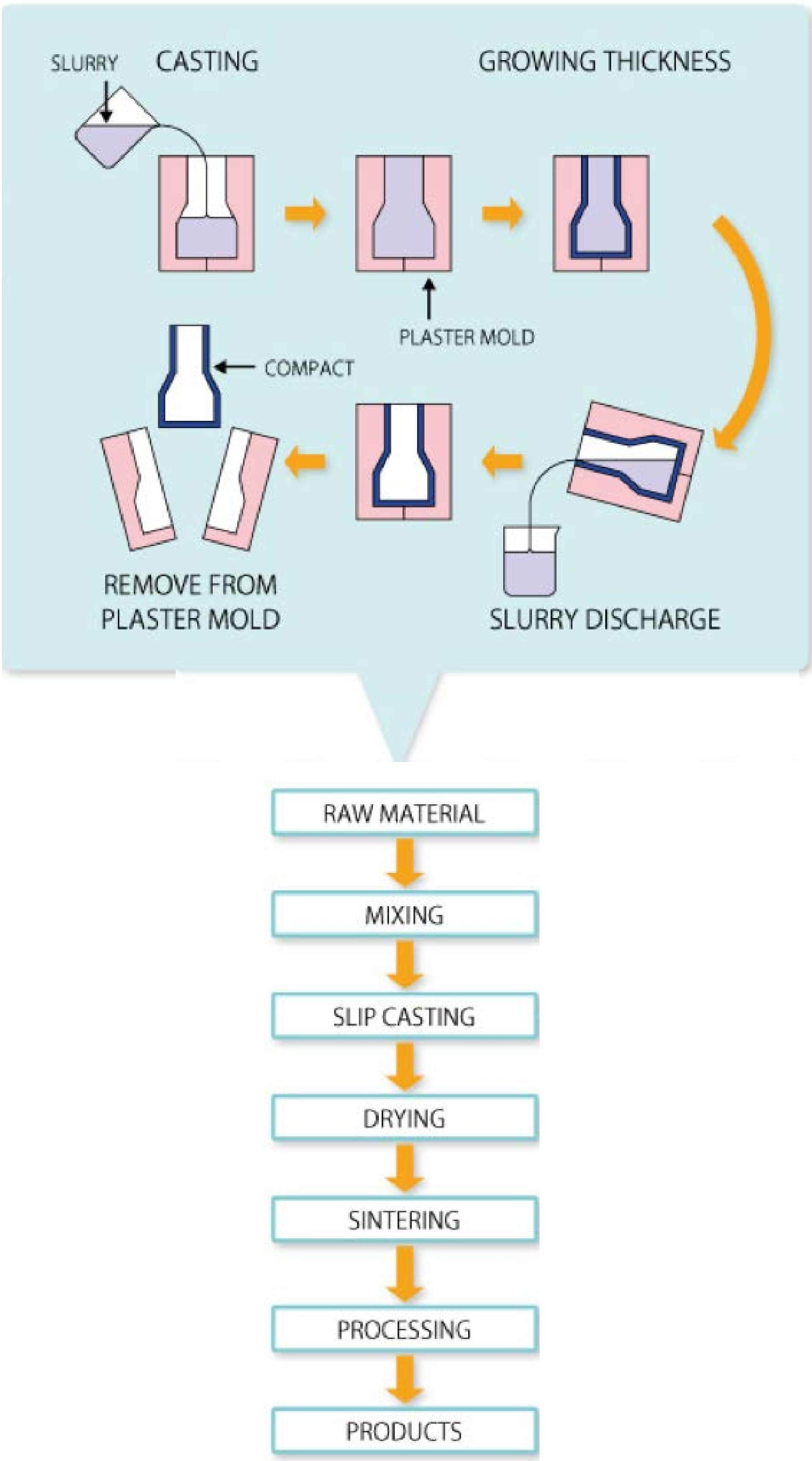


Figure 140: Ceramics manufacturing process (source: Japan Metals & Chemicals Co. [189])

[189] Japan Metals & Chemicals Co., Ceramics Group

Polymers

Polymers are materials made of long, repeating chains of molecules. The materials have unique properties, depending on the type of bonded molecules and the types of bonds. Some polymers bend and stretch, like rubber and polyester. Others are hard and tough, like epoxies and glass.

The diversity of polymers and their range of properties enable them to be used in a multitude of applications, from car and aircraft tires, to interior components in cockpits. Since their mechanical properties are in some cases limited compared to those of metal alloys and FRP, they are typically used in non-structural applications.

The conversion of raw materials into finished polymeric products involves a series of steps. First, additives and polymers are mixed to achieve required modifications of the properties of the polymer. The second stage is to create the desired shape. Inherent in the forming stage is the requirement to set or maintain that shape. Forming can be conveniently divided into two-dimensional forming, where products have a relatively simple geometry, and three-dimensional forming with complex geometries. In the main manufacturing processes, there are a number of finishing steps. Widespread polymer component manufacturing processes are, most generally, injection moulding, extrusion moulding, blow moulding and rotational moulding - summarized in Figure 141.

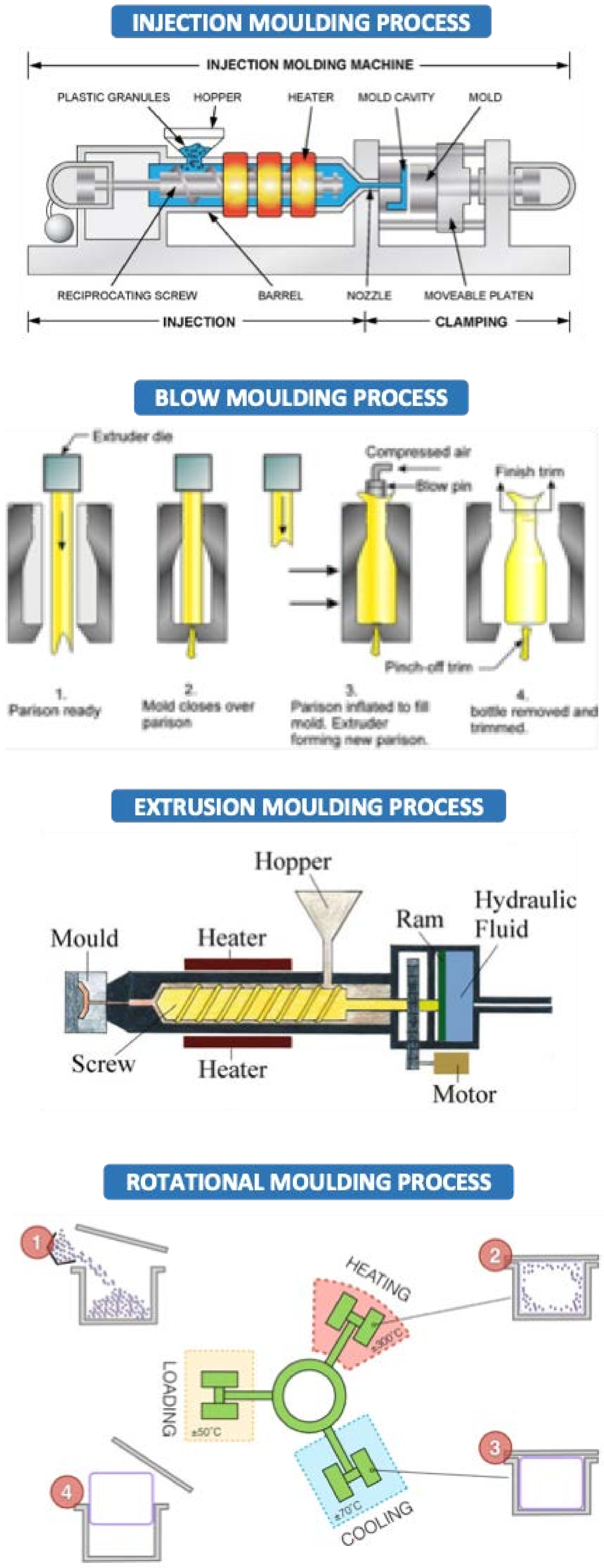


Figure 141: Polymer manufacturing processes (source: Hardie Polymers [190])

[190] Hardie Polymers, Polymer manufacturing processes

Advanced Glass

Glass is an amorphous, non-crystalline solid. The main raw material for its production is silica sand, while limestone, soda ash, and other chemicals can be used to colour or coat the glass.

Developments in glass manufacturing have increasingly enabled the use of glass in transportation applications (e.g. entire glass car roofs), whereas smart glass – which combines multiple functionalities – is increasingly used, e.g. in automotive cockpits.

The glass – float glass as we know – is manufactured by the PPG process illustrated in Figure 142.

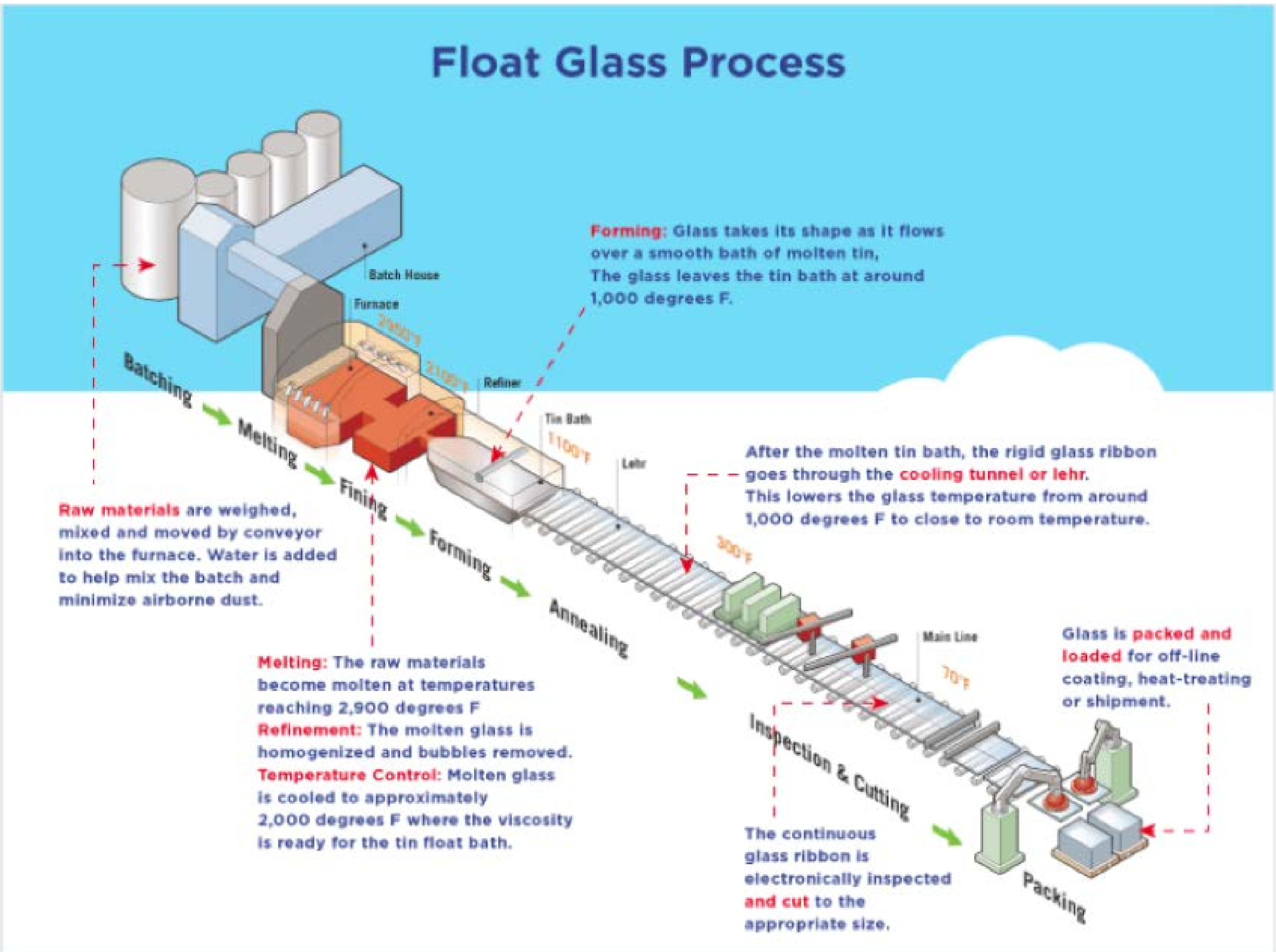


Figure 142: PPG process to obtain glass (source: AIS Glass[191])

191 AIS Glass, Glass Manufacturing Process, 2019

168 Figure 143 shows an overview of material performance for the various material families. The left figure shows a comparison between the Young's modulus – the ability of a material to withstand changes in shape in the elastic area – and density. The figure on the right illustrates a comparison between strength – the material resistance to loads – and toughness – the amount of deformation the material can withstand before failing; brittle materials will fail without deformation, while tough, or ductile material will undergo a plastic deformation (e.g. "necking") before failing.

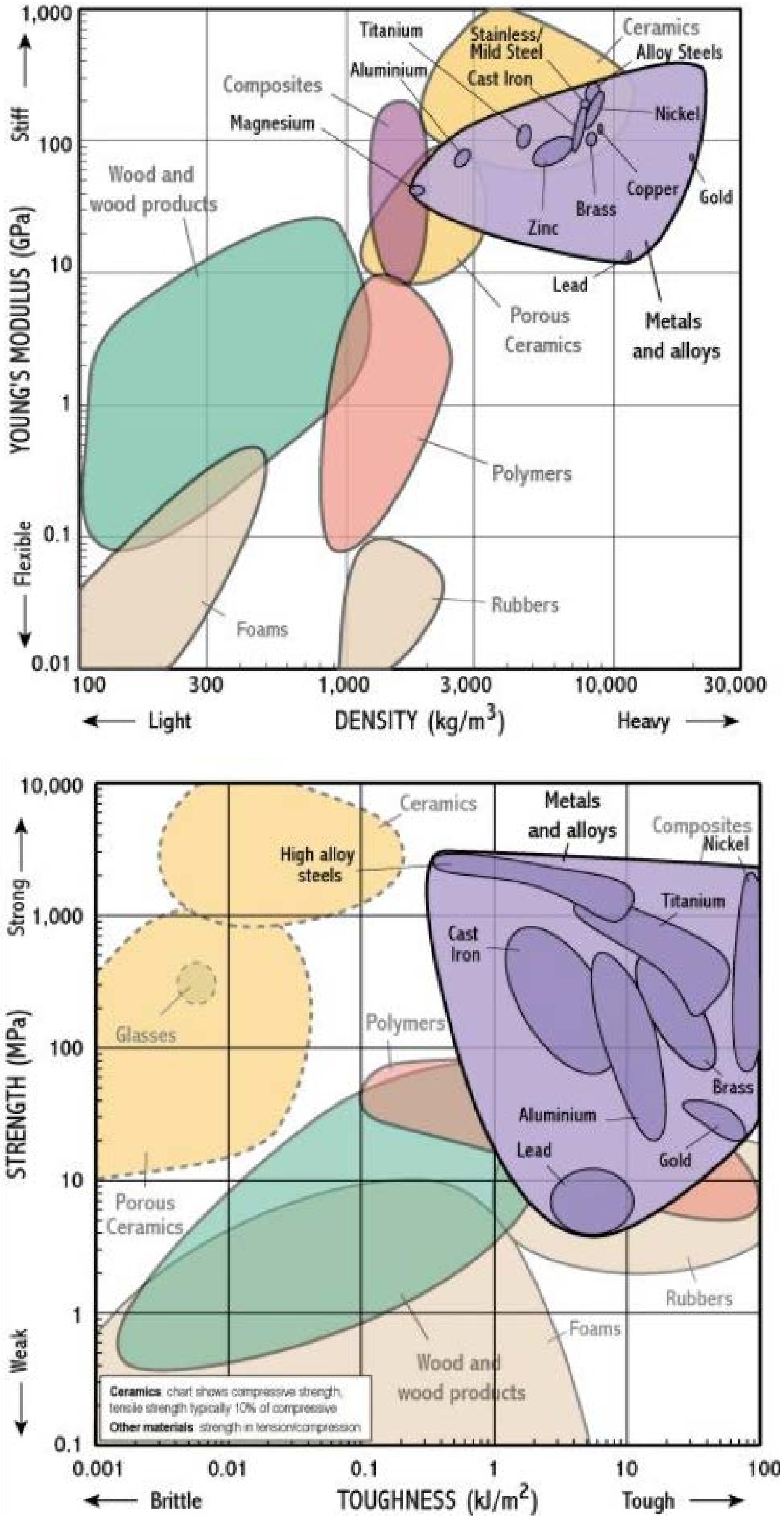


Figure 143: Material performance

[190] Hardie Polymers, Polymer manufacturing processes

Material	Type	Performance							Main Applications					
		Technical Performance	Lightweighting Potential	Environmental Impact	Recyclability	Manufacturability	Material Compatibility	Cost	Powertrain	Body-in-White	Suspension	Chassis	Closures	Interior
Steel		+++	++	+	+++	++++	+++	++++	•	•	•	•	•	
Aluminium		++	+++	++	++++	++++	+++	+++		•		•	•	
Magnesium		++	++++	-	++++	+++	+++	++	•	•		•	•	•
FRP	CFRP	++++	++++	-	+	++	+	-		•		•	•	•
	GFRP	+++	+++	+	-	++	+	++						•
Multimaterials		++++	++++	+++	-	-		+	•	•	•	•	•	•
Ceramics		++	+++	+++		+	-	-	•					
Polymers		+	+++	+		+++	++	++++						•
Glass		-	++			+++	-						•	

Table 34: Lightweighting technologies

Table 34 provides an overview of the main lightweighting technologies, their performance on a variety of parameters, and typical applications.
Technical performance refers to the ability of the material to comply with the mechanical requirements dictated by the application (e.g. resistance to cyclic loads, energy absorption, etc.). It is particularly important in structural applications.
Lightweighting potential refers to the possibility of the material technology to decrease the weight of applications either due to its low density, its high specific strength, or a combination.
Environmental impact refers to the intensity of the material processing due to extraction of raw materials, energy use for its processing (which results in greenhouse gas emissions), or consumables used (e.g. water).
Recyclability refers to the ability of the material to be recycled.
Manufacturability refers to the ease with which the material can be manufactured into components. The more complex designs a material can be employed for, the more "manufacturable" it is.
Material compatibility refers to the ability of the material technology to be combined with other materials.
Cost in lightweight applications is typically referred to as "cost of lightweighting" – the additional cost required to reduce the weight of an existing solution – and is measured in €/kg saved.

Cost structure

Figure 144 below provides a comparative cost breakdown for the manufacturing of the different lightweight technologies.

It is important to mention that the above figures only give a brief overview, as depending on the part and the material type and grade, the cost breakdown will vary. The figures given above are for the manufacturing of a representative automotive module (door) for medium to high volume production (~100,000 parts/year). Cost of energy does not include the energy necessary to extract the raw material, but its transformation from raw material into components.

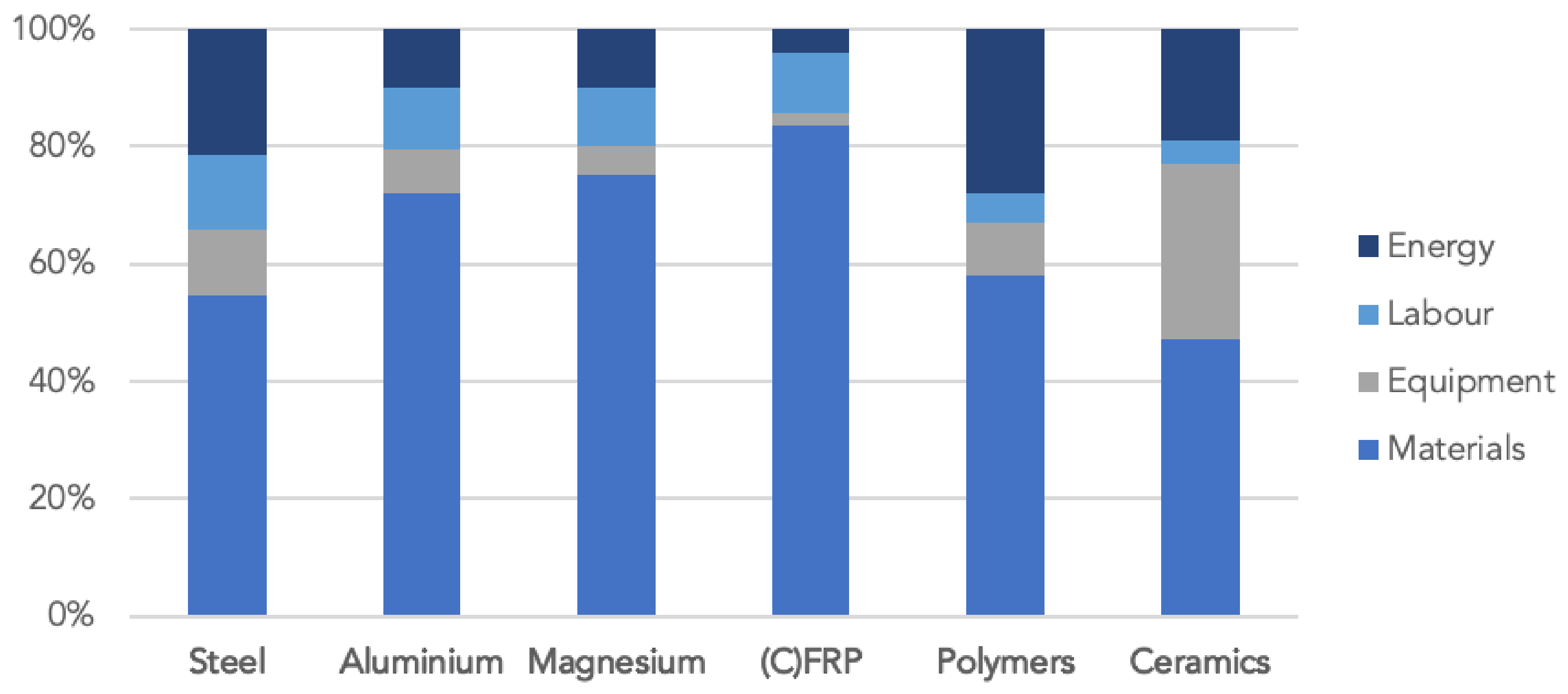


Figure 144: Manufacturing cost breakdown for the different lighweighting technologies (source: ENLIGHT [191], ALLIANCE [192], El-Hija et al.[193], IEEE GlobalSpec [194], adapted by Bax & Company)

It is important to mention that the above figures only give a brief overview, as depending on the part and the material type and grade, the cost breakdown will vary. The figures given above are for the manufacturing of a representative automotive module (door) for medium to high volume production (~100,000 parts/year). Cost of energy does not include the energy necessary to extract the raw material, but its transformation from raw material into components.

[191] M. Delogu, L. Zanchi, C. A. Dattilo, M. Ierides, Parameters affecting the sustainability trade-off between production and use stages in the automotive lightweight design, Procedia CIRP, Vol 69 (534-539), April 2018

[192] F, Del Pero, M. Delogu, V. Fernandez, M. Ierides, K. Seidel, D.Thirunavukkarasu, Lightweight Design Solutions in the Automotive Sector: Impact Analysis for a Door Structure, April 2019

[193] El-Hija, H. A. Krenkel, W., Cost Analysis for the manufacture of C/C-SiC Structural Parts. High Temperature Ceramic Matrix Composites, 846-851[192] F, Del Pero, M. Delogu, V. Fernandez, M. Ierides, K. Seidel, 854-851

[194] Kardys, G., Magnesium Car Parts: A Far Reach for Manufacturers? Part 1

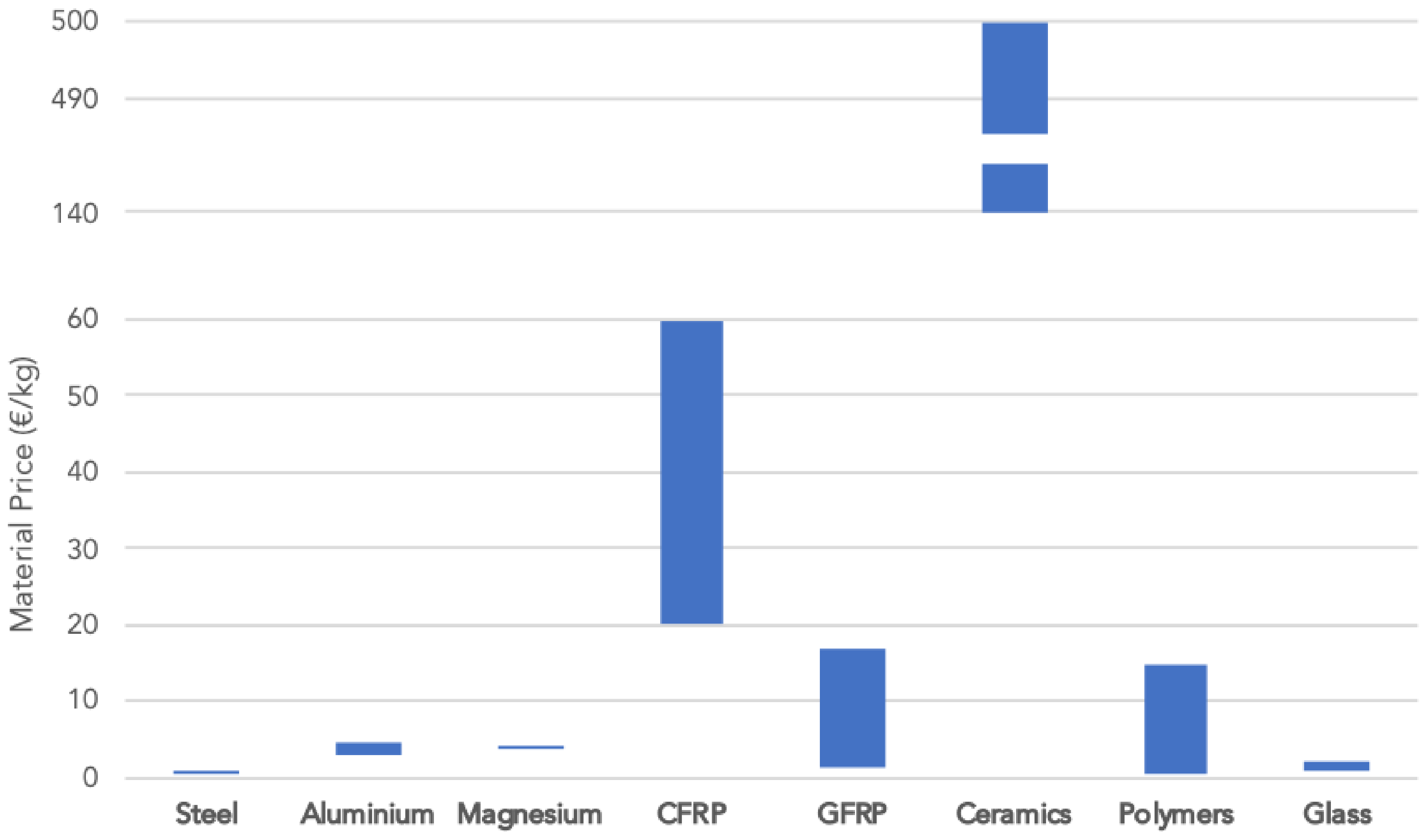


Figure 145: Material cost for different types of materials

Figure 145 gives an overview of the price ranges per kg of the different materials employed for lightweighting. As each material can have different grades, configuration and therefore properties and cost, the visual below gives an overview of cost for the different material families.

Figure 146 gives an overview of the share of cost per material type for the materials in focus, per application. One can see that the highest share of costs for automotive is still steel – although this is expected to change, with aluminium, composites and multi-materials being used increasingly. For aviation, half the costs account for FRP components, while steel accounts for less than 10% of costs. Similarly, the share of FRP is expected to increase as composite parts are expected to replace aluminium ones. Steel is expected to remain relevant for at least some components such as the landing mechanism and parts of the engine.European Landscape

Market and applications

The market for lightweight materials has mainly been driven by the need for emissions reduction, and especially in the last few years, by the use of alternative energy sources, and the need for autonomy (i.e. in electric vehicles). Considering that both drivers will only become more pressing, the market for lightweight materials is expected to see a continuous growth, exceeding 200 billion euros globally by 2025. The market is expected to be driven mainly by the automotive sector due to the high volumes, as well as the moderate penetration of lightweight materials (see evolution of material mix in Figure 148). Aviation and shipping are expected

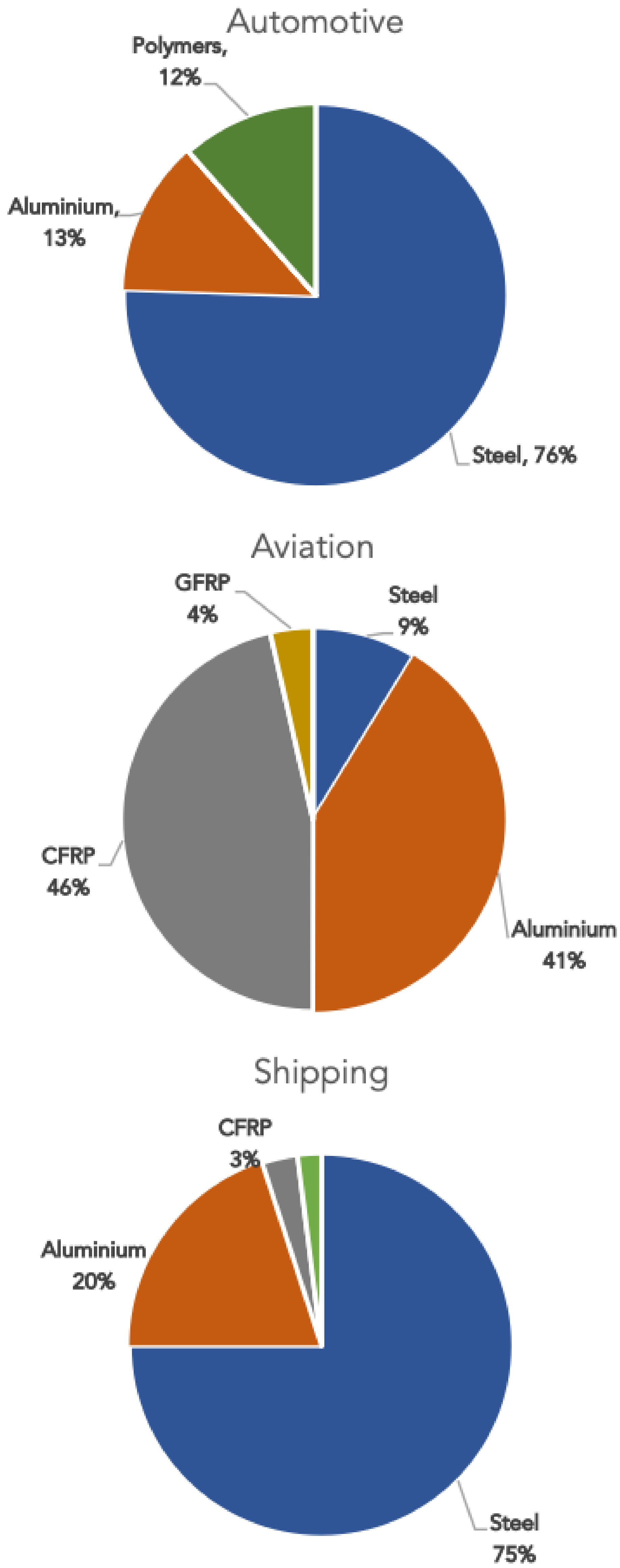


Figure 146: Share of costs per material type (for the materials in focus) per sector (adapted by Bax & Company)

to contribute less, due to volumes and already high penetration in the former, and due to lower importance of lightweighting in the latter. Figure 147 illustrates the absorption of lightweight materials among the main sectors.

Figure 148 illustrates the material breakdown for the sectors in focus, as well as forecast of such breakdown for 2030. As one can see, material breakdown in the aviation sector is not expected to change significantly. Main changes are the increase in use of CFRP, and reduction of use of metals. For the automotive sector, a much bigger shift is expected (which has already started taking place) with substitution of ordinary steel with HSS, as well as increase in use of FRP and aluminium.

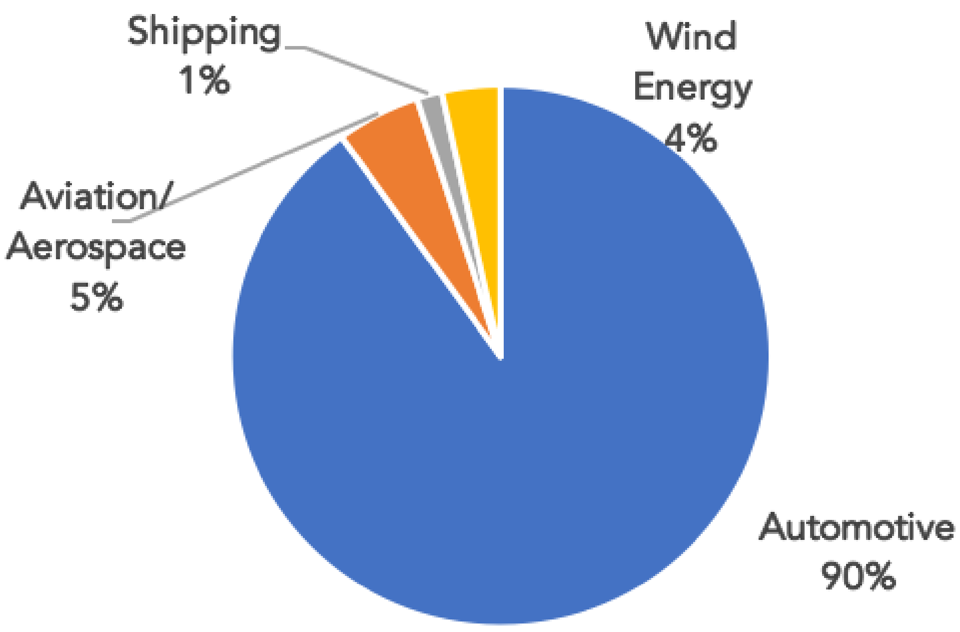


Figure 147: Share of lightweight materials and technologies for the main sectors (source: Allied Market Research)

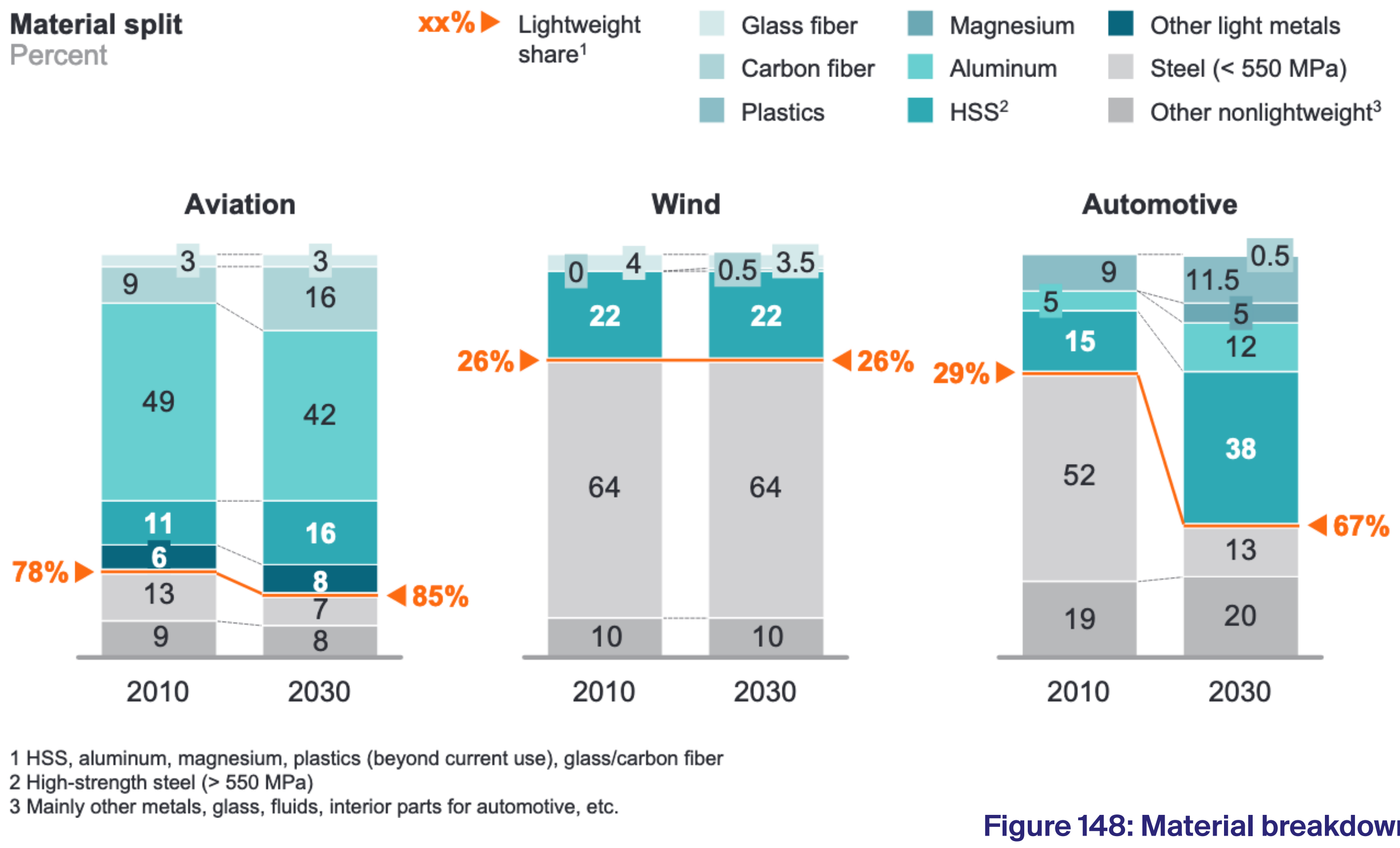


Figure 148: Material breakdown per volume, per sector (source: McKinsey [195])

[195] McKinsey&Company, Lightweight, heavy impact, January 2012

Value chain and key players

The value chains of lightweight technologies include numerous steps, from the sourcing of the raw materials and their processing, to design and manufacturing into parts, to integration into applications (vehicles), and subsequent EoL treatment. Table 35 presents a SWOT analysis of the European lightweight technologies landscape.

Value Chain Step	Strengths	Weaknesses	Opportunities	Threats
Advanced Materials	• Significant knowledge in advanced materials (metallurgy, material science) and their processing • Majority of advanced steel and aluminium alloys provided by European players	• Many important lightweight material suppliers (e.g. CF) outside of Europe • Collaborative innovation initiatives usually stop at TRL6/7, slowing down commercialisation of new technologies	• European Union's strict environmental laws could push European industry to find alternatives to less sustainable solutions (e.g. natural fibres instead of carbon fibres) • Production of primary aluminium in Europe has three times lower carbon footprint compared to China, which could attract environmentally conscious buyers • Use the modelling & simulation expertise to create common interfaces between tools, to further accelerate material development	• Some raw materials (e.g. alloying elements) do not exist in Europe; creates a material dependency
Design and Manufacturing into Components	• Significant know how in behaviour and design with FRP • Lightweighting has been targeted by the EU and several industrial and academic associations • Strong manufacturing base for components through the whole value chain • Several manufacturers of production machinery for advanced lightweight components in Europe	• Although significant know-how exists in Europe, collaboration between entities that possess this knowledge (particularly in FRP) is not strong • The application of novel materials into components (especially FRP) requires new know-how that does not exist in the manufacturing industry • Communication and openness between value chain stakeholders or even inter-company departments is not always optimal, leading to unclear application requirements and over-engineering	• Use the support tools that have partly pioneered in Europe (e.g. multi-parameter design) to turn Europe into the main engineering hub for lightweight manufacturing • Use the opportunity of new component designs to implement common design interfaces between parts. This would improve circularity, and potentially economies of scale	• Suppliers and/or equipment manufacturers (required for lightweight component manufacturing) being acquired by players outside the EU • Knowledge and expertise of suppliers outside of Europe growing rapidly
Integration into Applications and EoL Treatment	• Development of support tools (e.g. modelling & simulation) that can accelerate the development of lightweight technologies and their integration into applications • Key recycling players (especially for FRP) in Europe • Proof of concept in design for recycling of composites	• Main growth in applications (vehicles manufactured) comes from outside Europe (mainly US and Asia Pacific) • Lack of structure for transferring results of fundamental research to industry • Innovative materials not always adopted because of existing large-scale investments in "conventional" manufacturing lines by established European OEMs	• Strict regulatory framework on EoL treatment could push Europe in the forefront of recycling and reusing • Vehicle architectures are changing significantly due to new concepts (shared, autonomous, electrified mobility), presenting an opportunity to design new vehicle components from "scratch", having in mind the performance and design flexibility of novel lightweight materials • New emerging business models (e.g. mobility as a service) make more expensive lightweighting technologies viable • New cost-effective EoL procedures to valorise domestic scrap, in particular for the scarce materials, as the new "mine" for the EU	• Inability to develop sustainable EoL scenarios and technologies to treat EoL parts could decelerate the application of lightweight technologies • Lack of interdisciplinary engineering education programs might result in shortage of capable personnel in the future • European legislation on decarbonisation of transport is in some cases conflicting • Changing political environment/ instability (e.g. US and China trade war, Brexit, and overall instability in the middle east) creates disturbances in the complex and interwoven value chain that relies highly on partners in these regions

Table 35: SWOT analysis of lightweight technologies for the European industry (sources: EMIRI community)

Figure 149 below illustrates the steps of the value chain, along with the main players. European organisations are marked with a star. Europe is strong in adding value to raw materials (primary material supply), manufacturing of components, and automotive end users.

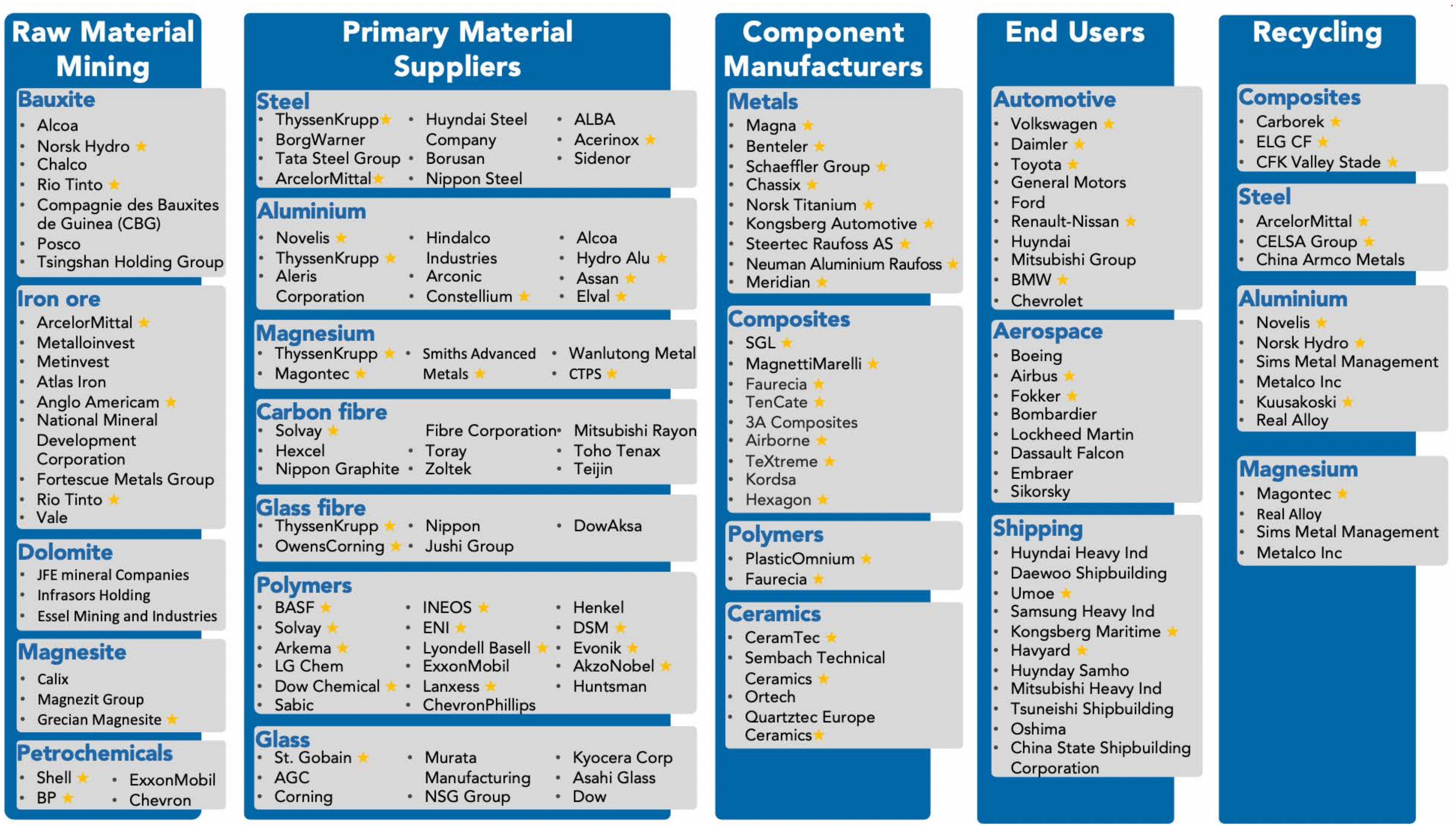


Figure 149: Value chain and key players in the field of lightweighting

Current Status/Market Overview

Main trends

This section lists the main trends that are expected to influence the evolution of the global lightweight technologies market. Those originate from policies, the society, and the technologies themselves.

Decarbonisation of mobility

While vehicle weight has been increasing since the mid-80's – mainly due to added safety and comfort equipment, as well by customer demand for bigger cars (e.g. SUVs) – all governments are imposing tougher CO2 emission standards – e.g. European regulations to decrease CO2 emissions from 142 g/km to 95 g/km, or 3.9% per year from 2010 to 2020 (Figure 149).

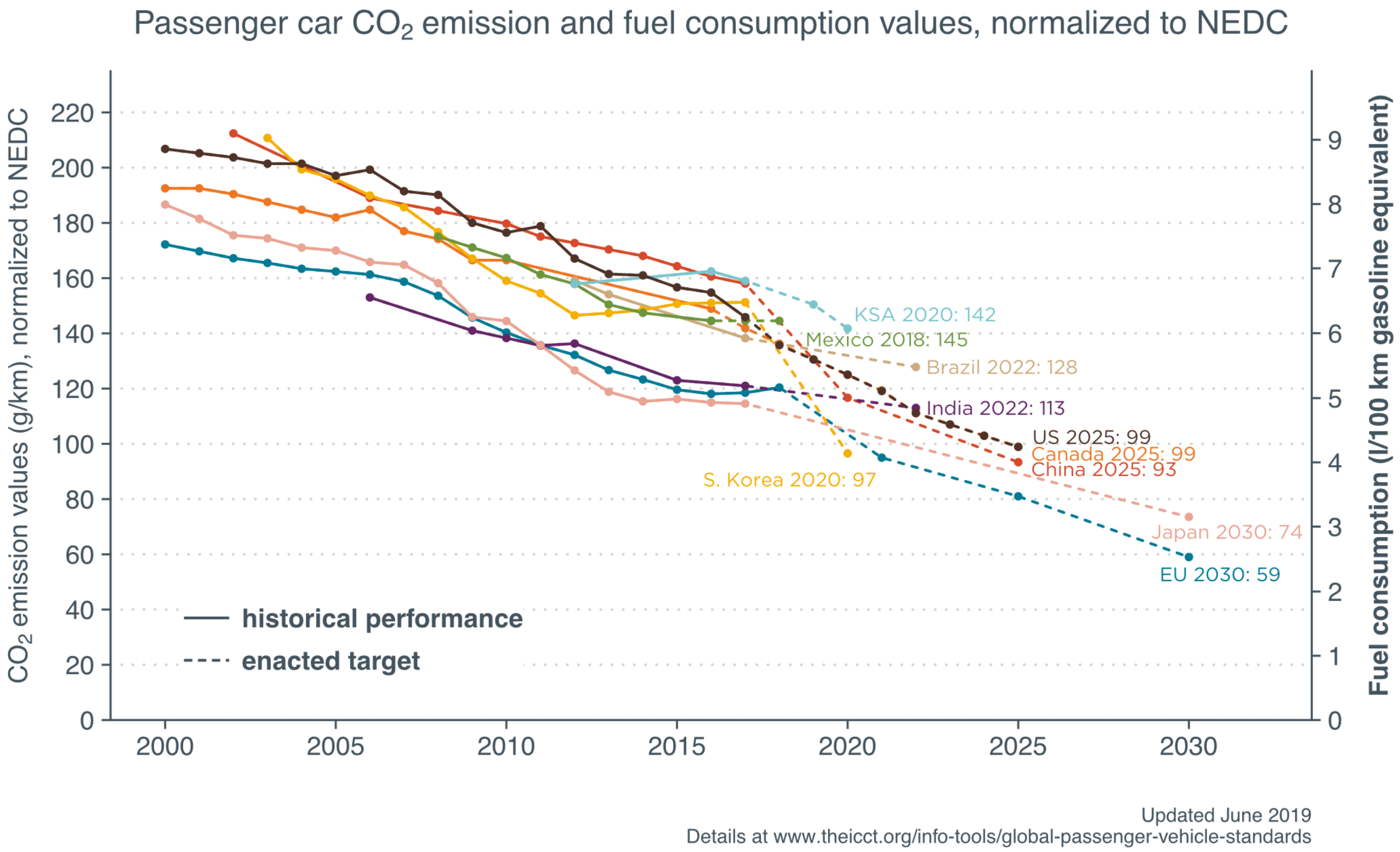


Figure 150: Evolution of emissions targets and objectives for the future (source: the International Council on Clean Transportation[197])

A way to achieve the ambitious vehicle emission targets is vehicle lightweighting. This has been widely acknowledged in Europe. Several research centres and industry-research alliances have been formed to develop novel lightweighting technologies to address the issue, while the EC has financially supported such initiatives through large scale financing structures such as the NMBP programme in the H2020 FP.

Evolving manufacturing technologies/Industry 4.0

Evolving manufacturing technologies as well as design tools (e.g. multi-parameter design, decision making tools) can enable the use of new materials in the manufacturing of components with complex shapes. More importantly, new design and manufacturing practices can enable the manufacturing of multimaterial, multifunctional components which can greatly help in reducing the weight of applications (e.g. combination of safety and energy storage in one part).

[197] The International Council on Clean Transportation, Chart library: Passenger vehicle fuel economy, April 2018

Energy efficiency

The rise of electromobility, as well as the increasing price of fuel is creating a demand from the end-users for more energy efficient vehicles. This translates into a higher range in the case of EVs, and a lower fuel or energy bill for both cases. Fuel efficiency is therefore one of the main priorities for car manufacturers which can be powered by an increased share of lightweighting materials in the vehicle structure.
Linked to that, the demand for more safety, electronic assistance and comfort systems as well as increased autonomy is expected to add more weight to vehicles. To counterbalance, OEMs need to employ lightweighting solutions to reduce the weight of vehicles and therefore energy consumption.

Main challenges

Table 36 below summarises the main materials related challenges that need to be addressed – per technology and application sector – within the next 10-15 years in order to increase Europe's competitiveness. The challenges were identified by the EMIRI community in workshops that took place throughout 2019.

Challenge	Application		
	Automotive/Rolling Stock	Aviation/Aerospace	Shipping
• Cost of lightweighting	FRP, Multi-materials, Ceramics	FRP	FRP, Multi-materials, Ceramics
• Availability of the raw material both globally and particularly in Europe	Steel, Aluminium	Steel, Aluminium	Steel, Aluminium
• Performance of the technology	Multi-materials, Ceramics, Polymers	Multi-materials, Ceramics, Polymers	Multi-materials, Ceramics, Polymers
• Ability of the material technology to be combined with other materials	Steel, Aluminium, FRP, Multi-materials, Ceramics, Polymers	FRP, Multi-materials, Ceramics, Polymers	Steel, Aluminium, FRP, Multi-materials, Ceramics, Polymers
• Manufacturability of the material	FRP, Multi-materials		
• Health and safety consequences of the material technology	Steel, Aluminium, FRP, Multi-materials, Ceramics, Polymers	FRP, Multi-materials, Ceramics, Polymers	Steel, Aluminium, FRP, Multi-materials, Ceramics, Polymers
• Recyclability	FRP, Multi-materials, Ceramics	FRP, Multi-materials, Ceramics	FRP, Multi-materials, Ceramics
• Life-cycle performance (circularity and environmental impact)	FRP, Multi-materials, Ceramics, Polymers	FRP, Multi-materials, Ceramics, Polymers	FRP, Multi-materials, Polymers

• Steel • Aluminium • FRP • Multi-materials • Ceramics • Polymers • Glass

Table 35: Main materials related challenges to be addressed

Proposed R&D topics

Table 37 below summarises the suggested calls to be included in the Horizon Europe framework program, based on the challenges identified above.

Identifier	Call Title	Type
LT1	Develop and/or upscale resource (energy, consumables) and cost efficient processing and manufacturing technologies	
LT2	Develop materials with inherent properties, and efficient recycling technologies, to increase the quality (in terms of properties) and quantity of materials retrieved from recycling	
LT3	Develop lightweight materials with improved performance, improved manufacturability, and substitute hazardous and scarce raw materials with safer and more abundant ones	
LT4	Develop technologies (materials, processing, joining) to enable multimaterials and multifunctionality*	
LT5	Develop the tools and know-how necessary to gain a better understanding of the cradle-to-cradle performance (environmental, mechanical properties, cost, social) of the materials	
B9M	Advanced materials for the reduction of EV weight in battery packaging, drivetrain and car body **	

* new materials should aim to not increase complexity of multimaterial applications, otherwise there is a reverse effect on circularity

** this call is included in the “Batteries for Mobility” section, as it is deemed highly related to batteries and battery casing

Table 37: Suggested materials related calls for lightweighting

Figure 151 below illustrates the importance and urgency of each call.

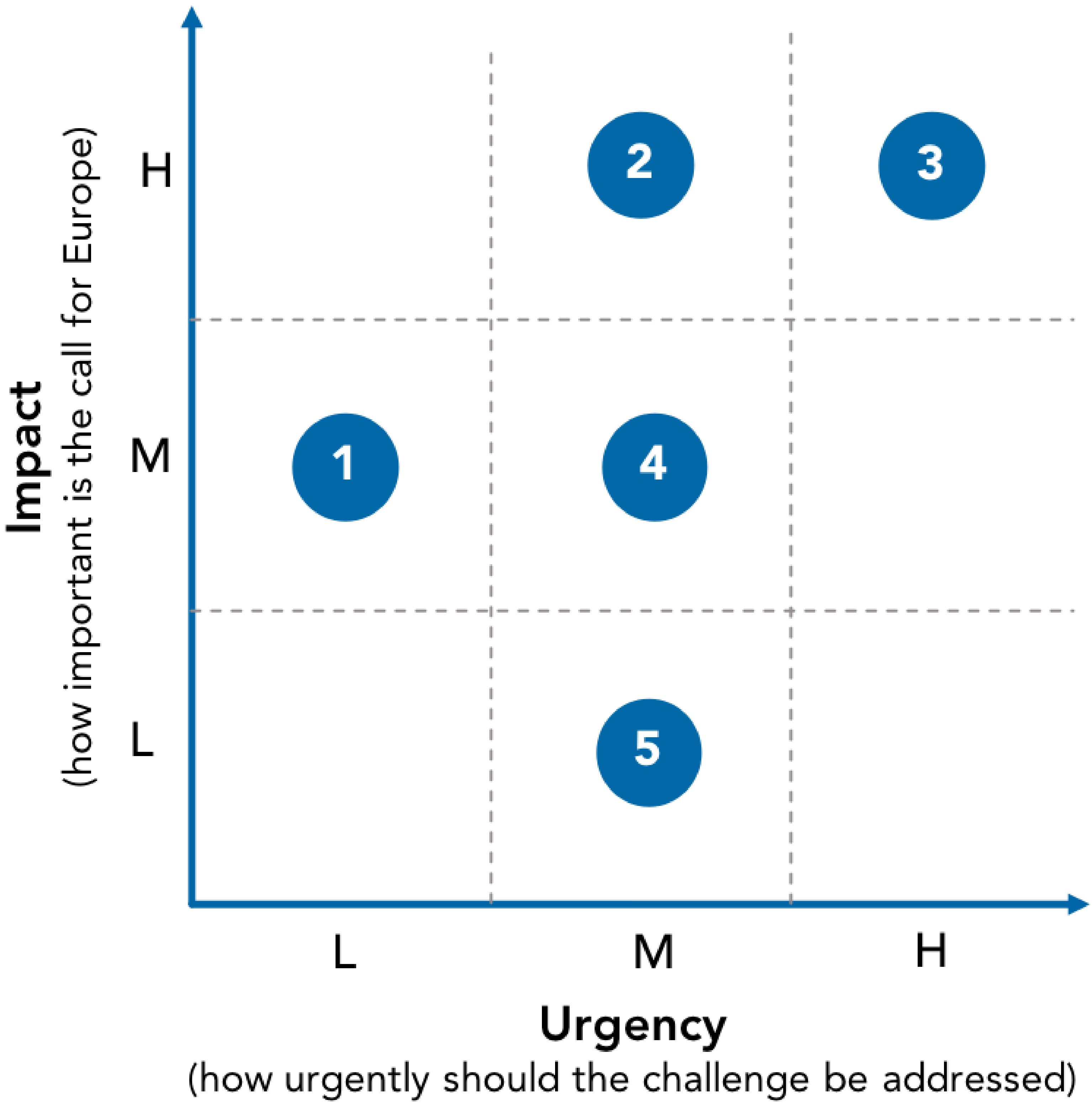
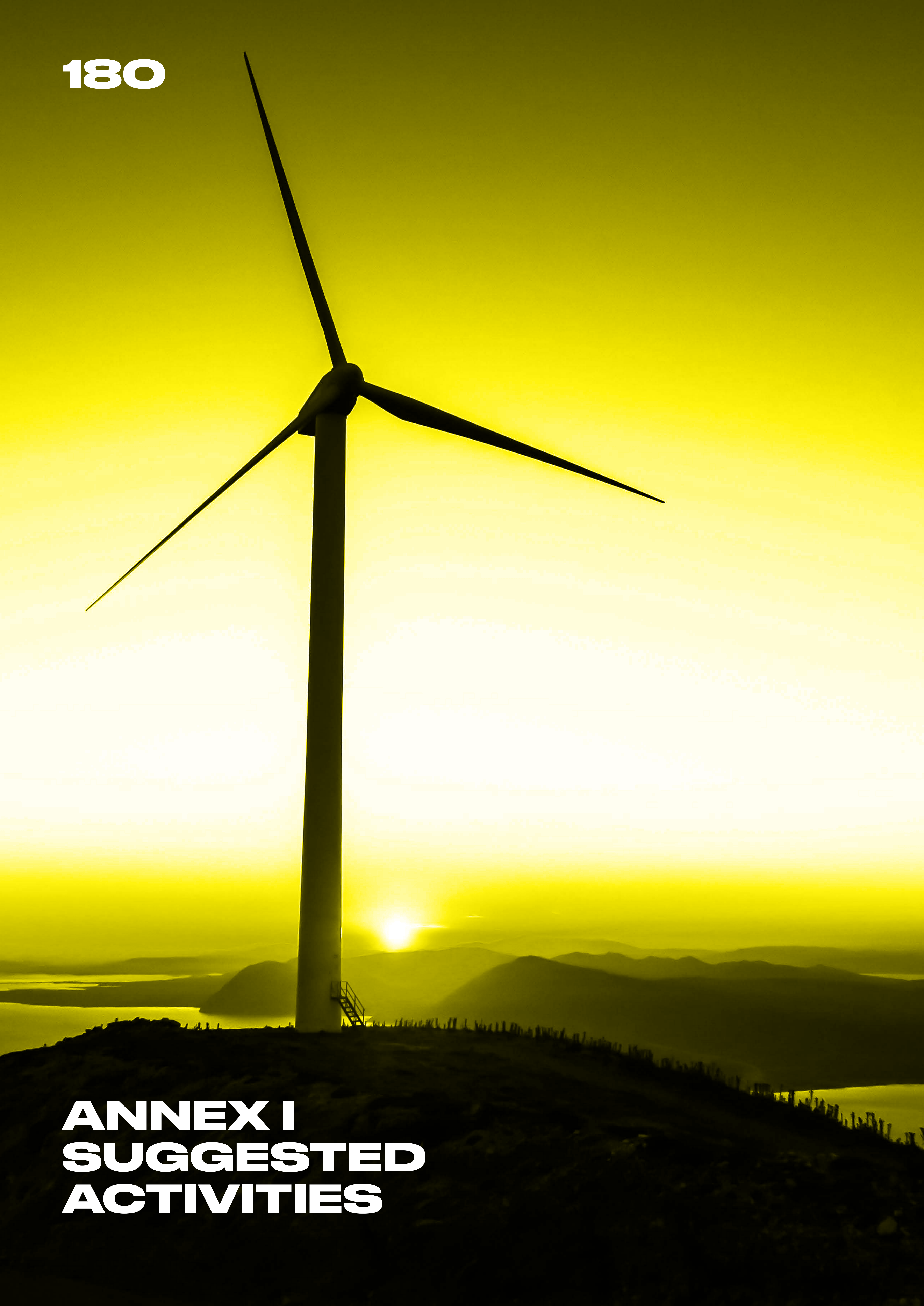


Figure 151: Prioritisation of lightweight calls



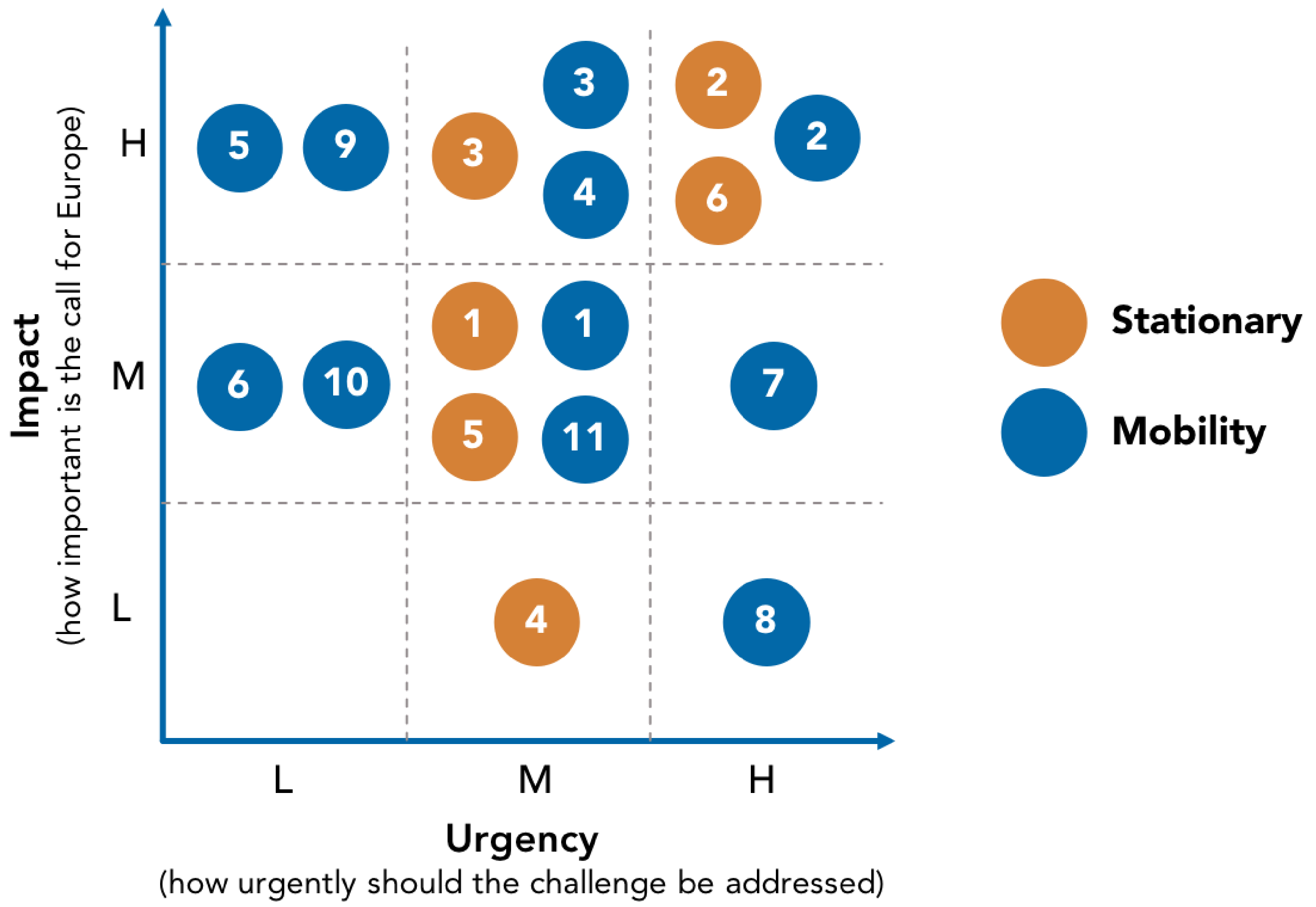
ANNEX I SUGGESTED ACTIVITIES

1. Battery Energy Storage

	Call #	Theme	Lead	Contact
Stationary	1	Na-ion stationary batteries for domestic applications (5-10kW, 4>P/E>1/3)	Estibaliz Crespo	ecrespo@cicenergigune.com
			Montserrat Galcerán	mgalceran@cicenergigune.com
			Montserrat Casas	mcasas@cicenergigune.com
	2	Li-ion stationary batteries for domestic applications (5-10-kW, 4>P/E>1/3)	David Merchin	david.merchin@umicore.com
	3	Redox flow stationary batteries for utility scale applications (>100MW, P/E<1/3)	Estebaliz Aranzabe	maddi.sanchez@tekniker.es
			Maddi Sanchez	estibaliz.aranzabe@tekniker.es
	4	Metal-air stationary batteries for utility scale applications (>100MW, P/E<1/3)	Edel Sheridan	edel.sheridan@sintef.no
	5	Li-ion stationary batteries for commercial applications (<100MW, P/E>4)	Daniel Biro	daniel.biro@ise.fraunhofer.de
	6	Li-ion stationary batteries for utility scale applications (>100MW, P/E<1/3)	Marcel Meeus	meeus.mar@gmail.com
Mobility	1	Li-ion generation 3b batteries for high voltage mobility applications	Victor Trapp	victor.trapp@isc.fraunhofer.de
			Sarah Hartmann	Sarah.Hartmann@isc.fraunhofer.de
	2	Li-ion generation 3b batteries for high capacity mobility applications	Frank Renner	frank.renner@uhasselt.be
	3	Li-ion generation 4a batteries (solid state with conventional materials) for mobility applications	Karolien Vasseur	Karolien.Vasseur@eu.umicore.com
			Pierre-Etienne Cabelguen	Pierre-Etienne.Cabelguen@eu.umicore.com
	4	Li-ion generation 4b batteries (solid electrolyte on Li-metal) for mobility applications	Karolien Vasseur	Karolien.Vasseur@eu.umicore.com
			Pierre-Etienne Cabelguen	Pierre-Etienne.Cabelguen@eu.umicore.com
	5	Li-ion generation 4c batteries (Li-metal and high voltage systems) for mobility applications	Gunther Brunklaus	g.brunklaus@fz-juelich.de
			Marcel Meeus	meeus.mar@gmail.com
	6	Li-ion generation 5 batteries (Li-Air, Li-S)	Marcel Meeus	meeus.mar@gmail.com

	for mobility applications		
7	Zero Strain Material (ZSM) batteries (e.g. TiO2) for high power mobility applications (trains, marine, buses)	Hugues Yanis Amanieu	hy.amanieu@leclanche.com
		Hilmi Buqa	Hilmi.Buqa@leclanche.com
8	Next generation Hybrid Supercapacitors for Power mobility applications	Estibaliz Crespo	ecrespo@cicenergigune.com
		Daniel Carriazo	dcarriazo@cicenergigune.com
9	Advanced materials for the reduction of EV weight in battery packaging, drivetrain and car body	Marcel Meeus	meeus.mar@gmail.com
10	Material technology and system solutions enabling user friendly and reliable ultra-fast charging stations for EVs	Edel Sheridan	edel.sheridan@sintef.no
11	Solid state technology 4b generation – Realization of processing and upscaling	Noshin Omar	Noshin.Omar@vub.be

Priorisation matrix



B1S – Na-ion stationary batteries for domestic applications (5-10kW, 4>P/E>1/3)

TYPE: RIA
DRAFT LEADER: MONTSE GALCERÁN, MONTSE CASAS - CIC ENERGIGUNE

CHALLENGE

Energy storage has become a growing global concern over the last decades in view of the increased energy demand of the modern society. In the last years, it is stated that the domestic electricity consumption has increased, making this sector one of the highest consumers of electricity. The use of battery energy storage systems has gained increasing interest for serving grid support, local load peak shaving and optimization of local RES exploitation (self-consumption). Lithium ion batteries have conquered the portable electronic market and currently are the principal candidate to power the electrical vehicles. However, for domestic applications, the high cost, the scarcity and technical constraints such us extreme sensitivity to over-temperature, overcharge, etc. are their major drawbacks.
One of the most appealing alternatives to lithium ion batteries is sodium ion batteries (NIBs or Na-ion), due to their low cost and virtually unlimited and geographically widespread resources. However, to reach the market and make European industry competitive, there is a need to develop Na-ion batteries with improved performances.
Energy storage must progress in the innovation chain, this would include adaptation of new materials and developments for improved safety. For the next years it is important that the European community develops materials (cathode, anode and electrolyte) to be integrated into systems (at proof of concept level) with higher energy density, longer durability, safety and lower costs. This enhanced sodium-ion storage technology has to contribute to the cost-efficient integration of stationary energy systems for domestic applications (5-10kW) in the near future.

SCOPE

The planned work should focus on developing the next generation of sodium-ion batteries by bringing them from TRL 3 or above towards TRL 5. The activities should consider multidisciplinary and interdisciplinary approaches as well as innovation that starts form synthesis and characterizations of materials (cathode, anode, electrolyte), and move towards their integration into novel sodium-ion pouch cell battery.
To achieve this, it is expected that the proposals should consider addressing the following drawbacks:
- Design of advanced cathode and anode materials with high energy density, long cycle lifetime and good stability based on low cost, non-critical and environmentally friendly materials: cathodes with higher voltage and high and stable capacity and anodes with lower voltage with high efficiency...;
- Development of new stable organic liquid electrolytes or new solid electrolytes for increasing the safety of the battery performance as well as for increasing the energy density;
- Development of maintenance-free, high capacity, next generation aqueous electrolyte-based battery systems;
- Development of new strategies of coatings for electroactive materials to improve safety and cyclability to reach at least 6000 cycles by 2030; Materials should be obtained by using one-step synthesis route to minimize the cost or using a cost-effective synthesis with an emphasis on cheap and straightforward synthesis routes.

Understanding intercalation and degradation mechanisms in half-cell and full-cell configuration is required. Development of techniques that probe the surface or the bulk of the electrode material under operating conditions and use of modelling combined with testing studies can help to this understanding.
A Proof-of-concept demonstration of the Na-ion technology at pouch cell level with a gravimetric energy density of at least 180 Wh/kg and a volumetric energy density of at least 500 Wh/l by 2030 makes part of the activities.
The goal is to reach performances and lower cost at pre-industrial pouch cell prototype level than current commercial batteries for domestic applications that will demonstrate the competitiveness of the Na-ion technology. The developed system should be maintenance free and environmentally friendly.

IMPACT

Proposals should demonstrate a sizeable step towards the quantified targets and demonstrate the material and technology capability to achieve these targets after further development and optimization. Successful development of new materials will sustain the leading position that European OLED materials manufacturers have in various materials classes and create new options with regard to re-use and recycling. Important side benefits can be expected towards the very large OLED display industry.

Novel integration of lighting will lead to new value chains that connect the very strong European lighting industry with leading European players in building and office materials, components and equipment. The efficacy and reliability targets will lead to substantial lower energy consumption and CO2 emissions. Light sources with better light utilization and personalization will contribute to increased well-being of building residents.

B2S - Li-ion stationary batteries for domestic applications (5-10kW, 4>P/E>1/3)

TYPE: RIA
DRAFT LEADER: DAVID MERCHIN

CHALLENGE

With the deployment of home PV panels and small wind turbines, more and more home storage applications are being installed. These home electric applications are often connected to a storage system, increasing self-consumption and energy autonomy. These behind the meter applications are mostly Energy oriented with storage time close to 2-3 hours. Average size of home applications is in the 5-10 kW range. Li-ion technology is the technology of choice for this application due to its versatility, low maintenance and high safety. The main technical challenges for this type of applications are as follows:
Cost per cycle with the metrics €/kwh/cycle going from 0.15 €/kWh/cycle to 0.05 €/kWh/cycle; Purchase cost: €/kWh price should go from 400-600 to 100-200 at the 2030 horizon; cycle life should be increased from 2.000 now to 15.000 in 2030. Such15.000 cycles would represent more than 40 years for a PV installation with one cycle per day.
The gravimetric and volumetric energy density of cells and of the system are not crucial parameters and should follow the trend of the Automotive sector as defined in the SET plan.
Eventually, since these systems should be installed in private homes, they should have a low environmental footprint and be as sustainable as possible. Therefore, they should encompass latest developments in terms of water-based binders, eco-friendly materials and manufacturing processes.
The activities are expected to bring the technology from TRL 3 to TRL 5.

SCOPE

To fulfil these challenges, proposals should address the following innovation topics to improve battery capacities:
- Develop and improve low Cobalt cathode materials to decrease cost (both €/kWh and €/kWh/cycle);
- Increase depth of discharge: going up to 90%-95% Depth of Discharge of batteries to increase real capacity;
- Reach extra-long cycle life (> 15 000 cycles): LTO anode may be used for extra-long cycle life for some niche markets;

The improvement of the ecological footprint of batteries is expected based on innovation actions such as the development of dry coatings and water-based processes to reduce cost plus eco footprint through NMP-free coating processes while maintaining cycle life, the study of the impact of water-based process on High Nickel NMC or Spinel and by actions considering second life applications.
Optimisation of pack design for cell replacement and easier dismantling and recycling are important innovation targets.

IMPACT

The Research and Innovation Activities that are being called for are supposed to have a primary and secondary impact on different levels: on technology level by a higher self-consumption of energy behind the meter and an optimized home to grid interaction allowing smarter grids and electrical networks. A sustained business effect on EU players present on this market will be the result of the developed research and development actions and the society will be gaining by an increase of private owners' energy self-consumption and strengthened European renewable energy penetration.

B3S - Redox flow stationary batteries for utility scale applications (>100MW, P/E<1/3)

TYPE: RIA
DRAFT LEADER: MADDI SANCHEZ, ESTIBALIZ ARANZABE

CHALLENGE

The use of fossil fuels will be continuously reduced and replaced by renewable energy sources that can be affected by the unpredictable and intermittent behaviour of the sun and the wind. The large-scale penetration of renewable energy can only be realised with the addition of electrical energy storage.
Redox flow batteries (RFB) show potential for renewable energy management because of: i) scalability between storage capacity and power; ii) short response time; iii) good cycling capability, iv) long discharge time and v) low cost potential.
However, currently used RFB are relatively costly. The challenge is therefore to reduce the cost by combining different innovations taking advantage of advanced materials, such as: (i) using other promising redox species with lower cost and higher efficiency, (ii) improving the whole battery durability by using new components based on advanced materials or (iii) designing new concepts incorporating the competitive advantage of advanced materials.
This challenge is in line with the identified priorities in the context of the SET-Plan.

SCOPE

The objective is to develop and validate new RFB based on new materials (new designs, components, redox couples and electrolytes) that are more price competitive, environmentally sustainable, having higher energy and power density and with higher durability.
Proposals should consider the scalability of the new developments as well as the sustainability and safety aspects of the new materials and the associated production processes (including recyclability).
The new solutions and respective output targets (cyclability, reliability, lifetime...) should be tested in a pilot facility simulating real working conditions and validated in a relevant industrial environment (TRL5).
This challenge is in line with the identified priorities in the context of the SET-Plan.
To allow comparison with currently existing solutions, a full life cycle assessment covering environmental and economic aspects of the proposed alternatives should be included. Since cost is the most important driver for electricity storage, targets for key performance indicators such as OPEX (€/kWh/cycle), CAPEX (€/kWh), energy cost (€/kg) and power cost (€/kW) should be set.

The activities are expected to bring the technology from TRL 3 to TRL 5.

IMPACT

The performance levels of the proposed solution(s) should be in line with those specified in the relevant parts of the SET-Plan and specifically focus on a reduction of the cost to < 0.05 €/kWh/cycle, an increased component lifetime of > 20 year and a wider operating temperature range. Batteries for large-scale grid storage require durability for large numbers of charge/discharge cycles as well as calendar life, high round-trip efficiency and the ability to respond rapidly to changes in load or input together with a reasonable capital cost. Higher sustainability by substituting the traditional V system by alternative redox couples will contribute to a more widespread use of the system in utility scale applications and to an increase of the production potential and competitiveness for European players.

B4S - Metal-air stationary batteries for utility scale applications (>100MW, P/E<1/3)

TYPE: RIA
DRAFT LEADER: EDEL SHERIDAN, ETIENNE KNIPPING

CHALLENGE

The electric power grid is changing. Traditionally, utilities could carefully control the supply of electricity from power plants and accurately predict end-user demand. Maintaining this balance is essential to the operation of a reliable and high-performance electric grid.
As the share of wind and solar PV sources in the mix grows and the use of high-power electric vehicle charging stations expands, the grid must adapt to meet more dynamic demands with an uncertain supply.
Historically, utility-scale energy storage has focused on pumped-hydro power plants. But these systems require a large infrastructure investment and are limited to regions with the proper hilly geography. Alternatively, stationary redox-flow and Li-ion battery storage plants have seen a boom in new installations. These battery plants are compact, modular, and accomplish their goals, but redox-flow systems are high-maintenance with low energy density, while Li-ion batteries are expensive and have a significant fire-hazard.
New advances in cheap, reliable, and safe electrochemical energy storage could help utilities adapt to these evolving needs. Metal-air batteries stand out as one such technology, with cell production facilities and material reserves already existing in Europe.

SCOPE

Metal-air batteries comprise a high-energy metal electrode (e.g. Li, Zn, Mg, Al, Si, Fe, etc.) and a bi-functional air electrode. They are desirable for their high energy density (theoretically thousands of watt-hours per litre) and superior safety. Each metal brings its own advantages and disadvantages, and some highlights of the technology include: metals are cheap, non-toxic, and available in Europe (Zn, Si, Fe, Mg); Zn electrodes can utilize simple water-based electrolytes; most materials do not require special dry rooms for manufacturing (Zn, Si, Fe).
Li-air and Zn-air are currently the most advanced chemistries.

Demand for stationary metal-air batteries exists among end-users including utilities (electric & water), industry, and renewable energy plant operators. Globally, over 300 MWh of utility scale Zn-air batteries are already announced and contracted.
The rechargeability and lifetime of metal-air batteries are traditionally limited by the poor reversibility of the metal electrode and the parasitic uptake of CO_2 in alkaline electrolytes. Actions to innovate upon the state of the art include:
- Improve the reversibility of the metal electrode (approach 2000-5000 cycles) by reducing dendrite formation & shape change, avoiding passivation by solid metal-oxide products and suppressing H_2 evolution (in aqueous electrolytes).
- Improve the power and lifetime of the air electrode (approach cell energy of 800 Wh/L) by the development of active, stable, and cheap ORR/OER catalysts and the management of electrolyte levels to avoid flooding and dry-out.
- Improve the lifetime of the electrolyte (extend calendar lifetime to 20+ years) by the integration an oxygen-selective membrane and improvement of separator technology (aim to reduce dissolved CO_2 concentration by two orders-of-magnitude), the investigation of alternative electrolyte compositions (e.g. near-neutral aqueous or ionic liquids) and the evaluation of electrolyte additives for improved anode and cathode performance.
- Develop sustainable cell designs (achieve >90% recyclability) by applying advanced physics-based models to optimi-

ze performance and design of next-generation batteries, exploring abundant, recyclable, and environmentally-friendly materials, developing a BMS for improved operation (e.g. pulse charging, passivation avoidance, etc.) and examination of the feasibility of re-using air electrodes and three-electrode cell designs.

Utility-scale Zn-air batteries are currently TRL 7 and Li-air batteries are TRL3/4. Other metal-air systems are TRL 3-4.

IMPACT

The Research and Innovation Activities that are being called for are supposed to have a primary and secondary impact on different levels: impact on technology by improved metal electrode design, development of new catalyst and electrolyte materials, enhanced battery science and modelling capabilities and optimized production methods. For the Industry impacts are expected on the potential for cell production and mining within Europe; lower energy storage costs (under €100 per kWh), greater energy storage versatility, lower health and safety risks and generation of intellectual property. The society will profit of greater public health through fewer emissions, increased renewable energy production & reduced environmental hazards, European energy independence and security and improved reliability of the electric grid.

B5S - Li-ion stationary batteries for commercial applications (<100MW, P/E>4)

TYPE: RIA
DRAFT LEADER: DANIEL BIRO

CHALLENGE

Existing power grids are expected to reach their limits in terms of their capability to cope with situations of temporary high loads as for example caused by fast charging of electric vehicles. In order to promote the use of electric vehicles by consumers, fast charging stations have to be distributed across the road network, including areas with limited grid power capacities.
This challenge can be met by fitting fast charging stations with suitable battery systems capable of balancing those loads appropriately. The benefit of such battery systems will also lie in its ability to store energy at times when the supply of energy especially by renewable energy carriers exceeds the demand and thereby enabling a higher share of renewable energy in the energy mix.
Batteries capable of dealing with this challenge are expected to meet the following key performance indicators: by 2030 CAPEX 100-200 €/kWh, OPEX <0.05 €/kWh/cycle, lifetime >6000, volumetric energy density >500 Wh/l, rate capability 5C.

SCOPE

Among other drawbacks of state-of-the-art Li Batteries that need to be addressed to reach the above mentioned KPIs, existing Li-Ion batteries have a power to energy ratio that is not high enough to be used in this application. Therefore, several measures are being proposed to address the existing shortcomings:
- Improve conductivity to increase power by e.g. incorporating structured carbons such as Graphene as conductive additive into electrodes or conductive 3D-structures into electrodes and by the development of power optimized architectures.
- Develop high capacity Li-based technologies by incorporating silicon into negative electrode and increasing Ni content in NMC.
- Decrease Cobalt content in NMC technologies improving the structural stability of NMC crystal lattice through doping (e.g. with Ti) or incorporating structural templates into NMC particles.
- Develop coated separators to improve safety.
- Incorporate shutdown mechanisms into separator materials or separator design and improve structural resilience of separators through new materials, designs or coatings.

The activities are expected to bring the technology from TRL 3 to TRL 5. The Commission considers that proposals requesting a contribution from the EU between EUR 5 and 7 million would allow this specific challenge to be addressed appropriately.

IMPACT

The Research and Innovation Activities that are being called for are supposed to have a primary and secondary impact on different levels: impact on technology by faster charging of Li-ion batteries, increased lifetime, lower OPEX and CAPEX for Li-ion stationary batteries for commercial applications (<100MW, P/E>4). The Industry will profit by improved competitiveness of European Industry, economic growth for applicable industries, new innovations for other applications, new business opportunities in service industries, boosting of KETs and load balancing and load shedding of existing power grid. The society will be impacted by lower costs for energy, increased reliability of power supply, increased consumer independency, improved viability of electric mobility, increased wealth through value added and economic growth, decreased emissions and decreased dependency on imports.

B6S - Li-ion stationary batteries for utility scale applications (>>100MW, P/E<1/3)

TYPE: RIA
DRAFT LEADER: MARCEL MEEUS- SUSTESCO

CHALLENGE

Electricity storage will play a crucial role in enabling the next phase of the energy transition. Along with boosting solar and wind power generation, it will allow sharp decarbonisation in key segments of the energy market. As variable renewables grow to substantial levels, electricity systems will require greater flexibility. Wind and solar generation both experience intermittency, a combination of non-controllable variability and partial unpredictability. Large scale utility Li Ion energy storage may assist RE integration in several ways. These uses include matching generation to loads through time shifting, balancing the grid through ancillary services, load-levelling, managing uncertainty in RE generation through reserves and smoothing output from individual RE plants. Li Ion stationary electricity storage can provide a range of key energy services in an affordable manner. As the cost of Li Ion technologies falls further, storage will become increasingly competitive, and the range of economical services it can provide will only increase.
This makes that large Li Ion stationary storage has been steadily in the news over the last months/years: plant capacities increased in the multi MW/MWh size and grew to dimensions never seen before requiring energy storage for longer periods generally in the order of 3-4 hrs (energy applications). Evidence is growing that large Li Ion plants even can replace Gas Peaker Plants to generate power on days when consumer demand for electricity is highest.
To fully exploit these opportunities, cycle cost has further to be decreased to < 0,05€/kWh/cycle meaning further drastic improvements in cycle and calendar life whilst at the same time optimising reliability and safety by the development of advanced materials to meet these needs. Also, storage time in these utility large scale applications is usually close to 3-4 hours, generally to fully store the energy from one day of sun. Power is less a critical criterion than Energy and cost per cycle.

SCOPE

While capable of high energy density, the materials set for current Li-ion batteries are too expensive and may not offer sufficient performance for widespread large stationary applications. Improvements and innovation actions include:
- Develop new intercalation compounds with low cycling strain and fatigue for Li-ion batteries; aim for >10,000 cycles at 80% depth of discharge;
- Improve cycle lifetime and calendar lifetime to develop reliable and costs-effective products;
- Develop fast-charging Li-ion negatives other than lithium titanate;
- Develop high-energy-density electrodes with high ionic and electric conductivity;
- Develop a highly conductive, inorganic, solid-state conductor for solid-state Li-ion batteries for safety improvement;
- Characterisation of the interfaces needed to address system lifetime and performance by using predictive models of interfaces and reactions to understand performance and degradation;
- Decrease the Cobalt content in NMC cathode materials and introduce 622 and 811 chemistries;
- Decrease Balance of System cost and improve management, protection and diagnostic functions;

The TRL level of the project should start at TRL 3 and reach TRL5/6 at the end of the project. The Commission considers that proposals requesting a contribution from the EU between EUR 6 and 8 million would allow this specific challenge to be addressed appropriately in a consortium comprehending a battery producer, a system integrator and a utility provider.

IMPACT

Focus area is large energy storage with Li Ion systems well above 100 MW targeting 1 GW with P/E ratio <1/3 and potentially studying the substitution of Gas Peaker Plants. KPI's are the ones targeted in SET Implementation Plans of Actions 4 and 7.
The market for large storage Li ion batteries is rapidly evolving and it is becoming clear that large scale battery production from materials to final packs may soon be well established in Europe. To ensure the success of European battery material and cell producers, and the availability of battery supply to grid utilities, Europe must become a market leader rather than a follower, with regards to safety, performance and cost of Li Ion technologies.

B1M - Li-ion generation 3b batteries for high voltage mobility applications

TYPE: RIA
DRAFT LEADER: VICTOR TRAPP, SARAH HARTMANN- FRAUNHOFER ISC

CHALLENGE

Decarbonization is one of the crucial tasks for today's society to reduce greenhouse gases (GHG) emission and thus the negative impact on our climate. All over Europe, transportation accounts for almost 25% of total European CO2-emissions (EEA Report 2018). Even though restrictions for the CO2 emissions of internal combustion engine vehicles (ICEV) have being toughened for the last decades, due to increased mobility in all fields of the transportation sector the emission of GHGs is still increasing.
Therefore, the need to reduce the emission of GHGs within the transportation sector is of highest priority, which we will only achieve by pushing electro mobility and thus, increasing the number of electrified vehicles onto the roads. Lithium ion batteries are the key technology for electro mobility.
What we can see today is that a high market diffusion of EVs highly depends on enhanced driving distances and cycle life, but also on reduced costs for the battery pack and hence for the cells and materials, respectively. For example, on the cell level it is expected that cylindrical cells having gravimetric energy densities of today 240-270 Wh/kg (volumetric 650-750 Wh/l) will have to increase up to 300-350 Wh/kg (volumetric 800-950 Wh /l). For the prismatic Li-ion cells which possess today energy densities of 120-140 Wh/ kg (volumetric 230-350 Wh / l), it is expected that by 2025 the target is 200-260 Wh/kg (volumetric 400-700 Wh/l) whereas for pouch cells even 250-300 Wh/kg (500-800 Wh / l) are to be achieved (today: 150-180 Wh / kg and 250-450 Wh/ l, respectively). (Fraunhofer ISE Energie Speicher Roadmap 2017).

SCOPE

These targets are to be addressed either by the development of new or modified active materials.
The graphite anode of state-of-the-art (SoA) lithium-ion batteries are already close to the theoretical energy limit. A further improvement of capacity can be achieved by the incorporation of silicon which is abundant and non-toxic, and which redox potential of <0,5 vs. Li/Li+ is compatible with graphite. Today SiO/C anodes with 2-5% SiO are on the market, but it is estimated that by introducing 20% Si into graphite energy densities of 300 -350 Wh/kg (or volumetric 1000 Wh/l) and cycle stability of up to 500 cycles can be achieved. Besides, silicon would also allow for larger charging currents of up to 3C. (Market introduction expected until 2030.)
In combination with ≥ 4.7 V high voltage (HV) spinels or Li-rich Mn NMCs (e.g. x y Li2MnO3*(1-y) x LiMO2 with M = Ni, Co, Mn) on the cathode side, the requirements of increased energy densities for Generation 3b HV Li-ion batteries will be met.
For the development of new HV cathode materials such as HV spinels or NMC based materials with minimized contents of critical elements such as Co, research is needed to overcome Mn-leakage and stability issues, which is introduced when Co is substituted by Ni to reach ≥ 4.7 V.
Cell potentials of ≥ 4.7 V can only be achieved when cathode active material and electrolyte are tailored for each other. Surface modification of the cathode active material by applying coating and the development of either electrolyte additives or new electrolytes based on ionic liquids, can help to reduce the risk of oxidative decomposition at the interface of cathode / electrolyte.
Besides safety, also lowering the costs for the different cell types is crucial to be competitive with state-of-the-art cells from Asia. For example, cylindrical cells with costs of 150 - 200 €/kWh today are expected to drop to 100€ / kWh by 2025 whereas the costs of prismatic cells will decrease from 200-300 €/ kWh to approx. 100-150 €/ kWh (2025), and pouch cells from 200-300 €/kWh to ~100-150 €/kWh.
But not only materials have to be developed or modified, also adjusting process parameters can help to increase energy densities by either structuring of electrodes but also increasing layer thicknesses of the electrodes. Furthermore, the ecological foot print of the electrode preparation needs to be reduced by decreasing the amount of energy and/or by replacing organic solvents such as NMP by water.

IMPACT

The Research and Innovation Activities that are being called for are supposed to have a primary and secondary impact on different levels: on technology level by increasing the gravimetric energy densities up to 300 Wh/kg and volumetric to 1000 Wh/l ,increasing cycle life of Li-ion cells and charging currents of up to 3C ,the development of close-to market Ni-rich cathode materials and voltage stability additives for electrolytes and the enhancement of safety for electro-mobility by employing stabilized active materials such as coated Ni-rich cathode materials and oxidation optimized electrolytes or even non-volatile electrolytes such as ionic liquids. The Industry impact is expected for the implementation of Si into the graphite anode and European materials manufacturers have for this a wide patent port-folio. A reduction of pack costs to 70 - 100 €/kWh will help the market diffusion of electrified vehicles for the transport system and long-term development towards all-solid-state batteries for high energy battery systems. Finally, the outcome of the proposal will contribute to the reduction of the ecological foot print by developing aqueous electrode processing routes, the reduction of GHG emission for the transport sector and the increase of purely electric driving ranges and securement of jobs within Europe. Battery trainings will be needed for the high market diffusion of electro mobility. New recycling routes and processes for the different cell chemistries are to be developed for recovery of lithium, nickel and lithium ion cell compounds.

B2M - Li-ion generation 3b batteries for high capacity mobility applications

TYPE: RIA
DRAFT LEADER: MARCEL MEEUS, FRANK UWE RENNER

CHALLENGE

A high market diffusion of electrified vehicles (xEV) highly depends on enhanced driving distances and cycling life of the electrochemical battery cells, but also on reduced costs for the battery pack and hence for the cells and materials, respectively. To achieve a substantial increase in market share and European-based production of prevalent Li-ion technology (generation 3b), the consolidated global competiveness must be strengthened by European innovation in terms of increasing performance, safety, cycle and calendar life of the components and systems including a view on the energy and environmental footprint of the chosen technologies. With the intended research the consolidation and increase of a strong European industrial base in this field will be supported.
High capacity Li ion batteries for a wide range of applications include anodes of graphite composites including 3-5% of Si or SiOx combined with different possible cathode materials. The high capacity Li Ion battery cathodes can be pursued at higher voltages (≥ 4.7 V), subject of call description B1M and where still fundamental issues are to be resolved e.g. at electrolyte level stable at these voltages.
High capacity Li ion batteries using cathodes at lower voltages 4.3-4.7 V in combination with suitable anodes such as graphite-Si or graphite SiOx composites are easier and more rapidly to be introduced in the market and are subject to this call description B2M.
Current Li-ion batteries for e-mobility are not yet close to their fundamental limits illustrated e.g. by their gravimetric & volumetric energy density, with current cell level state-of-the-art at 90-235 Wh/kg & 200-630 Wh/l and the expected fundamental limits at 350-400 Wh/kg and 1000 Wh/l. Such a drastic improvement of performance must be achieved through the development of Advanced Materials covering cathode, anode, binders, separators, electrolyte, current collectors and packaging materials as to enable new Li-ion batteries, with a focus on generation 3b High Capacity.

SCOPE

The activities will be based on a multidisciplinary approach that includes the system knowledge for the most promising electrochemical systems and related monitoring systems / smart management to achieve possible production-readiness by two to three years after the end of the project.
Critical advanced performance parameters such as low cost per unit of energy and power capacity, safety, resistance to high-power charging, durability, environmental sustainability (energy-efficient manufacturing, recyclability and 2nd life usage) and aspects for large scale manufacturing solutions must be considered.
Innovation activities on Advanced Materials and High Capacity Li Ion system should include at least one of the following bullet points (although a full integration of more aspects would provide the best impact):
- Development of advanced high-capacity Gen3b cathode materials operating in 4.3-4.7 V; protective coatings for safety improvements, gradient materials, etc.; High nickel is part of the solution towards higher energy density (e.g.811 composition). However, fundamental drawbacks still must be considered and resolved such as limited cycle life;
- Work to increase Si content in Si/C anodes to achieve above 700 mAh/g, even full Si anodes might be possible, develop strategies to improve the cycle life of Si/C composite and Si anodes e.g. by stabilizing interfaces, preconditioning, or pre-lithiation;
- Development of suitable inactive materials (binders, conductive carbons, current collectors, separators e.g. ceramic coated membranes for high capacity systems);
- Development of electrolytes stable in 4.3-4.7 V zone, stability and safety additives to the electrolyte;
- Development of advanced processing/production routes for the novel materials (e.g. aqueous processing, solvent-free processing, conductive binders, etc.);
- Development of advanced electrode and cell/module designs and formats to maximize the energy content while ensu-

ring a high-power density and safety;
- Higher energy density at reduced safety is no compromise, understanding of surface and interface degradation effects of electrode materials is essential;
- Fast charging is of importance and materials/design should allow for it.

An integrated modelling approach is requested from atomistic level of materials to multiphysics modelling and transport on the electrode (mm) level to understand performance and ageing.

Focus should be on sustainability (materials), CO2-footprint (energy-efficient processes) and “smart batteries” (sensing technologies, etc.). Design must be such that the batteries are easily reusable for second life applications. Design of smart cells and battery packs in a way that they can be dismantled and recycled in a cost-efficient way (cost reduction, circular economy).

TRL level at beginning of the project is at 3 and at the end expected to be at 5/6.

IMPACT

Research and innovation activities will consolidate the strong position of European industry on the world market advancing the technological knowledge for competitive Li-ion cell based (3b) mass production in Europe. The proposed solutions should demonstrate technological readiness and safety through prototypes in accordance to the required TRL levels (TRL 5-6), improving cell-level energy densities to at least 300-350 Wh/kg and 850-1000 Wh/l, and costs lower than 100 €/kWh at pack level, with at least 3C (preferably more) fast charging capability while keeping a useful life of at least 3000 deep cycles (with 10% fast charging) to 80% residual capacity and in view of a second-life application 5000 deep cycles to 60% residual capacity. Impact on Industry is expected for the implementation of Si into the graphite anode and consequently increase of European material’s manufacturers patent port-folio and the reduction of pack costs to 70 – 100 €/kWh will boost the market diffusion of electrified vehicles. Impact on Society will be realized by reducing the ecological foot print developing aqueous electrode processing routes, reduction of GHG emission for the transport sector, improving the purely electric driving ranges and securing jobs within Europe. Battery trainings will be needed for high market diffusion of electromobility. Improved recycling routes and processes for the different cell chemistries are to be developed e.g.at battery dismantling level.

B3M - Li-ion generation 4a batteries (Solid State with conventional materials) for mobility applications

TYPE: RIA
DRAFT LEADER: MARCEL MEEUS, FRANK UWE RENNER

CHALLENGE

A high market diffusion of electrified vehicles (xEV) highly depends on enhanced driving distances and cycling life of the electrochemical battery cells, but also on reduced costs for the battery pack and hence for the cells and materials, respectively. To achieve a substantial increase in market share and European-based production of prevalent Li-ion technology (generation 3b), the consolidated global competiveness must be strengthened by European innovation in terms of increasing performance, safety, cycle and calendar life of the components and systems including a view on the energy and environmental footprint of the chosen technologies. With the intended research the consolidation and increase of a strong European industrial base in this field will be supported.
High capacity Li ion batteries for a wide range of applications include anodes of graphite composites including 3-5% of Si or SiOx combined with different possible cathode materials. The high capacity Li Ion battery cathodes can be pursued at higher voltages (≥ 4.7 V), subject of call description B1M and where still fundamental issues are to be resolved e.g. at electrolyte level stable at these voltages.
High capacity Li ion batteries using cathodes at lower voltages 4.3-4.7 V in combination with suitable anodes such as graphite-Si or graphite SiOx composites are easier and more rapidly to be introduced in the market and are subject to this call description B2M.
Current Li-ion batteries for e-mobility are not yet close to their fundamental limits illustrated e.g. by their gravimetric & volumetric energy density, with current cell level state-of-the-art at 90-235 Wh/kg & 200-630 Wh/l and the expected fundamental limits at 350-400 Wh/kg and 1000 Wh/l. Such a drastic improvement of performance must be achieved through the development of Advanced Materials covering cathode, anode, binders, separators, electrolyte, current collectors and packaging materials as to enable new Li-ion batteries, with a focus on generation 3b High Capacity.

SCOPE

The activities will be based on a multidisciplinary approach that includes the system knowledge for the most promising electrochemical systems and related monitoring systems / smart management to achieve possible production-readiness by two to three years after the end of the project.
Critical advanced performance parameters such as low cost per unit of energy and power capacity, safety, resistance to high-power charging, durability, environmental sustainability (energy-efficient manufacturing, recyclability and 2nd life usage) and aspects for large scale manufacturing solutions must be considered.
Innovation activities on Advanced Materials and High Capacity Li Ion system should include at least one of the following bullet points (although a full integration of more aspects would provide the best impact):
- Development of advanced high-capacity Gen3b cathode materials operating in 4.3-4.7 V; protective coatings for safety improvements, gradient materials, etc.; High nickel is part of the solution towards higher energy density (e.g.811 composition). However, fundamental drawbacks still must be considered and resolved such as limited cycle life;
- Work to increase Si content in Si/C anodes to achieve above 700 mAh/g, even full Si anodes might be possible, develop strategies to improve the cycle life of Si/C composite and Si anodes e.g. by stabilizing interfaces, preconditioning, or pre-lithiation;
- Development of suitable inactive materials (binders, conductive carbons, current collectors, separators e.g. ceramic coated membranes for high capacity systems);
- Development of electrolytes stable in 4.3-4.7 V zone, stability and safety additives to the electrolyte;
- Development of advanced processing/production routes for the novel materials (e.g. aqueous processing, solvent-free processing, conductive binders, etc.);

- Development of advanced electrode and cell/module designs and formats to maximize the energy content while ensuring a high-power density and safety;
- Higher energy density at reduced safety is no compromise, understanding of surface and interface degradation effects of electrode materials is essential;
- Fast charging is of importance and materials/design should allow for it.

An integrated modelling approach is requested from atomistic level of materials to multiphysics modelling and transport on the electrode (mm) level to understand performance and ageing.
Focus should be on sustainability (materials), CO2-footprint (energy-efficient processes) and "smart batteries" (sensing technologies, etc.). Design must be such that the batteries are easily reusable for second life applications. Design of smart cells and battery packs in a way that they can be dismantled and recycled in a cost-efficient way (cost reduction, circular economy).
TRL level at beginning of the project is at 3 and at the end expected to be at 5/6.

IMPACT

Research and innovation activities will consolidate the strong position of European industry on the world market advancing the technological knowledge for competitive Li-ion cell based (3b) mass production in Europe. The proposed solutions should demonstrate technological readiness and safety through prototypes in accordance to the required TRL levels (TRL 5-6), improving cell-level energy densities to at least 300-350 Wh/kg and 850-1000 Wh/l, and costs lower than 100 €/kWh at pack level, with at least 3C (preferably more) fast charging capability while keeping a useful life of at least 3000 deep cycles (with 10% fast charging) to 80% residual capacity and in view of a second-life application 5000 deep cycles to 60% residual capacity. Impact on Industry is expected for the implementation of Si into the graphite anode and consequently increase of European material's manufacturers patent port-folio and the reduction of pack costs to 70 – 100 €/kWh will boost the market diffusion of electrified vehicles. Impact on Society will be realized by reducing the ecological foot print developing aqueous electrode processing routes, reduction of GHG emission for the transport sector, improving the purely electric driving ranges and securing jobs within Europe. Battery trainings will be needed for high market diffusion of electromobility. Improved recycling routes and processes for the different cell chemistries are to be developed e.g.at battery dismantling level.

B4M - Li-ion generation 4b batteries (Solid State with Li metal-based anode) for mobility applications

TYPE: RIA
DRAFT LEADER: KAROLIEN VASSEUR, PIERRE-ETIENNE CABELGUEN - UMICORE, MONTSERRAT CASAS, ANNA LLORDÉS - CIC ENERGIGUNE

CHALLENGE

International developments towards less air pollution and CO2 production are pushing towards a rapid implementation of electrification of transport. In addition, according to market forecasts, a rapid growth of the sales and deployment of battery electric vehicles (BEV) is predicted corresponding with estimated ca 700 GWh capacity already by 2025. Considering the global competition, the rush for better technology implies also the need for a better traction battery technology as a key enabling technology whereby improved Li Ion batteries are expected to remain the technology of choice for several decades to come. Europe must regain its competitiveness in markets that nowadays are dominated by non-European countries. This could occur by developing a new European owned battery technology.
New chemistries, materials and production technologies must be developed to strengthen the European industrial base, in line with the EU initiatives as the Strategic Energy Technology Plan (SET Plan) Implementation Plan for Action 7 ('Batteries') and in support of the Šefčovič battery initiative "EU Battery Alliance", to be ready for market deployment by 2026.
Solid State Li Ion batteries are considered as a major step in next Li Ion development.
Lithium batteries with conventional active materials (SiC composite as the anode, and layered oxides as the cathode) are reaching their limits in terms of energy densities. There is a critical need for the development of new active materials and solid electrolytes that can be coupled with metallic lithium at the anode. In that context, solid-state electrolytes enable overcoming current limitations in terms of voltage and safety (dendrite formation).

SCOPE

New materials and/or chemistries must be developed to increase the energy densities beyond the state of the art of batteries used in automotive applications.
At the anode side, lithium metal seems to be the only choice in terms of gravimetric energy density. Reversibility, homogeneity and density of electrodeposition process should be improved by doping or coating strategies. Also, solutions for manufacturing and handling long and thin Li metal sheet in dry atmosphere (mechanical and chemical issues) should be investigated. Another technology, so called anode-less, could also be developed by designing suitable current collectors for reversible electrodeposition of lithium.
At the cathode side, chemistries ensuring a gravimetric energy density >850 Wh/kg at the material scale should be developed. Solid-state electrolytes and lithium metal anodes open the way to new cathode chemistries reaching high energy density: lithium-free cathode in combination with lithium metal or Li-excess cathode exhibiting high irreversible capacity in the anode-less configuration or high voltage materials (up to 4.5V) allowed by solid electrolytes.
The development of new or interfacially improved solid electrolytes should be done in the view of integrating such new cathodes, for example by allowing high voltage operation or sulphur-based active materials.
Material production aspects should be considered during the prototyping phase and should be reflected in the choice of materials.
System demonstrating acceptable performances should be developed within the call, TRL 3 to 5.

IMPACT

The Research and Innovation Activities that are being called for are supposed to have a primary and secondary impact on different levels: technology will be impacted by the development of interfacially controlled systems enabling Li metal that will allow to achieve higher energy densities in batteries and increased safety. Industry will profit from the development of solid-state batteries based on Li metal requiring new cost-effective manufacturing concepts opening an opportunity for companies that can't otherwise compete at Asian scale. Moreover, a significant reduction of greenhouse gases and air pollutants is expected through the enhanced deployment of electric vehicles enabled by high performing, cost efficient and "user friendly" batteries.

B5M - Li-ion generation 4c batteries (Li-metal and high voltage systems) for mobility applications

TYPE: RIA
DRAFT LEADER: MARCEL MEEUS - SUSTESCO

CHALLENGE

International developments towards less air pollution and CO2 production are pushing towards a rapid implementation of electrification of transport. In addition, according to market forecasts, a rapid growth of the sales and deployment of battery electric vehicles (BEV) is predicted corresponding with estimated ca 700 GWh capacity already by 2025. Considering the global competition, the rush for better technology implies also the need for a better traction battery technology as a key enabling technology whereby improved Li Ion batteries are expected to remain the technology of choice for several decades to come. Europe must regain its competitiveness in markets that nowadays are dominated by non-European countries. This could occur by developing a new European owned battery technology.
New chemistries, materials and production technologies must be developed to strengthen the European industrial base, in line with the EU initiatives as the Strategic Energy Technology Plan (SET Plan) Implementation Plan for Action 7 ('Batteries') and in support of the Šefčovič battery initiative "EU Battery Alliance", to be ready for market deployment by 2026.
Solid State Li Ion batteries are considered as a major step in next Li Ion development.
They use both solid electrodes and solid electrolytes, instead of the liquid or polymer electrolytes found in conventional Lithium-ion or Lithium polymer batteries. They are the next step in major OEM's roadmaps as they are an enabler for doubling the driving range due to their higher energy density. Additionally, they provide enhanced intrinsic safety and reduced charge time compared to lower-generation LIBs, but still suffer from lower cyclic performance.

SCOPE

Advanced Materials activities should develop further the solid-state battery technology beyond the current state-of the art and target maximum performance of this chemistry.
Solid state technology is known to be classified in 3 sub-generations:
- generation 4a with conventional Li-ion materials (as NMC/C Si to be developed by 2020-2022)
- generation 4b with Li-metal as anode (to be developed by 2025-2030)
- and generation 4c with Li- metal as anode and in a high voltage configuration > 4.75 V combining a solid electrolyte with newly to be developed stable high voltage cathode materials such as Li Rich NMC or spinels.

This call addresses specifically 4c generation (Li Ion solid state/ Li metal anode/High voltage cathode materials) and is expected to be market ready by 2030.
The work should include: A drastic improvement of performance by the development of Advanced Materials covering cathode, anode, binders, separators, electrolyte and current collector materials to enable new Li-ion batteries in an all solid Li metal-based configuration combined with higher voltage (> 4,75V).
All developed Advanced Materials are to be investigated for phenomena and problems at the interfaces of the components of the battery cell, which are often not well understood; tailoring of the morphology and/or composition of such interfaces should be also considered. Special consideration needs to be given to safety issues (such as thermal runaway). Knowledge on the ageing processes to understand cycle and calendar life prospects, battery degradation and state-of-health, should also be given attention. Material production aspects should be considered during the prototyping phase and should be reflected in the choice of materials. Last, but not least, elements of circular economy (access to raw materials and recycling) are to be incorporated into the development of the Advanced Materials.
Specific innovation activities will include the development of HV stable cathode materials (spinels, Li- and Mn-rich NMCs, phosphates, disordered materials) with as low content in Co as possible and compatible with the 4c generation, the development of solid electrolytes with ionic conductivity comparable to liquid electrolyte (organic, inorganic, hybrid).
Interface design and compatibility of materials is to be studied to achieve optimal integration of electrolyte, cathode and anode as well as the design geometry of the interfaces to match system and material compatibility. A minimum use of CRM (mainly Co) or rare earth materials is to be realised.

Development of Li-metal materials for anode (Li-metal, Li-alloy) avoiding Li dendrite formation and protection of Li metal surface are to be focused.
Development of (predictive) modelling & simulation and characterization tools for the new materials may contribute, as well as the development of analytical test methods for the new technologies (for durability, performance, characterisation, ...). A design for recyclability and LCA is to be developed.
A special attention should be given to IP protection and know how creation. A solid analysis and description of the state of the art of specific R&I and the patent situation must be included.
The developed cells should meet EV operating conditions in a broad temperature range, i.e. -20 to + 80 °C and fast charging requirements of BEV should be targeted (10 mins for 80% SoC);
The choice of the electrolyte to be developed must be duly justified in terms of chances of market success in the coming years. Validation of a pre-industrial prototype in relevant industrial environment must include an assessment of the scale-up potential in view of large-scale manufacturability.
The TRL level of the project starts at 3 to reach 5 at the end of the project.
The Commission considers that proposals requesting a contribution from the EU between EUR 6 and 8 million would allow this specific challenge to be addressed appropriately. Nonetheless, this does not preclude submission and selection of proposals requesting other amounts.

IMPACT

Solid State Li Ion batteries are considered to become the technology of choice in EV's for the next decades and are expected to become commercially deployed by 2025-2030. The maximum intrinsic properties of this technology are expected to be realized in the 4c generation as proposed in this call. Targeted KPI's at cell level are as follows: gravimetric energy density >500 Wh/kg, volumetric energy density >1000 Wh/l, cost ≤75 €/kWh, cycle life 3000 at 80% DoD. IPR protection needs to be guaranteed and demonstrated and the European materials modelling capacity and ecosystem should be increased. The European battery value chain towards cell production in Europe is to be strengthened. The proposal must do a thorough Life Cycle Analysis cradle to cradle and consider recycling as far as possible.

B6M - Next generation 5 batteries for mobility applications (e.g. Li Air, Li S)

TYPE: RIA
DRAFT LEADER: MARCEL MEEUS – SUSTESCO; ETIENNE KNIPPING- LEITAT

CHALLENGE

International developments towards less air pollution and CO2 production are pushing towards a rapid implementation of electrification of transport. In addition, according to market forecasts, a fast growth of the sales and deployment of battery electric vehicles (BEV) is predicted corresponding with estimated ca 700 GWh capacity already by 2025. Considering the global competition, the rush for better technology implies also the need for a better traction battery technology as a key enabling technology. Europe must regain its competitiveness in markets that nowadays are dominated by non-European countries. This could occur by developing a new European owned battery technology. New chemistries, materials and production technologies must be developed to strengthen the European industrial base, in line with the EU initiatives as the Strategic Energy Technology Plan Implementation Plan for Action 7 -and in support of the Šefčovič battery initiative "EU Battery Alliance", to be ready for market deployment by 2026. Current EV traction batteries are, to a large extent based on Lithium-ion chemistry but their maximum energy density will be limited to approximately 350- 400 Wh/kg in a liquid electrolyte system. Higher performance needs the gradual introduction of solid-state Li Ion batteries or/ and the development of a new generation battery (post Li Ion) the latter called Generation 5 and being the subject of this call. At this stage, the technologies probably offering the best chances for success are Li- Air and Li S but this call is not limited to these systems provided that the targeted KPI's would be met. E-Mobility covers the wide range of applications: passenger cars, buses, trains, heavy duty, forklifts, maritime...

SCOPE

Advanced Materials activities should develop further the solid-state battery technology beyond the current state-of the The wide range of new candidate systems covers among others Lithium-air, lithium-sulphur and new ion-based systems (Na, Mg or Al). Advanced Materials developed herein shall cover cathodes, anodes, electrolytes, separators, binders and packaging materials. Depending on the system performance issues generally include poor cycle life, low power, low efficiencies and limited safety and they need to be addressed and through advanced materials research and solutions brought from TRL levels 3 to 5 Innovation activities are dependent on the system addressed, but typically should include;

- For Li (or any other Metal) -Air battery system: improved metal/electrolyte/separator combinations to better control and optimize metal surface reactivity (e.g. reduce dendrite growth for Li metal anodes); the interface compatibility between different materials needs further improvements; safe electrolytes to be developed for reversible systems with high O2 solubility; the development of bi-functional air catalysts; the development of a three-electrode system. In general, the improvement of 1) safety, 2) cycle life, 3) volumetric energy density and 4) power density is targeted. Integration of a hybrid system with a supercapacitor to improve power rating is possible.
- For Li-S, a clear statement at the beginning of the project must be indicated related to the maturity already achieved and the research proposed to tackle the specific bottlenecks of this conversion technology for e-mobility application. The use of sulphur-based cathode is expected to be safer versus layered or high voltage material. The limitations at anode such as non-interrupted chemical reaction and associated thermal runaway must be solved protecting the lithium and developing a stable electrolyte. Thanks to low density active materials, Li-S is lighter than any other intercalation chemistry using high density material, but drastic improvements are required for volumetric energy density which is currently limiting its integration. Clear strategies must be proposed from the material to the cell manufacturing to reach the production of thinner and denser components together with a lower amount of inactive material. Finally, the technology must be demonstrated in a simulated environment proving its safety and performance fitting with the application.
- For new ion-based technologies (Na, Mg, Al) optimised insertion materials and suitable electrolyte formulations need further development depending on the system considered. Research and innovation will be needed for advanced material coatings and the development of new ceramic/ polymer/ hybrid structures with high conductivity and low impedance and non-

flammable, stable and conductive electrolytes. Methodologies for large-scale new materials manufacturing processes, environmentally friendly, need to be developed to reduce the battery
system cost.
Considering the rather fundamental character of most of the technical drawbacks of the post-Li ion systems, a good understanding of the cell reactions (cathode, anode...) is required and modelling of the cell reactions is recommended for better comprehension. The cell development needs to be accompanied by appropriated sensing, monitoring, thermal management and safety systems.
Output targets should be demonstrated at cell level from TRL 3 to 5 in a Consortium comprehending a European Battery Manufacturer and OEM in a 4-year research and innovation program. Potential for upscaling and recyclability must be addressed in the development.

IMPACT

Post Li Ion batteries (Generation 5) for EV's still need fundamental breakthrough research and innovation and are not commercially expected before 2030. Targeted KPI's in this call are at cell level: gravimetric energy density >500 Wh/kg, volumetric energy density > 1000 Wh/l, power density > 500 W/kg, cost 75 €/kWh, cycle life @80% DOD > 800.
Li-S/Li-Air are using less critical materials and may reach a cost lower than commercial lithium ion batteries assuming equivalent mass production. Industry will profit from the development of gen.5 batteries requiring new cost-effective materials and manufacturing concepts opening an opportunity for European companies to take distance from Asia.

B7M - Zero Strain Material (ZSM) batteries (e.g. TiO2) for high power mobility applications (trains, marine, buses)

TYPE: RIA
DRAFT LEADER: HILMI BUQA, HUGUES-YANIS AMANIEU – LECLANCHÉ

CHALLENGE

Graphite-based Li-ion cells are often seen as the main technology driver for future energy storage systems (ESS) due to its sinking cost (€/kWh) and high energy density. However, ESS markets have a high granularity in terms of requirements: power, safety, operational expenditures (OPEX). Several types of cells are seen as the right technology for power applications and already represent multi-billion-euro markets. Today G/LFP technologies can enable high power in discharge but fail at being charged several thousand time at high C-rate (>2C). Otherwise, NiMH are used in high frequency applications such as HEVs but have a small energy density.
Using higher voltage cathode (NMC) and a zero-strain material Lithium titanate (LTO, Li4Ti5O12) and/or TiO2 as alternative anode material instead of graphite in the Li-ion technology can lead to a serious contender. It allows obtaining very safe lithium batteries that will not catch fire or explode in case of thermal problem or shirt circuit, due to the low electrolyte reactivity- and decomposition at the working potentials for LTO based electrodes. The electrolyte is a critical component in lithium batteries as it allows its functioning by lithium-ion conduction for charge equilibration at charge/discharge. The electrolyte is thermodynamically not stable at the (graphite based) anode and cathode surface in the charged state of the battery. A graphite-based lithium-ion battery can only function correctly as there is a solid electrolyte interface (SEI) formed on the surface of the graphite anode which permits Li+- conduction while hindering the electrolyte from diffusing to the anode surface. On the surface of the cathode there is a SEI-like formed too, which is however, less well investigated.
Titanate Lithium-ion based cells show a few advantages in comparison with graphite-based Li-ion cells such as high electrochemical stability, high cycle stability, high power in (symmetrical) charge/discharge, zero train insertion material, so low mechanical ageing, no lithium metal plating on LTO anode, thermally stable, low temperature and deep discharge tolerance.
This is due to several reasons. One of these reasons is that no or an only very thin SEI is formed. The electrolyte is generally considered stable at the working potential of a lithium titanate electrodes.
LTO lithium-ion batteries provide very high mechanical, inherently high safety and electrochemical stability during cycling and allow for tenths of thousands full-DoD cycles to be reached, even in highly demanding conditions. The main drawbacks of the LTO based cells are the low cell energy density (due to low potential) and higher cell cost. To make the LTO based Li-ion cells more competitive to graphite-based cells, a lot of development work needs to be invested in developing high capacity Titanium dioxide (TiO2) materials, as a lighter and cheaper zero strain material to replace LTO.

SCOPE

Advanced Materials activities should develop further the solid-state battery technology beyond the current state-of the Tang et al. showed the capacity for the bronze structure (TiO2-B) to cycle at a very high C-rate for more than 10.000 cycles with little capacity loss. It has a theoretical capacity of 335 mAh/g, yet it loses part of it upon first lithiation and stabilizes around 250 mAh/g (LTO: 175 mAh/g). This crystal structure, when Nano-sized, has the potential to disrupt high power markets.
It needs however further development to scale up materials production and industrialization up to TRL7, namely: the improvement of TiO2-B with a stable capacity density >250 Ah/kg at materials level, work on trade-off between high surface ratio and cycle life (by particle shapes, or surface functionalization).
Assessment of toxicology and development of fit manufacturing processes is to be done as well work to ensure low risk for using nanomaterials in a production environment through different solutions (dilution, bound, etc.).
Other aspects and innovation include reduction of negative impact of catalytic effects on the cycle life.
Regarding electrode/cell manufacturing, important are gassing control (work on electrolyte), development of a recipe to

bind nanotubes and the search for the best conductive additives.
On Full Cell development, to be studied are the combination of high voltage cathodes with symmetrical charge/discharge of 10 C-Rate and the scale-up to reach <15€/kg for production of TiO_2 with bronze structure.

IMPACT

Combining new types of cathode (high voltage NMC) and of ZSM-based anodes (TiO_2) can lead to dense and cheaper high-power cell technologies. Niche markets exploring Li-ion high power technologies represent in Europe a few GWh/years, namely robotics and city transportation. But once industrialized and widely demonstrated, this technology will be a serious threat to NiMH in hybridizing EVs. This market alone represents up to 5 GWh/year by 2020 and will keep growing until late into the 2030s.
Target KPIs to reach this impact are at cell as follows: gravimetric energy density > 150 Wh/kg, volumetric energy density > 300 Wh/l, Gravimetric power density > 1.500 W/kg, volumetric power density > 3.000 W/l, cost 300 €/kWh, cycle life @80% DoD > 15.000 cycles, discharge and charge operating temperature (°C) -20, +80.

B8M - Next generation Hybrid Supercapacitors for Power mobility applications

TYPE: RIA
DRAFT LEADER: DANIEL CARRIAZO - CICE

CHALLENGE

The electric vehicle is emerging as a critical application that greatly affects the research that is carried out in energy storage. The projections on the use of energy and greenhouse gas emissions in industrialized countries show a continuous growth in the number of vehicles and their use. In this sense, the International Energy Agency (IEA) foresees that until 2030 the global demand for energy from transport increases on average by 1.6% per year. Thus, according to the most optimistic forecasts, the market for supercapacitors will reach a value of 3.1 billion dollars in 2026, with an annual growth of 15.5% from 2017 to 2026, mainly related to the growing demand for hybrid vehicles.
Supercapacitors have been so far mainly used for energy conservation and energy harvesting applications and their market is considered to have an upside potential for the years to come. In most scenarios' supercapacitors are used to complement batteries but owing to their excellent low temperature performance, calendar and cycle life, fast charge-discharge and reliability, they can even replace them in those applications where size and weight are not of major concern.
There are already in the market some hybrid supercapacitors (JM Energy (Japan) or Yunasko (Ukraine) with energy densities up to 37 Wh/kg at cell level. To extend the applications of hybrid supercapacitors and make them more attractive for the electric mobility (including elevators, electric trams or buses), it is needed to improve the cell energy densities up to 200 Wh/kg, and costs lower than 100€/kWh at pack level, with fast charging capability while keeping long cycle life (over 50,000 cycles) to 80% residual capacity. Moreover, it is important that European research community have the knowledge for the development of next generation hybrid supercapacitors technology that will show improved values in terms of energy density while keeping some of their intrinsic good figures in terms of safety, power density, environmental impact and cycle life.

SCOPE

The activities will be focused on a multidisciplinary approach that will cover the development of novel materials and electrolytes with improved properties and performances and their integration into different energy storage asymmetric systems, as well as the fabrication of prototypes (TRL 5 achievement at the project end). Innovation focuses on different research orientations:
- Research in materials science and electrolytes:
- Maximize energy and power density;
- Reduce the amount of critical raw materials (cobalt or nickel) used per unit stored energy;
- Development of new electrolytes with improved performance and safety;
- Environmental sustainability of chemistries and processes achieve all the above while further reducing cost, particularly by pursuing cost reduction of electrode active materials.
- Research on pre-lithiation processes and the use of sacrificial salts.
Both high energy anodes and hard carbons (main components of the hybrid supercapacitor technology) lack lithium in their pristine structure, so new approaches and strategies for the pre-lithiation of the active materials are needed for the successful development of this technology.
- Research on electrode processing, additives and cell configuration.

IMPACT

Research and innovation activities will bring European industry to a stronger position on the world market having the technological knowledge and be prepared for a fast implementation to launch competitive next generation hybrid supercapacitors cells in Europe.
The proposed solutions should demonstrate technological readiness and safety through prototypes in accordance to the required TRL levels (TRL 5), devices with improved cell energy densities up to 200 Wh/kg, and costs lower than 100 €/kWh at pack level, with fast charging capability while keeping long cycle life (over 50,000 cycles) to 80% residual capacity.

B9M - Advanced materials for the reduction of EV weight in battery packaging, drivetrain and car body

TYPE: IA
DRAFT LEADER: MARCEL MEEUS - SUSTESCO

CHALLENGE

International developments towards less air pollution and less CO2 production are pushing towards a rapid implementation of electrification of transport. In addition, according to market forecasts, a rapid growth of the sales and deployment of battery electric vehicles (BEV) is predicted. However, to optimise EV's for the OEM's and the consumer, lightweight measures and materials are needed in the car body of Battery Electric Vehicles (BEV's) to compensate for the additional battery weight (300 kg for a mid-size car and up to 700 kg in a top model long range passenger car). Such increase of weight may lead to decreased driving dynamics and shorter range.

Moreover, advanced lightweight materials when used in the battery packaging will contribute to increase the gravimetric energy density of the battery system and novel lightweight components in the EV drivetrain will further improve vehicles' energy efficiency. Lightweight materials in battery pack and drivetrain should contribute to cost reduction as both are important for the total cost structure of a battery electric vehicle. Reduction of car weight has direct implications on the reduction of emissions.

SCOPE

Moderate and extreme packages of advanced lightweight materials are to be developed in EV's design based on the use of materials such as glass fibres, carbon fibres, new plastics, magnesium, aluminium, high strength steels and others. Significant weight reduction targets are set forward.
Innovation activities include:

- Development of low-cost materials with high strength-to-weight ratio suitable for structural and functional automotive parts;
- Development of high-performance coatings to protect light alloys against wear;
- Development of low weight battery packaging materials;
- Development of effective low cost and energy efficient manufacturing processes for these high strength- to weight new advanced materials;
- Use of markers, tracers, additives to increase separation, sorting, and recycling of lightweight materials;
- Development of predictive models;
- Development of multi material solutions and cost-effective joining of dissimilar lightweight materials;
- Development of methods to mitigate corrosion to improve durability using low cost techniques such as performant coatings;

Proposed solutions are to be brought from TRL level 3 to TRL 5/6 at the end of the project.
Output targets should be demonstrated in a Consortium comprehending a European Battery Pack Manufacturer, an OEM producer of EV's, a drive train components producer and light weight material suppliers in a 4-year research and innovation program. Potential for upscaling and recyclability must be addressed in the development.

IMPACT

New technologies developed for lightweight materials and their manufacturing processes will enhance European EV competitiveness. European Industry will create new business for internal and external markets (export) and this will lead to significant job creation.
Following KPI's are targeted in comparison with the state-of-the-art: total weight reduction EV car body of 40%, weight reduction battery packaging of 70 %, attain lightweight materials (HSS, Al, plastics…) share in EV's of 65%, drive train cost reduction of 30%, durability improvement of 30%, driving range 700 km, recyclability of 99%.
Longer driving range automatically leads to less recharging times and cost reduction for the consumer. There may be no impact or compromise on the safety of the EV's.

B10M - Advanced Material technology and system solutions enabling user friendly and reliable ultra-fast charging stations (350 kW) for EVs

TYPE: IA
DRAFT LEADER: MARCEL MEEUS - SUSTESCO

CHALLENGE

The availability of high-power ultra-fast charging stations enables more convenient long-distance electromobility and can support the transition of more users to electric vehicles. Large electric vehicle fast- charging station networks in Europe have partnered to create new integrated alliances, and partnerships have been formed to install networks in Europe with ultra-fast chargers of 350 kW.
High power levels for ultra-fast charging increases the challenges for designing practically convenient and reliable equipment for transferring energy from charger station to vehicle. Today the Combined Charging System (CCS) defines a standard for cable/plug-based systems for use in vehicle charging stations. Concepts for contactless charging and automated charging are available as well, although for lower power levels. Increased power transfer requirements for 350kW range ultra-fast chargers will challenge the current system design for charging stations. Cables and plugs will become less user friendly to handle since they will be heavier and bulkier, the large currents might give unacceptable temperature rise in cables and plugs, and consequences of wear and tear, dirt and corrosion will become more critical.
The upcoming challenge is to utilize state-of-the-art material technology in combination with innovative solutions for Advanced Materials to develop technology for user friendly and reliable ultra-fast charging stations with power transfer capability exceeding 350kW.

SCOPE

Proposals will have to address one or more of the following technical areas:
- New technologies and solutions for user-friendly and reliable connection of vehicles to ultra-fast charging stations at 350kW power level (manual or automated, conductive or contact-less);
- Material technology (insulation, conductors, cooling) and connection methods for safe, reliable and easy-to-handle 350kW charging cables and plug connections;
- Solutions for automated plug connections at 350kW power transfer;
- Technology for contact-less power transfer up to 350kW;
- Development of material technology and solutions enabling a low weight of on-board equipment for high power contactless charging;
- Components and topologies for low cost and high efficiency ultra-fast charger stations with multiple charging connections;

For each of the technical areas any proposal should consider safety, cost, weight and volume of the necessary equipment on-board the vehicle, possibilities for automation, efficiency, ruggedness against worldwide environmental challenges such as high and low temperature, high humidity, salt, dust, snow and ice. The user experience must also be targeted such that comfort and convenience of long range EV travel can reach equivalent or higher levels than for fossil fuelled cars.
Challenges related to grid impact of fast chargers and measures to cope with limitations in grid infrastructure is not within the scope of this call.
Proposed solutions are to be brought from TRL level 3 to TRL 5/6 at the end of the project.

IMPACT

The impact of the proposal will be on different levels, in the first place on the development of the EV market and EV users' comfort.
Increased use and acceptance for EVs will be the consequence of increased user experience for EV long range travel. If BEVs are to make a significant increase in the market share of passenger cars, ultrafast charging in less than 10 min (focus on 5 min) will be needed to improve the range and allowing these vehicles to be charged with comparable speed as Internal Combustion Vehicles. Ultrafast charging technology will also be a key asset for European charging station manufacturers.

B11M - Solid state technology 4b generation – Realization of processing and upscaling

TYPE: IA
DRAFT LEADER: NOSHIN OMAR, SHOVON GOUTAM, VRIJE UNIVERSITEIT BRUSSEL (VUB)

CHALLENGE

Energy generation and storage is a key technology in the modern world. Batteries have been identified by the European Union (EU) as a key technology to aid the transition to a low-carbon economy. Europe's future battery cell business is especially important as many European nations make plans to phase out the internal combustion engine over the next two decades. The EU has recently launched a "Battery Alliance" initiative that supports the development of battery cells for future electric vehicle (EV) and technology applications. EV production in the European Union got a further spur on November 8th, 2017 as EU regulators installed stricter emission curbs on vehicle manufacturers. The European Commission proposed a 30% reduction in CO2 emission of vehicles by 2030 compared to 2021 levels, intensifying the fight against global warming. The plan, which will progressively tighten existing CO2 limits, features incentives for automakers to shift to EVs. All these regulations stimulate the EU battery industry to close the technological gap with Asian countries.
In this context, solid state technology generation 4b based on advanced chemistries, I. e. Li metal (Li M). as an anode combined with composite high energy cathode such as NMC 811 with inorganic, organic or hybrid solid state electrolyte is expected to be on the market by 2030. Nevertheless, this technology is facing many challenges. Besides the material optimization, processing technology, upscaling and manufacturing are also key challenges, where in EU there is limited knowledge available. The development process from material to full large cell is depending on many parameters and up to our knowledge these parameters are not fully understood or known. Therefore, there is a dedicated need to address all these aspects, which will affect highly the selected processing and manufacturing technology in the industry.
In addition, processing and manufacturing is responsible for a significant part of the cost. A solid knowledge in this field will enable to select the most appropriate technology and thus to control the cost in a better way. The new solutions and production technologies must be developed to strengthen the European industrial base, in line with the EU initiatives as the SET plan and in support of the Šefčovič battery initiative, to be ready for market deployment by around 2026.
This challenge is based on the results of the stakeholder consultations (workshops January 11th and 12th 2018) and is complementary to the topic published in the Sustainable Transport Challenge of 2019 on "Next generation of high energy density, fast chargeable lithium ion batteries".

SCOPE

The considered activities should develop further the Gen4b solid-state battery technology and present solutions beyond the current state-of the art processing and upscaling techniques. The ideal project will provide solutions regarding the following points:
- Development and upscaling of Gen4b solid-state cell manufacturing processes, from coin to large cells (>20 Ah) at batch of minimum 100 cells with ±5% statistical variation;
- Analysis of different green processing technologies for Gen4b solid state batteries full cells;
- Analysis of the different manufacturing steps and the needs to modify or optimize them towards Gen4b solid state cell;
- Understanding of the relevant parameters that are affecting the battery behaviour and quality during processing, upscaling and manufacturing from coin to a large cell;
- Development of a database of the influencing parameters on the behaviour and quality/reproducibility of battery cells;

- Development of a manufacturing model that can estimate and predict the impact of different process parameters on the battery behaviour and quality.

Activities should start at TRL 3 and achieve TRL 6 at the end of the project.

The Commission considers that proposals requesting a contribution from the EU between EUR 6 and 10 million would allow this specific challenge to be addressed appropriately. Nonetheless, this does not preclude submission and selection of proposals requesting other amounts.Challenges related to grid impact of fast chargers and measures to cope with limitations in grid infrastructure is not within the scope of this call.

Proposed solutions are to be brought from TRL level 3 to TRL 5/6 at the end of the project.

IMPACT

The Activities that are being called for are supposed to have a primary and secondary impact on different levels: on technology level the reduction of the development cost by 30% compared to state-of-the-art solutions, reduction of trial errors by a factor 3 again compared to state-of-the-art solutions. The Industry will be supported e.g. equipment suppliers for solid state technologies, sustainable process technology for solid- state battery within EU will be developed as well as close to market solutions.

Guidelines for skill development of process engineers and technician for solid state technology will be made. The project will lead to less dependency on non-EU players and critical raw materials.

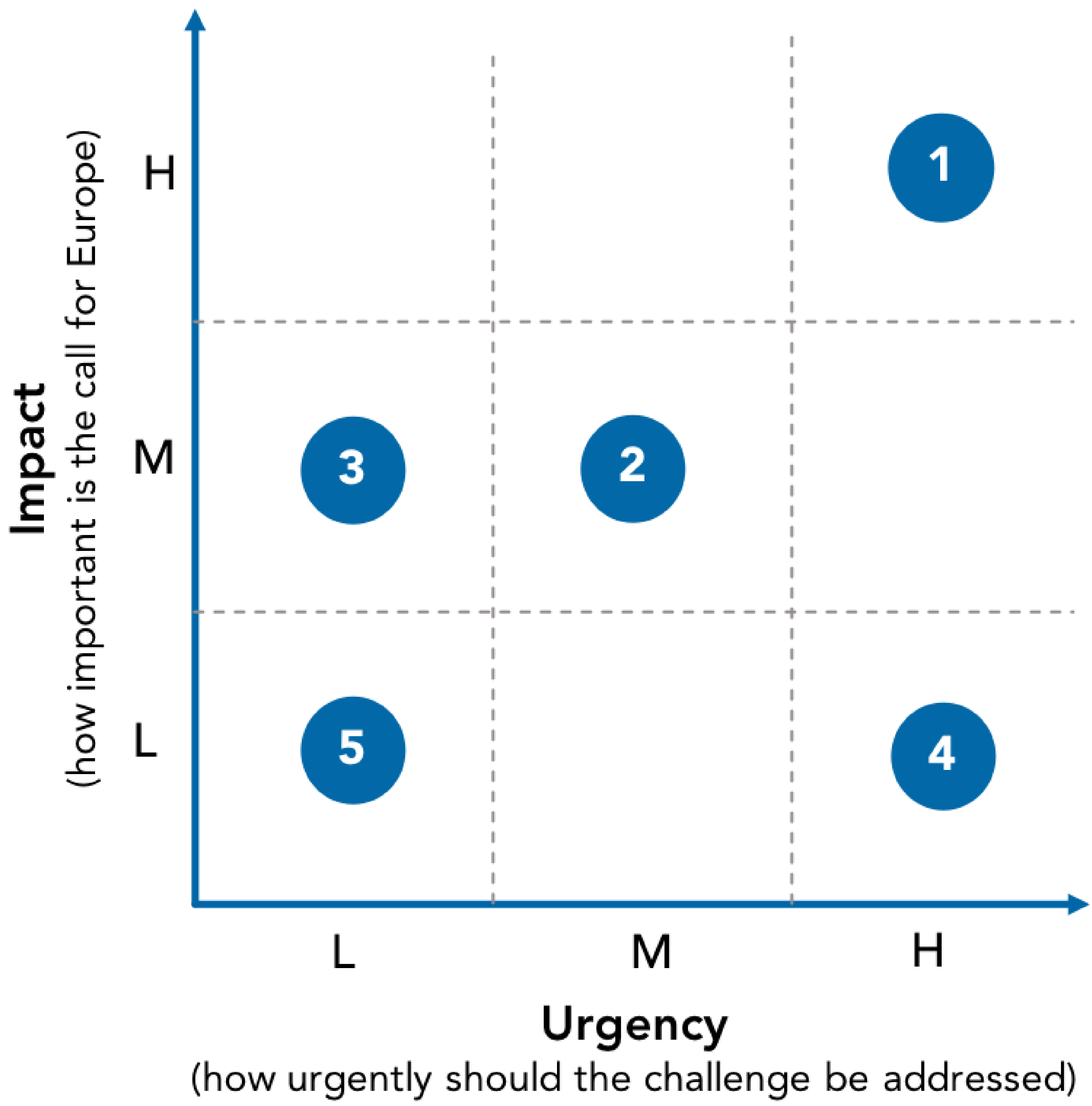
Competitiveness of European industries in the field of Solid-State manufacturing at a global level will be improved and production of batteries in EU facilitated.

Reinforcement of European skills and knowledge on next generation storage technologies will be favoured.

2. Hydrogen for mobility

Call #	Theme	Lead	Contact
1	Improve durability, efficiency and cost through new advanced materials for low temperature PEM FC (60 - 95 °C)	Carsten Cremers	carsten.cremers@ict.fraunhofer.de
		Eva Gutierrez	eva.gutierrez@tekniker.es
2	New advanced materials for high temperature PEM FC (> 120 °C)	Laurent Antoni	laurent.antoni@cea.fr
		Thierry Prim	thierry.priem@cea.fr
3	Combination of advanced materials and industrialisation aspects for low TCO PEM FC system	Winfried Keiper	winfried.keiper@de.bosch.com
		Alvise Bianchin	research@mbn.it
4	Advanced materials for on-board hydrogen storage tanks (including tanks for vehicles and for tanks for transportation of hydrogen)	Winfried Keiper	winfried.keiper@de.bosch.com
		Alvise Bianchin	research@mbn.it
		Tine Naerland	Tine.Naerland@ife.no
5	Advanced materials for on-board H_2 generation	Ekain Fernandez	ekain.fernandez@tecnalia.com

Priorisation matrix



H1M - Improve durability, efficiency and cost through new advanced materials for low temperature PEM FC (60 - 95 °C)

TYPE: RIA
DRAFT LEADER: CARSTEN CREMERS - FRAUNHOFER, EVA GUTIÉRREZ - TEKNIKER

CHALLENGE

A number of economic factors still hinder the wider market introduction of fuel cells in particular for automotive drive trains. The overarching challenge thereby is costs, which can be broken down into several direct issues like the still too extensive use of expensive and critical raw materials like platinum, the still insufficient lifetime and a MEA level performance which still gives room to improvement. Hence, the challenges are to further reduce the platinum group metal loading to values well below 0.2 mg cm-2 total approaching 0.1 mg cm-2 keeping power densities of ≥ 1 W cm-2 or to significantly raise the power densities to values approaching 2 W cm-2 keeping todays PGM loading.
There are however also indirect issues which need to be addressed in order to accomplish the desired reduction of cost. One is the more stringent design of materials and structures for the later recycling. A second issue is the design of materials, which can reduce cost of handling during production e.g. a membrane design, which allows mounting the membrane in a state that reduces the break-in time during end of line testing.
A further challenge is free trading of fuel cell components such as MEAs or bipolar plates. One of the issues here is to define verifiable quality criterions. A major challenge therein can be the reliable and reproducible measurements of properties e.g. conductivity of bipolar plates by different parties. The definition of such criterions as well as appropriate standardized measurements of the physical properties on which they are based is a key to enhancing trade of such components and opening opportunities for second sources vendors, which also will have a beneficial effect on costs.

SCOPE

One or several of the following material issues shall be addressed in answer to above challenges. 1. Catalyst research should encompass following innovation activities:
- Improvement of substrate support corrosion by replacing carbon black with less sensitive materials such as carbon materials with higher resistance against corrosion e.g. with high degree of graphitisation or doped diamond like structures. Electronically conductive metal oxides or other metal chalcogenides are also material possibilities. Criteria to the substrate are: high electric but also high thermal conductivity, substrate must allow for the highly disperse deposition of the active catalysts especially platinum, and it must be able to stabilize active catalyst nano-particles.
Additional provision of proton conductivity is recommended if not compromising other goals and the support structure must facilitate mass transport and reduce sensitivity against water so that mass transport limitations in 30% nitrogen in hydrogen / air mode are not observed for current densities lower than 1.8 A cm-2
- Improvement of the stability of active metal by avoiding the loss of active area by the utilization of platinum or other active materials in thin but closed layers featuring low number of edges and steps, thus reducing corrosive attacks. Supports or modification of supports that inhibit effects like Oswalt ripening need also to be considered as well as material improvements that reduce platinum dissolution e.g. via the better control of local pH or water accumulation.
In total, the loss of active surface area after relevant accelerated degradation test should be limited to 30%– 40 % and after catalyst degradation test, more than 75% of the mass activity should be retained Research shall be directed to the decrease or completely removal of CRM (in particular Pt) content.
Increase of the platinum mass specific performance of platinum-based catalyst, for the ORR values > 0.5 A mgPt-1 @ 0.9V vs. SHE. should be achieved
The structure of the catalyst and its support needs to be improved so that mass transport limitations are avoided despite reduced number of active sites. Its activity need to be increased so that MEA level performance targets can be reached at lower currents reducing mass transport and heat rejection issues together with an improved stability of PGM free catalyst.
The number of reaction steps are to be decreased required in the synthesis of PGM free catalysts and the use of non-

PGM catalyst to be evaluated in other low temperature fuel cells e.g. DMFC for first market introduction. Decrease of sensitivity to pin hole formation by material improvements that either reduce the proneness of the membrane for pin hole formation or can lead to self-healing capabilities (in particular for membranes with thickness <10μm).
Thereby pin hole formation can occur either before beginning of life, i.e. during the MEA manufacturing and stack mounting e.g. by mechanical or chemical stress (solvents) or during stack life also by mechanical stress e.g. wet dry cycling or chemical attack e.g. from hydrogen peroxide
Material improvements best should address several of these issues
3. Bipolar plates:
Develop materials to decrease weight while maintaining or improving performance of bi-polar and end plates. Research is on graphite and graphite compound materials able to be formed into bipolar plates fulfilling the 1.5 mm cell pitch requirement from AutoStack Drives using economical viable forming technology and on metallic materials which are light and cost effective for bipolar plates with high conductivity and high corrosion resistance.
The materials must be able to protect themselves against further corrosion at points of failures of the protective coating. Passivation at such point must not creep under unharmed part of the protective coating. Protective coatings are to be developed for either today's standard materials (316L, 1.4404) or the new materials which avoid use of CRM as far as possible and are easy and cost efficient to apply. Application of protective layer onto the unformed metal before forming process (pre-coating) is preferred. The coating must not disturb later joining of bipolar half plates by laser welding or other ways of joining. The development of a solder is to be considered which is compatible with the coating and for which in case of coating after forming (post-coating), the coating and soldering process can be integrated into the same equipment to reduce costs.
Protections for drill holes e.g. for coolants is another research item.
4. Reducing of environmental impact by
Design for circularity for all components (re-use, re-purpose, sorting, separation, recycling). Investigation of typical damage occurring at automotive fuel cell stacks during operation and dismantling needs to be performed and evaluation of stack refurbishment and re-use of stack parts.
Other investigations are on material improvements facilitating the reuse of stack components e.g. scratch protection of BPP and on processing of stack components towards material recycling beyond PGM recycling, e.g. recovery of fluorinated oligomers or monomers from membrane and ionomer, carbon fibre recovery from GDL.
Material modification is to be considered which can facilitate the later recycling without compromising durability targets.
A good understanding of LCC/LCA is to be developed elaborating fuel cell specific aspects and by the development of standard processes which consider these fuel cell specific aspects.
The expected duration of the project is 3-4 years and will start at TRL 4-5 to end at TRL 6 -7. Proposals requesting a contribution from the EU of EUR 4 million would allow this specific challenge to be addressed appropriately. Nonetheless, this does not preclude submission and selection of proposals requesting other amounts.

IMPACT

It is expected that the project results will impact the mobility fuel cell technology by reduced CAPEX, increased performance, efficiency and lifetime. The automotive fuel cell industry is expected to additionally benefit from improved balance of plant efforts by increased efficiency and the standards for the establishment of a supply chain with second sources. On society level the impact is expected in a decreased dependence on critical raw materials and the opening of a pathway to versatile low carbon individual mobility and heavy-duty traffic.

H2M - New advanced materials for high temperature PEM FC (> 120 °C)

TYPE: RIA
DRAFT LEADER: LAURENT ANTONI & THIERRY PRIEM – CEA

CHALLENGE

The maximum performance in terms of specific or mass power density of the current PEMFC technology is reached for a nominal operating temperature range between 60 and 95°C. Above this value the produced water is not sufficient to maintain optimal hydration level of the proton conducting polymer electrolyte constituting the membrane and the electrodes, leading to a dramatic decrease of efficiency. Indeed, whereas there is generally a large amount of liquid water at temperatures up to about 80°C, higher operating temperatures lead to high loss of humidity unless during transient operations. Despite the expected loss of power, an increase of the operating temperature to around 110°C, in as dry as possible conditions (<50% RH), would greatly simplify the system and allow to downsize the heat exchanger to similar dimensions as those of the current cars. In addition, increasing temperatures make the PEMFC more tolerant to pollutants contained in the gases and especially to carbon monoxide (CO) which is present in hydrogen coming from the reforming process. Moreover, the absence of liquid water enhances the transport of oxygen but despite these advantages, there is nearly no demonstration of PEMFC stack operating in the high temperature range and only few studies have been reported about small size single cell level. These latter reveal that the materials used in the components of low-temperature PEMFC (60-95°C) are still currently used for operation at 110- 120°C although they require improvement to enhance performance and durability at this range of temperature in dry condition. This is particularly clear for the proton conducting ionomer whose proton transport properties must be improved for low water activity, and whose gas permeability must be decreased. Regarding the durability even less information is available. It is assumed that the degradation mechanisms are the same as for low temperature PEMFC with increased kinetic leading to a reduced lifetime. However, no extended studies are available and since some of the degradation mechanisms are exacerbated as water activity increases (platinum dissolution or carbon corrosion, loss of hydrophobicity of GDL), they might be mitigated in high temperature condition for which relative humidity is lower. At least, it is known that the current gasket or sub gasket, or membrane reinforcement, used in Membrane Electrode Assembly (MEA) for low temperature PEMFC are not suitable at medium temperature. Thus, the prevalent degradation mechanisms and proper mitigation strategy at the material level have not been properly defined for high temperature operation.
To sum up, despite there will be a huge interest on the system point of view in increasing operating running PEMFC around 120°C or higher (simpler water management) there are still lots of issues regarding the materials that must be specifically and properly designed for this range of temperature. Improvement and understanding are still needed to fulfil the requirement in term of performance and durability for transportation applications.

SCOPE

The project shall include the following innovation activities:
- Development and fabrication of components from optimised materials with related processes to enhance performance and durability of PEMFC operating at medium temperature. Those improvements could deal with the membrane: ionomer and reinforcement; the catalyst layer: the catalyst, the catalyst support, the binder; the gas diffusion layer: support, hydrophobic treatment, microporous layer; the bipolar plate: composition, coating; the gasket; the sub gasket; the coolant and the end plates. The operating tests will be run from the single repeat unit to a 2kWel stack scale.
- Evaluation of these materials and components in nominal and transient operating conditions and upscaling of the processes for the fabrication of materials and components for high temperature PEMFC - Modelling of the thermomechanical behaviour of the stack and of the degradation mechanisms of the materials for prediction.

- Ex-situ and Operando degradation studies of the materials in the temperature range around 110-120°C, especially in dry conditions (RH between 20 to 60%) and their effect on performance at lower temperature (60-95°C) in humidified conditions to mimic the transient conditions (including start-up/shut-down) in presence of liquid water. Especially, the hydro-thermomechanical effects on the component must be evaluated.

The materials and processes must be demonstrated to be available at a scale compatible with an industrial production of a 100-kW range PEMFC stacks for either automotive vehicles or heavy duty vehicles (HDV). The models, characterisations and tests methods must not be developed in this topic and must have been previously established. The expected duration of the project is 3-4 years and starts at TRL 3-4 ending at TRL 5-6.

Proposals requesting a contribution from the EU of EUR 4 million would allow this specific challenge to be addressed appropriately. Nonetheless, this does not preclude submission and selection of proposals requesting other amounts.

IMPACT

The project shall result in validation of the developed materials with operating temperature up to 120 °C without performance losses compared to standard PEMFC operated at 60-95 °C. It will identify and characterize the performance limitations and the effective properties of the MEA while quantifying and predicting the local operating conditions inside a MEA. Recommendations will be designed for components to increase performance of MEA, and eventually durability (not mandatory).

The main KPIs to be achieved are the following: Power density > 1.1 W/cm2 at 0.66 V, operating temperature of 120 °C or above, less than 10% loss in performance at 0.66V after 5,000 hours for automotive vehicles or 40,000 hours for HDVs. These KPIs must be reached under automotive operating conditions (as defined in the harmonised EU test procedure) and at single cell level.

H3M -Combination of advanced materials and industrialisation aspects for low TCO PEM FC system

TYPE: IA
DRAFT LEADER: WINFRIED KEIPER – BOSCH, ALVISE BIANCHIN – MBN

CHALLENGE

Cost (TCO) remains one of the most important factors for the widespread introduction and adoption of PEM Fuel Cell technology for mobility of people and goods. The challenge is to prove (long-range) performance and reliability, inducing customer acceptance at competitive costs.
Emission regulations for inner cities or environmental zones create an increasing demand for low- and zero- emission mobility. Fuel Cell systems can contribute essentially to this task, but only if they are economically feasible and cost-competitive.
This topic is not mainly intended to support basic R&D on new Fuel Cell systems and components. Instead, projects should demonstrate, on the basis of state-of-the-art components, that the technology, optimized system design, and advanced manufacturing can be combined to achieve major improvements in TCO for mobile Fuel Cell systems in PC, on-road and off-road CV, busses, rail-bound and maritime applications. This requires innovative materials and fuel cell designs.
Low TCO will require a combination of moderate to low system costs, cost-efficient manufacturing, long duration / slow degradation of the FC system, and moderate operating costs.

SCOPE

The proposal should include several of the following innovation activities:
- Reduce cost-sensitive materials, esp. the catalyser, assess supply chains for low-cost raw and recycled materials, high-temperature PEM solutions with much reduced balance-of-plant cost concepts, energy-efficient stack for minimal operating costs during useful life, cooling concepts with low-cost components.
- An increased Balance of Plant (BoP) net overall efficiency must be obtained: BoP energy consumption below 10% of energy turn-over of the FC assembly – not only at nominal power but also at low and medium power output, reducing OPEX. Low-cost components need to be upscaled from laboratory scale to mass production and in in general manufacture and assembly of Fuel Cell components with minimal cost must be realized.
- Alternative MEA designs and assembly approaches with lower costs and materials and designs optimized for long duration and useful life, thereby reducing TCO are focused as well as cost-efficient coatings to protect the low-cost materials used and corrosion-proof low-cost catalyser support.
- New low-cost, upscaled joining technologies for stack components, esp. half plates, are to be developed as well as an optimized operating strategy for application specific drive cycles with TCO reduction in mind and optimized fuel cell battery hybridization with respect to low CAPEX and OPEX.
- Proposals should encompass best-in-class manufacturing technologies, production processes, equipment and tooling with cost impact on Fuel Cells and their components. Automated assembly, short cycle times, continuous production, lean manufacturing, or additive manufacturing should be considered.
- To achieve cost reductions, the project may also propose and develop industry-wide agreements for structured BoP components and their interfaces and controls.
- Members of the consortium should comprise FC component suppliers and manufacturers (stack, power electronics, control, BoP) and FC system integrators as well as vehicle OEMs and different vehicle users, thereby representing the European FC technology value chain.

TRL at start of the project should be 5-6, and target TRL 7-8 is expected at the end.
Design, model-based tools, and implementation steps for a Circular Economy (re-use, re-purpose, sorting, separation, recycling), an environmental assessment of the project, and a solid base for LCA must be addressed. Safety regulations as EC79/2009 and the EN 62282 series have to be respected.

IMPACT

The impact of the project will be a massively reduced target costs (TCO) of Fuel Cell-powered vehicles, aiming to achieve €0.3/km or lower, an increased efficiency of major FC system components and competitive fuel cell driven power trains manufactured in the EU in high market volumes and share.
It will result in very significant environmental benefits by emission reduction and better air quality through higher proportion of FC powered vehicles, especially in the inner cities. Affordable clean mobility without compromise on exhaust gases will be obtained as well as a sustainable FC design and manufacturing fit for Circular Economy.
The European industry will be strengthened, establishing and stabilizing a Europe-based component and system Fuel Cell production, suppliers' network, and value chain and the industrial development with European lead will result in many jobs.

H4M - Advanced materials for on-board hydrogen storage tanks (including tanks for vehicles and tanks for transportation of hydrogen)

TYPE RIA
RESPONSIBLE WINFRIED KEIPER - BOSCH, ALVISE BIANCHIN - MBN, TINE NÆRLAND - IFE

CHALLENGE

Hydrogen tanks are an essential element and a pre-condition for a large market penetration of Fuel Cell driven vehicles (PC, CV, Bus and other vehicles). Safe, cost-efficient and reliable hydrogen tanks with large H2 capacity, which can provide extended ranges of FC vehicles, are necessary for the rollout of fuel cell mobility on a large scale. Once hydrogen mobility matures, it will offer substantial economic opportunities for Europe. Hydrogen tanks are high-value components and account for a sizeable portion of these opportunities. Today's hydrogen tanks are bulky and difficult to integrate into vehicles, especially in PCs, so the vehicle markets require new concepts of cost-efficient free-form hydrogen storage.
The following challenges are fundamental about hydrogen tanks:
- Cost: the CAPEX of tank + filling devices, valves, and sensors should come down to less than 10 EUR / kWh and the application-specific storage cost should be below 300 EUR/kg H2
- Performance: efficient storage of H2 means a gravimetric hydrogen storage density of > 5,5% and lifetime and durability (filling cycles) in step with FC system specifications (application-dependent)
- Shape: a major challenge is the required flexibility in shape, the spacial degrees of freedom in multi-tank assembly and free form geometry (for PC). This is required for the easy integration of tanks into vehicles, leading to better trade-offs w.r.t. vehicle range.

SCOPE

The proposed project should include new technical solutions for the safe and efficient storage of hydrogen, at affordable cost, for fuel cell vehicles (PC, CV, Bus, off-road vehicles, service trucks, maritime). There are no preconditions w.r.t. the hydrogen storage principle (high-pressure tank with various materials, adsorptive hydrogen storage, cryogenics, others).
The following should fall into the scope of the project:
- as to the requirements: free-form and/or modular storage tanks that can be easily fitted to space-critical vehicle applications targeting CAPEX of tank system < 75 EUR/kWh, target storage cost <400 EUR/kg H2 assuming 100,000 units/year. The storage gravimetric density is to be higher than 6% and operating temperatures between -60 °C and 110 °C. Tank, all valves, and the hydrogen control devices need to have negligible hydrogen leakage rates over lifetime and refill times should not exceed 4 minutes for PC cars. Should also include increased permissible upper temperature during re-filling to 110° for low-cost, energy efficient re-filling processes.
Methods of (model-based) design of H2 fuel tanks need to be developed, covering all requirements and specs, and including the aspects of manufacturing and assembly, as well as disassembly, re-use, and recycling of fuel tanks. „Design for recycling "and for retrieval of valuable materials will be an asset.
- Depending on the storage principle included are advanced functional materials, H2 traps, surface layers and passivation, diffusion barriers (in the case of high-pressure hydrogen tanks), cost- and energy-efficient solutions for cryogenic storage and adsorptive hydrogen storage with energy-efficient charge / discharge procedures
- Additional requirements to the project: technical solutions of the Hydrogen tanks must be fit for mass production, with resilient supply chains of materials. The use of critical materials is discouraged. The projects are expected to build on previous or current national or EU-funded R&D projects in the field, e.g. FCH-01-3.2018. A good understanding of influencing factors of a Life Cycle Assessment is necessary and the highest safety standards are to be respected, e.g. EC79 and UNECE R134 GTR 13. Test activities must be carried out according to standard procedures.
It is expected that TRL at start is 3-4 and TRL at the end is 6

IMPACT

The hydrogen storage project should deliver all the following: a strategy defining a solution for the challenge, high-performing hydrogen storage tanks with novel geometry at appropriate cost, validated prototypes of the technical solution and a strategy defining manufacturability and sustainability of the technical solution. It will strengthen the European design and supply chains for on-board hydrogen storage, developing skills and expertise in Europe and disseminating the know-how within Europe.

H5M - Advanced materials for on-board H2 generation

TYPE: RIA
DRAFT LEADER: EKAIN FERNANDEZ - TECNALIA

CHALLENGE

The current fuel cell based light and heavy-duty vehicles, trains and ships are fed by pure hydrogen. The H2 used in mobility is first produced off-site or onsite by e.g. electrolysis, then compressed up to 105 MPa to be stored in Hydrogen Refuelling Station storage in order to be finally filled and stored in the vehicle's tanks using special materials at 700 bar for light vehicles, at 350 bar for heavy duty vehicles, trains and ships, or liquefied up to -253oC and stored in cryogenic tanks with very high materials requirements. Thus, the compression, liquefaction and storage (onsite and on-board) steps represent a relevant part of the whole hydrogen chain costs. Currently, the compressed hydrogen energy density is less than 40 kg of hydrogen per cubic meter of volume and for the liquefied hydrogen the energy density is less than 70 kg of hydrogen per cubic meter of volume. An increase of the hydrogen energy density of storage is thus required in order to increase the range, reduce the weight and reduce the cost. In order to reduce these costs, on-board hydrogen generation is a promising alternative where alternative fuels would be fed to the vehicles, trains and ships, stored at low pressure or liquefied tanks (using cheap materials) and converted to hydrogen on-board suitable for the application using it in a fuel cell.
The conversion of alternative fuels to pure hydrogen may involve a reaction and a purification step. Currently, this type of conversion is performed onsite, and there are few examples performing this conversion on-board. Due to possible restrictions (weight, space) for on-board implementation, development of high-performance materials and processes must be performed targeting light and heavy-duty vehicles (such as, trucks, ships, etc.).

SCOPE

The proposals should address the following issues for meeting the above challenges:
- Development of the key materials for pure hydrogen generation from alternative fuels and prove their cost effectiveness, manufacturability at larger scale, long-term stability. The following material issues shall be addressed: the catalysts used for the conversion towards pure hydrogen must avoid using nickel (carcinogenic) and must reduce the use of Platinum Group Metals by at least 50%. The hydrogen purification materials should show an enhanced stability to the compounds present in the fuel (acids, bases, contaminants such as sulphur compounds).
The recovery and recycling of the key materials should be addressed; it is a must in case critical raw materials are considered.
- Demonstration of the pure hydrogen generation process at a relevant scale from at least one selected hydrogen carriers. The selected alternative fuel must be easy to handle and competitive from an economical point of view.
- The on-board H2 generation process must be energy-efficient, adaptable to frequent start-ups and shutdowns, sufficiently flexible to respond rapidly to changes in fuel cell demands (stop-and-go driving). A techno-economic assessment of the on-board hydrogen generation system needs to be performed for at least one type of the vehicles, including materials, conversion steps, BoP; and comparison with conventional fossil fuel-based vehicles and newer fuel-cell based vehicles based on compressed or liquefied hydrogen.
Activities should start at TRL 3-4 and achieve TRL 5 at the end of the project.

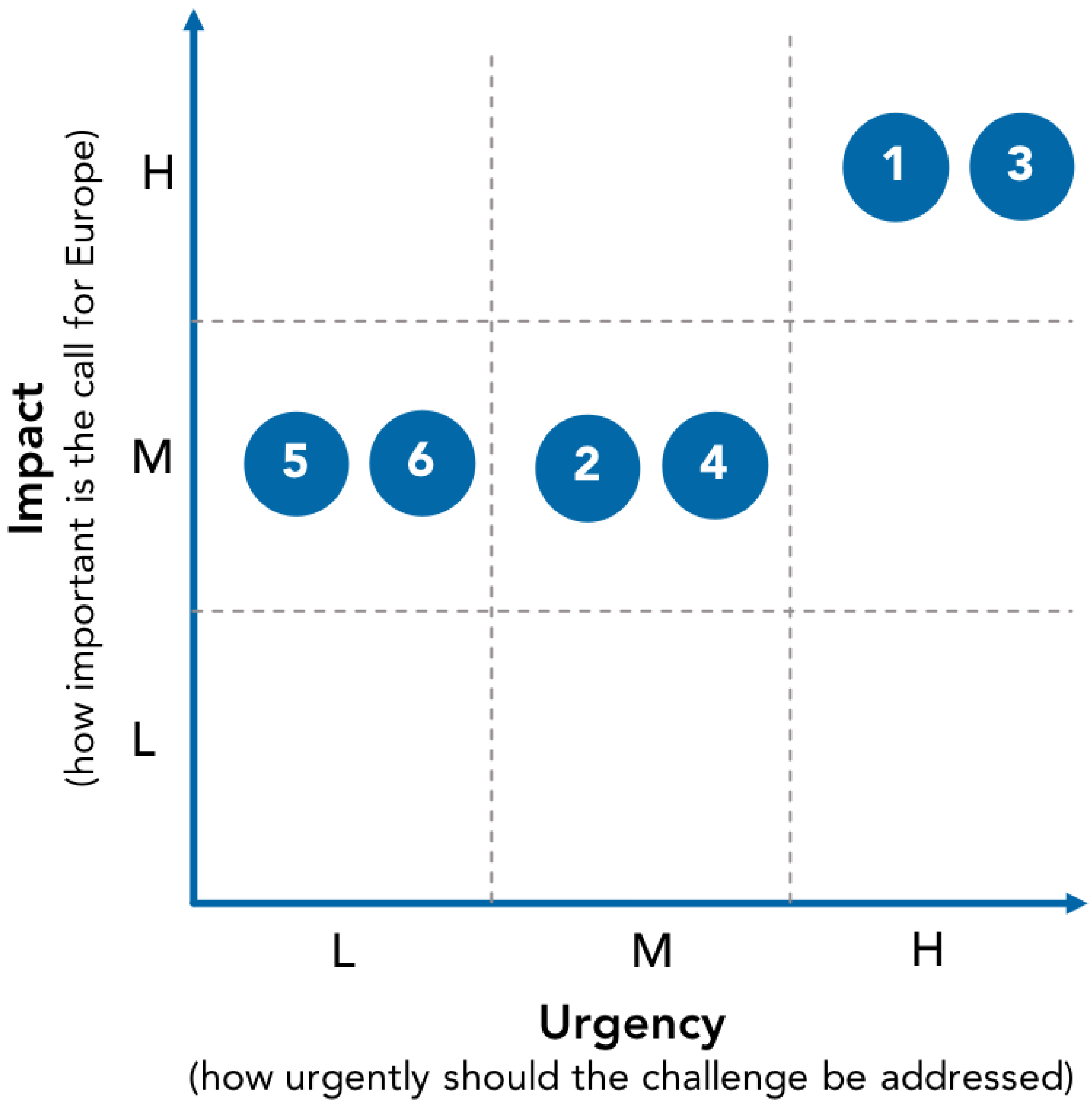
IMPACT

The advanced key materials and conversion steps for the on-board pure hydrogen generation will significantly contribute to the target of hydrogen stored capacity in-light vehicles > 8 kg H2, for heavy duty vehicles > 40 kg of H2, for trains > 220 kg of H2 and for ships > 500 kg of H2. Total energy efficiency for the on-board storage system will be improved to >83 % including hydrogen production, purification and BoP.;
Long-term stability and performance of the key materials and conversion routes will be demonstrated (at least for 5000 h). Hydrogen purity >99.97% will be obtained, ready for feeding proton exchange fuel cells.
The complexity and the CAPEX and OPEX for the hydrogen refuelling stations will be reduced at least by 70%. New technologies and business opportunities will be created for alternative fuel-based vehicles across Europe, especially in the area of materials for conversion to pure hydrogen.

3. Hydrogen for Stationary Applications and Carbon Capture and Utilisation

Call #	Theme	Lead	Contact
1	Advanced materials for PEM electrolysers	Laurent Antoni	laurent.antoni@cea.fr
		Marcel Meeus	Meeus.mar@gmail.com
		John Oakey	j.e.oakey@cranfield.ac.uk
2	Advanced materials for SO electrolysers (incl. co-electrolysis)	Thierry Priem	thierry.priem@cea.fr
		Julie (CEA)	
3	Advanced materials for the generation of clean hydrogen and/or syngas (not through electrolysis)	John Oakey	j.e.oakey@cranfield.ac.uk
		Tine Naerland	Tine.Naerland@ife.no
		Ekain Fernández	ekain.fernandez@tecnalia.com
4	Advanced materials to enable carbon capture and purification (make CO2 ready for utilisation)	John Oakey	j.e.oakey@cranfield.ac.uk
		Tina Naerland	Tine.Naerland@ife.no
		Ekain Fernández	ekain.fernandez@tecnalia.com
5	Advanced materials for electricity generation from H_2 (e.g. SOFC, gas turbines, or combination)	John Oakey	j.e.oakey@cranfield.ac.uk
6	Advanced materials for catalytic conversion of CO_2 into fuels, chemicals, and e-fuels	Laurent Bedel	laurent.bedel@cea.fr
		Ekain Fernández	ekain.fernandez@tecnalia.com

Priorisation matrix



H1S – Advanced materials for PEM electrolysers

TYPE: RIA
DRAFT LEADER: LAURENT ANTONI - CEA, MARCEL MEEUS - SUSTESCO, JOHN OAKEY - EUMAT/CRANFIELD

CHALLENGE

The need for energy storage to balance intermittent and inflexible electricity supply with demand is driving interest in conversion of renewable electricity via PEM electrolysis into a storable gas. Hydrogen produced via electrolysis can result in zero greenhouse gas emissions, depending on the source of the electricity used. Green hydrogen production via electrolysis is being pursued from renewable (wind and PV) energy options. These pathways result in virtually zero greenhouse gas emissions. In times of excess electricity production from wind farms, instead of curtailing the electricity as is commonly done, it is possible to use this excess electricity to produce hydrogen through PEM electrolysis. This green (or decarbonised) hydrogen can be used in a variety of applications such as Power-2-Power, Power-2-Gas, Power-2-Industry, Power-2-Fuels etc. In this scenario, PEM electrolysis is becoming a very promising choice, because of intrinsic load flexibility, efficiency, hydrogen purity and pressure.
Additional research on PEM Electrolysers is needed for overcoming challenges such as reducing the capital cost of the electrolyser unit, the balance of the system and further improving energy efficiency for converting electricity to hydrogen. General purpose is to produce green hydrogen at a price comparable with less ecological Steam Methane Reforming (SMR), provided a low-cost electricity source is available.
The key areas for innovation are related to new advanced materials for catalysts, electrodes and membranes at the cell-level and optimised system components and their methods in design and manufacturing. Design for recycling is also a key objective.

SCOPE

Main innovation activities with a particular focus on Advanced Materials cover following areas:
- The development of new catalyst and materials is needed for lowering the costs and improving performance with lower or no CRM content (Pt, Ir) while maintaining the lifetime.
- Research is to be done to improve materials, components, systems durability, reliability and robustness in order to reduce costs while optimizing production technologies through design optimization.
- Better electrode stability and efficiency is further to be realized. Research on multifunctional components can help address some cost and stability issues.
- Development of substrate, membrane, or bi-polar plates with materials less sensitive to corrosion is more to be pursued as well as cheaper improved transport layers with lower corrosion.
- A reduction of the Titanium content in the bi-polar plates is aimed for. Membranes need to be improved with high yield by addressing permeation and selectivity as well as novel coating techniques for membranes or porous transport layers.
- Work is to be done to optimize MEA/electrolyte by improving ionic conductivity, material stability and reducing cost and to improve MEA designs for higher power density, e.g. through membrane patterning. Operation of low cost, highly efficient PEM electrolyser operating at high pressure is to be shown as well as the design for recycling retrieval of CRM and other valuable materials after the useful life of devices.
- Scaling of PEM electrolysis in multi MW designs is targeted. Proposals are expected to bring technologies from TRL 3 to TRL 6-7.

IMPACT

The research results will lead to a major improvement of PEM electrolysers for cost and performance:
the CRM content (Pt, Ir) (mg/cm2) will be reduced to 0 -0.5 max while enabling lifetime stack or gas path components of a minimum 60.000 hrs, conversion yield will be improved to >80% and CAPEX reduced to < 500 €/kW and OPEX < 2% of the CAPEX / yr.
- Hydrogen produced by optimised PEM electrolysers will contribute to “sector coupling” between the electricity system and industry, buildings and transport, increasing the level of flexibility while facilitating the integration of Renewable Energy into the power system.

H2S - Advanced materials for SO electrolysers (incl. co-electrolysis)

TYPE: RIA
DRAFT LEADER: THIERRY PRIEM – CEA, JULIE - CEA

CHALLENGE

The high-temperature electrochemical systems appear as a promising technology for the efficient and reversible gas to electricity conversion. Indeed, thanks to their high flexibility, the same electrochemical device can be alternatively used in fuel cell mode for electrical power generation and steam electrolysis mode for dihydrogen production (i.e. in Solid Oxide Fuel Cell – SOFC – mode or in Solid Oxide Electrolysis Cell – SOEC – mode). The system is also able to reduce the carbon dioxide to produce a syngas of H2 and CO in the so-called co-electrolysis mode.
This type of high-temperature electrolyser-fuel-cell is constituted by a stack of elementary Solid Oxide Cells (SOCs), each one being composed of a dense electrolyte sandwiched between two porous electrodes. Nowadays, the degradation of SOCs materials when operated in electrolysis and/or co-electrolysis modes is of critical importance for the technology limiting the global lifetime of the system. Indeed, even if standard SOC cell materials and microstructures have been successfully used to reach high electrical efficiency, it has been reported that the degradation is strongly promoted by an operation in electrolysis mode with an accelerated ageing for the H2 and O2 electrode materials. Besides, the impact of thermomechanical and loading cycling in a reversible application is also liable to favour the degradation. In particular, it has been shown that a major part of the degradation rates was due to microstructural evolutions and physic-chemical destabilization of the cell materials associated with a reactivity at the electrode/electrolyte interfaces.
As the material deterioration in operation is associated to thermally activated processes, lowering the operating temperature down to 600-700°C should allow mitigating the degradation in performances. In this case, an electrode microstructural optimization is still necessary in order to maintain the high performances at these 'intermediate' operating temperatures. In that view, the design of specific architectures is still required to improve the durability and reliability all together. In this frame, the challenge is to propose improved and more reliable electrode microstructures and cell architectures in order to enhance the durability, reliability of SOCs when operated on electrolysis, co-electrolysis or reversible modes.

SCOPE

The objective is to propose new concepts of cell electrodes and interfaces architectures, to improve their stability, reliability and flexibility while maintaining their performance for SOEC and rSOC operation at intermediate temperature. Stability includes long-term operation in steady state but also load and thermal cycling. It is not excluded to consider simultaneously materials beyond the state of the art if they have already proved their potential in terms of performance and durability at small scale in SOEC/rSOC operation. Moreover, self-healing strategies associated to reversible operation mode are considered relevant strategies for increasing the durability.
The materials/architectures and processes proposed need in addition to cope with future industrial needs, that is to say they must be industrially scalable for mass production, at low cost, compatible with the size requested for stacks, and they should consider a smart use of raw materials and environmentally friendly routes (aqueous solutions rather than organics, or use of non-toxic (CMR) organics, zero or low amount of wastes in the process or eco-designed manufacturing processes, decrease of the use of energy during the whole process).
Modelling activities as well as microstructural and advanced characterizations should be performed to support the understanding of the link between performance, durability and microstructures.
Proposals are expected to bring technologies to TRL 6-7.

IMPACT

The associated expected impacts are a reduction by at least 25% of the use of toxic organics or materials and stackable cells with a minimum of 100cm2 of active area are an expected output by the end of the project. The project shall guarantee the achievement of the following performances:

- Current densities better than 1 A/cm2 at 1.3 V are expected in SOEC mode at 700°C or below;
- Degradation rate below 1%/1000h in SOEC or rSOC mode, for a level of performance similar as the one achieved with state-of-the-art cells, measured for durations above 2000h at single cell level, and above 1000h in stack environment (700°C or below);
- Stability upon SOFC/SOEC cycling: similar as compared to individual SOFC or SOEC modes;
- Stability upon load cycling: similar as compared to steady state operation;
- Stability upon thermal cycling: 50 cycles performed in a representative stack environment with less than 0.5 mV lost per cycle;
- Finally, a projected cell manufacturing cost similar to standard cells.

H3S - Advanced materials for the generation of clean hydrogen and/or syngas (not through electrolysis)

TYPE RIA
RESPONSIBLE JOHN OAKEY - EUMAT, TINE NAERLAND - IFE, EKAIN FERNANDEZ - TECNALIA

CHALLENGE

Most of the hydrogen is currently produced by steam reforming of natural gas, an abundant fossil fuel. In order to move towards a non-fossil fuel-based hydrogen economy, in addition to hydrogen generated by electrolysis, the conversion of available bio-based sources (such as biomass, biogenic waste, etc.) into pure hydrogen and/or syngas through several chemical routes (e.g. gasification, reforming) is a promising alternative.
For this to become real, high performance, cheap, durable materials are required for cost-effective hydrogen and/or syngas production. The integration of the key material components (i.e. catalysts, membranes and sorbents, depending on the conversion process selected) and process design will be crucial in creating process improvements and flexibility, as well as addressing the global climate challenges.

SCOPE

Innovation activities of the call include the development of advanced catalytic materials, separation membrane materials and chemical routes for clean hydrogen and/or syngas production from bio-based sources. Proposal should focus on new integrated approaches that reduce the energy required and the waste streams from the process. Solutions that are applicable to more than one of the following routes should be preferred:
- Conversion of biomass (e.g. via gasification);
- Conversion of biomethane or biogas coming from landfills or anaerobic digesters as long as it doesn't increase costs;
- Conversion of bio-alcohols;
- Conversion of DME or formic acid;

For technologies producing pure hydrogen, purity of >99.95% should be achieved, service lifetimes of materials and processes proven to exceed 1000 h.
Activities should start at TRL 4 and achieve TRL 5-6 at the end of the project.

IMPACT

The chemical routes for clean hydrogen and/or syngas production from bio-based sources based on advances materials will reduce the dependence from the current fossil fuel resources (mainly natural gas) for heat, power and hydrogen production and at the same time the CO2 emission by >90%.
- Clean hydrogen production costs (CAPEX and OPEX) will be provided comparable to production from current fossil fuel sources.
- For technologies producing hydrogen-rich gaseous fuels from renewable carbon-neutral bio-based sources, it will be able to produce a gas compatible with the requirements of the heat/power generation devices, maintaining efficiency and performance with no increase in operating costs (allowing for support measures for the use of renewable bio-based sources).
- New markets and business opportunities will be created around SMEs and industries holding bio- based sources.

H4S - Advanced materials to enable carbon capture and purification (make CO2 ready for utilisation)

TYPE: IA
DRAFT LEADER: JOHN OAKEY – EUMAT/CRANFIELD, TINE NAERLAND – IFE, EKAIN FERNANDEZ – TECNALIA

CHALLENGE

Carbon capture and utilisation (CCU) is a key element in the EU low-carbon policy, and in particular for carbon- intensive sectors, in order to provide an added value to the CO2 that is emitted intrinsically in their processes. Firstly, cost-effective carbon capture and purification solutions are required. While there is a need to demonstrate current state-of-the-art capture technologies in real market conditions, promising new material solutions have been under development for the next generation carbon capture technologies that are expected to reach the markets beyond 2025. These solutions could dramatically improve the efficiency of CO2 capture but the materials manufacturing processes need further development to provide higher yields while conserving functionality at a lower cost. In addition, the captured CO2 streams obtained should present the required CO2 purity for their appropriate utilisation (conversion to e.g. fuels and chemicals). In this sense, this call is directly linked to the call on “Advanced materials for catalytic conversion of CO2 into fuels and chemicals (excl. methane)- e-fuels” (H6S).

SCOPE

Proposals should benefit on promising material solutions for the next generation CO2 capture and purification technologies for reducing the CO2 emissions of carbon-intensive sectors (such as cement industry, refinery, iron and steel industry, chemical industry, medium to large size power and heat generation, biogas upgrading to biomethane, etc.) and for creating new markets around them by CO2 utilisation. Recently, materials and capture techniques based on e.g. nanostructured hybrid materials, membranes and sorbents have made progress to the extent that their cost and performance competitiveness with respect to the state- of-the-art technologies (at least at demonstration level) should now be tested. The proposed solutions need to prove their cost-effectiveness and provide the required final CO2 purity for further utilisation, and their viability in terms of manufacturability, yield, long-term stability and ease of regeneration. Environmentally benign material solutions should be pursued. Finally, the high efficiency concepts should be techno- economically assessed and developed to the readiness level for pilot manufacturing in order to integrate the advanced materials in existing demonstration projects.
This topic calls for proposals with focus on the manufacturability of advanced materials for CO2 capture and purification, and obtainment of CO2 concentrated streams with the adequate purity for their subsequent utilisation.
Proposals are expected to bring technologies to TRL 6-7. This topic calls for proposals with focus on the manufacturability and competitiveness of advanced materials for CO2 capture and purification.

IMPACT

The performance levels of the proposed materials solution(s) should be in line with those specified in relevant part of the SET-Plan: further optimise capture technologies for expanding their use into carbon-intensive sectors, increased competitiveness of CCU, in particular by reducing the cost of CO2 and purification capture (<50 €/ton), and supplying tuned-purity CO2 streams (>90%) for further utilisation.
- Advanced materials will be integrated in existing and next generation demonstrators and the lifetime of materials and processes must be >1000 h.
- The result will be a strengthened European materials industry in a highly competitive market.

H5S - Advanced materials for hydrogen and hydrogen/natural gas mixtures transport and use

TYPE: RIA
DRAFT LEADER: JOHN OAKEY – EUMAT/CRANFIELD

CHALLENGE

The transport and use of hydrogen (pure or in mixture with natural gas) in the existing infrastructures, plants and appliances probably represent one of the most convenient routes to provide a large end-use market for hydrogen produced by excess electricity from Variable Renewable Sources (VRE's).
Natural gas transport pipelines and distribution grids represent a large and well diffused infrastructure throughout Europe and, at some extent, can be exploited to collect hydrogen from many different sources and bring it to all possible users. Hydrogen concentration, on the other hand, is today limited to very small values, and the feasibility and safety of using this infrastructure up to high hydrogen partial pressures can be challenging, in terms of lifetime, integrity (e.g. address embrittlement phenomena) and leak tightness of usual metal and polymeric materials.
New materials and coatings are probably necessary to provide a safe and convenient transport network for high hydrogen concentration mixtures.
Gas turbines are well established for electricity generation (in simple and combined cycle modes, including CHP), and have been shown to operate successfully with hydrogen or hydrogen-rich gases; in addition, they offer a direct route to mechanical drives for pumps, compressors, and other rotating equipment devices. As such machines are well-established in industry, their conversion to hydrogen or CO2-free, hydrogen-rich gas firing will ensure rapid take-up and minimize the economic impacts on industry. In addition, there has been rapid recent growth in the application of small gas turbines, from a few kW scale for domestic applications to intermediate (few MW) scale for distributed generation and industry-based power generation/mechanical drive uses. The use of gas turbines with lower purity hydrogen/hydrogen-rich gases from bio-based sources offer alow-costroute for decarbonizing European industries. Advanced materials (e.g. hot gas path components using high strength alloys, ceramics and coatings) and manufacturing methods (e.g. additive manufacturing) are required to minimize the cost of conversion to hydrogen firing.
Similar considerations apply to Internal Combustion Engines (ICE's), which are largely used both in natural gas fuelled vehicles and in stationary heat and power generation at small to medium scale. Also, thermal uses of hydrogen or hydrogen rich gases will make it necessary to investigate the behaviour of components and equipment (burners, boilers, heat exchangers etc.) when used with hydrogen gases, in terms of integrity (e.g. embrittlement), durability and safety.

SCOPE

Proposals should benefit on promising material solutions for the next generation CO2 capture and purification technoInnovation activities deal with the development of advanced structural and functional materials, coatings and low-cost manufacturing methods, for gas transport and distribution networks, hydrogen-fired gas turbines and ICE's related power and mechanical drive systems, gas burners and boilers for domestic and industrial applications.
Proposals should cover at least one of the following options:
- Structural and functional materials and coatings for gas transport and distribution networks,
including metal and polymer-based materials;
- Advanced alloys, coatings and ceramics for hydrogen gas turbine applications at all operating scales,
minimizing the use of critical raw materials;

- The application of advanced manufacturing methods, such as additive manufacturing, using new materials formulations for low-cost, customized components. These may be replacements for current components or may be bespoke, new designs improving the functionality of the equipment. Activities should start at TRL 3-4 and achieve TRL 5-6 at the end of the project.

IMPACT

The advanced materials and manufacturing methods will provide a well-established and widely available infrastructure for hydrogen collection and delivery in large amounts, widen the opportunities for hydrogen use in electricity generation and mechanical drives, deliver performance and durability equivalent to current state-of-the-art gas turbine and ICE's materials at lower cost and/or through improved component design (e.g. > 24,000h inspection intervals for large frame gas turbines).
- They will allow the use of CO2-free, hydrogen-rich gases, while being resistant to the damaging effects of gas-borne contaminants which may be present in the fuel or air/oxygen streams used.

H6S - Advanced materials for the catalytic conversion of CO2 into fuels, chemicals, and e-fuels

TYPE: RIA
DRAFT LEADER: EKAIN FERNANDEZ – TECNALIA; LAURENT BEDEL – CEA; SUSCHEM

CHALLENGE

Global warming due to rising levels of greenhouse effect gases, such as CO2, and energy efficiency are the major challenges in the energy field. The efficient CO2 capture technologies combined with advanced technologies for the utilisation of CO2 as new sources of carbon for the production of fuels and chemicals can effectively contribute to reducing the industrial CO2 emissions. Catalytic conversion is a promising route for CO2 utilisation where the captured and purified CO2 (either combined or not with low-carbon hydrogen sources) is transformed into valuable products (e.g. methanol, formic acid) using advanced materials (e.g. catalysts, membranes, etc.).
These new solutions are essential to valorise CO2 from carbon-intensive sectors (such as, cement industry, refinery, iron and steel industry, chemicals, etc.).
This call is directly linked with the previous call on “Advanced materials to enable carbon capture and purification (make CO2 ready for utilisation) (H4S)” where the CO2 is captured and purified to the required purity for its conversion to fuels and chemicals in the solutions proposed in the present call.

SCOPE

Innovation actions in the proposals should deal with the development of novel catalytic materials and routes for the transformation of captured and purified CO2 from carbon-intensive industries into fuels and chemicals that allow for upscaling in the short to medium term. Advances in catalyst development are needed e.g. catalysts based on earth abundant materials, catalysts allowing the direct use of flue gases of varying composition and catalysts that are able to be recovered economically. One or several routes that involve the conversion of CO2 into valuable products (different than CO) should be explored, such as catalytic, photocatalytic, electrochemical or other novel process technologies.
Especially the effects of typical impurities on the performance should be demonstrated.
Activities should start at TRL 3-4 and achieve TRL 5-6 at the end of the project. Projects on CO2 capture will not be considered eligible in this call topic.

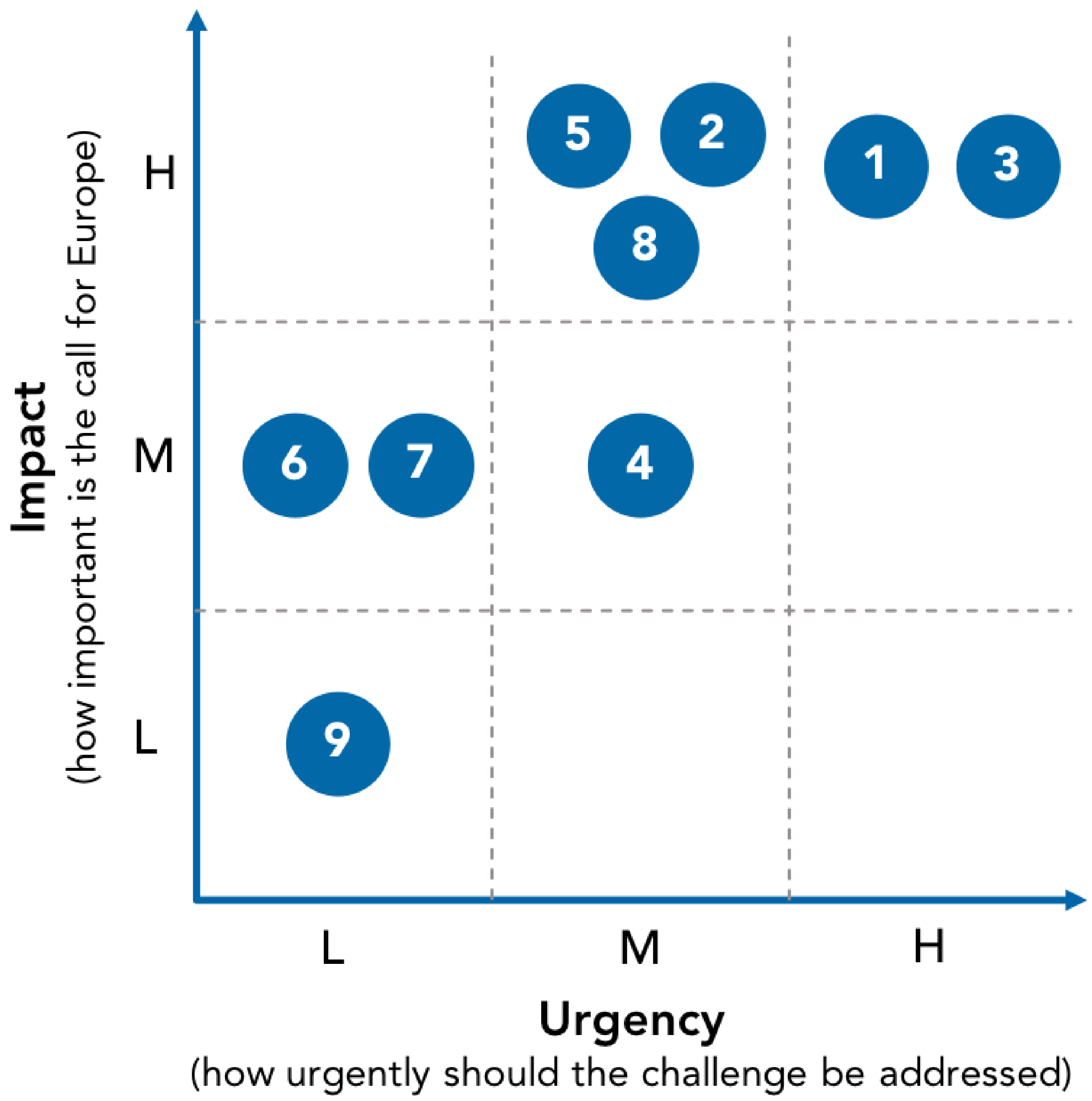
IMPACT

Novel materials for the valorisation of CO2 captured from carbon-intensive industries will enable the production of chemicals, materials and fuels with a lower carbon footprint and create new technologies and business opportunities around across Europe, especially in the area of catalytic materials.
Service lifetimes of materials and processes exceeding 1000 h will be demonstrated by the project. Improved efficiency of more than 10% compared to conventional conversion processes should be obtained.

4. Solar Energy Harvesting

Call #	Theme	Lead	Contact
1	Innovative materials and production processes for high-performance crystalline silicon photovoltaics	Simon Perraud	simon.perraud@cea.fr
		Simon Philipps	simon.philipps@ise.fraunhofer.de
		Ivan Gordon	ivan.gordon@imec.be
2	Innovative materials and production processes for cost-effective and sustainable crystalline silicon photovoltaics	Simon Perraud	simon.perraud@cea.fr
		Ivan Gordon	ivan.gordon@imec.be
3	Materials and processes for silicon-based tandem photovoltaics with perovskite top cell absorbers	Bart Vermang	bart.vermang@uhasselt.be
		Simon Perraud	simon.perraud@cea.fr
		Simon Philipps	simon.philipps@ise.fraunhofer.de
4	Materials and processes for advanced cost-efficient thin-film PV	Bart Vermang	bart.vermang@uhasselt.be
		Simon Perraud	simon.perraud@cea.fr
		Simon Philips	simon.philipps@ise.fraunhofer.de
5	BIPV for opaque elements (incl. c-Si & thin-film)	Alejandro Pérez	aperezr@irec.cat
		Eva Gutiérrez	eva.gutierrez@tekniker.es
		Ana Cruz	acruz@leitat.org
6	Materials and processes for next generation (semi)transparent BIPV	Michael Daenen	michael.daenen@uhasselt.be
		Eva Gutiérrez	eva.gutierrez@tekniker.es
		Michael Demeyere	Michael.Demeyere@eu.agc.com
7	Materials and processes for silicon-based tandem photovoltaics with advanced top cell absorbers	Alejandro Pérez	aperezr@irec.cat
		Frederic Monnaie	Frederic.Monnaie@engie.com
		Michael Demeyere	Michael.Demeyere@eu.agc.com
		Simon Philips	simon.philipps@ise.fraunhofer.de
8	Advanced materials and coatings and innovative designs for durable and more efficient solar energy harvesting (Concentrated Solar Power - CSP)	Amaya Igartua	amaya.igartua@tekniker.es
9	Materials and processes for next generation cost effective MJ cells and arrays for CPV and Space	Gianluca Timò	Gianluca.Timo@rse-web.it

Priorisation matrix



SP1 - Innovative materials and production processes for high-performance crystalline silicon photovoltaics

TYPE: IA
DRAFT LEADER: SIMON PERRAUD – CEA, SIMON PHILIPPS – FRAUNHOFER ISE, IVAN GORDON – IMEC

CHALLENGE

Crystalline silicon remains the mainstream photovoltaic (PV) technology for both grid-centralized and grid- distributed applications, with a market share of more than 90%. Innovation will play a major role to further reduce the levelized cost of energy (LCOE), enabling a massive deployment of PV worldwide in the coming years (with an expected annual global market of several hundreds of GWp). Moreover, in order to accelerate the growth of PV in world regions with challenging climatic conditions, it is necessary to select the most performant PV cell and module technologies for a given location. Decreasing the LCOE will require a strong effort to introduce high-power, high-quality and reliable PV modules combined with lower cost materials and processes. The development and upscaling of advanced approaches, such as high-efficiency cells, high-voltage modules and high bifaciality, will open the door to new premium technologies with potentially high impact on the European PV value chain.

SCOPE

Proposals submitted under this call should address the following:
- Develop and upscale innovative materials and processes for high-efficiency PV cells (e.g., passivated contacts, heterojunction, back contacts) leading to high-power modules. Particular attention should be paid to improving materials and processes for transparent and passivating contacts in order to decrease non-radiative surface/interface recombination and reduce parasitic losses (e.g., passivation of solar cell edges of cut cells, highly transparent and high-mobility cost-effective transparent conductive oxides, damage-free local processing).
- Develop and upscale innovative materials and processes for 100%-bifacial PV cells and modules, and/or for advanced PV module designs adapted to the targeted cell technology (e.g., new interconnection schemes, modules based on 1⁄2 and 1⁄4 cells, light management, high packaging density, modules with metal-free cells, significant improvement of shading behaviour).
- Evaluate PV module technologies in different locations and/or climate conditions, and use modelling, simulation and advanced material characterization to understand degradation and ageing mechanisms and perform failure analysis. When possible, adapt PV module technologies to specific locations in order to improve lifetime and reliability.
Projects are expected to bring the technology from TRL 4 to TRL 6.

IMPACT

Projects should achieve the following impacts:
- Decrease LCOE (0.015-0.04 €/kWh, depending on the irradiance conditions), by increasing cell efficiency (26-27% for industrial-size cells) and module power output (400 W for 60-cell mono-facial modules, 480 W for 60-cell bifacial modules under BiFi20 conditions).
- Increase module lifetime in specific locations by 20%, by selecting the most appropriate PV technologies and/or adapting those technologies.
- Strengthen and develop the PV value chain in Europe (notably materials suppliers, production tool suppliers, cell and module manufacturers), hence creating new jobs and new businesses.
- Contribute to the transition towards a low-carbon economy.
- Improved public perception of technology.

SP2 - Innovative materials and production processes for cost-effective and sustainable crystalline silicon photovoltaics

TYPE: IA
DRAFT LEADER: SIMON PERRAUD – CEA, IVAN GORDON – IMEC

CHALLENGE

The European photovoltaic (PV) value chain needs to introduce new sustainable materials and processes as a mean to face worldwide competition. There is a strong potential to decrease the levelized cost of energy (LCOE) of crystalline silicon technologies by reducing material and manufacturing costs across the whole process flow (from silicon ingot production and wafering up to module fabrication). Furthermore, the reduction of the environmental impact of the whole manufacturing process has to be addressed.

SCOPE

Projects should deal with the reduction of material costs and the improvement of material-resource efficiency, at different stages of the process flow:
-silicon material: simplifying the purification process, improving the ingot crystallization processes (increasing silicon material purity and decreasing dislocation density, in particular in the vicinity of the ingot edges), decreasing the wafer thickness, reducing kerf loss, increasing the recycling rate in wire sawing, or alternatively by developing kerf-less processes (e.g., epi wafers);
-cell metallization materials: decreasing the amount of silver or developing silver-free metallization (e.g., metal plating with or without a seed layer);
-module materials: substituting copper with other materials (e.g. aluminium).
In addition, projects should address the reduction of manufacturing costs by improving manufacturing equipment performances, i.e., throughput (10,000 wafers per hour or more), production yield (in particular in the case of thin wafers), and machine uptime (by predictive maintenance and machine-learning routines following the concept of industry 4.0), and quality control issues and characterization.
Reducing material and manufacturing costs as well as the environmental impact of the manufacturing process should be done while maintaining (and if possible, improving) cell efficiency, module power output and module reliability and durability. Projects are expected to bring the technology from TRL 4-5 to TRL 6-7.

IMPACT

Projects under this call should achieve the following impacts:
-Decrease LCOE (0.015-0.04 €/kWh, depending on the irradiance conditions) by decreasing module cost (0.15 €/Wp).
-Strengthen and develop the PV value chain in Europe (notably materials suppliers, production tool suppliers, cell and module manufacturers).
-Reduce the life-cycle environmental impact of crystalline silicon PV cell and module manufacturing.
-Contribute to the transition towards a low-carbon economy, e.g. local production based on sustainable energy of PV production.
-Demonstrate scalable and competitive manufacturing costs or proposals shall explicitly address performance and cost targets together with relevant key performance indicators.

SP3 - Materials and processes for silicon-based tandem photovoltaics with perovskite top cell absorbers

TYPE: IA (FOCUSED ON SI + PEROVSKITE)
DRAFT LEADER: BART VERMANG – UHASSELT, SIMON PERRAUD – CEA, SIMON PHILIPPS – FRAUNHOFER ISE

CHALLENGE

Crystalline silicon based solar cells as well as some thin film technologies are gradually reaching their theoretical efficiency limit. The most promising approach (at least on the short and medium term) to go beyond this limit are tandem technologies. A very promising option is to combine a perovskite top cell with a crystalline silicon bottom cell. This option has found increasing attention over the last years and impressive efficiencies up to 27.3% (status: September 2018) have been proven in the lab. In addition to further technology improvement, the important next step is to raise this technology to an industrial level.
Therefore, high efficiencies need to be demonstrated on large area. For this, optimized ways of absorber layer fabrication and interface design need to be established. Furthermore, large area modules need to be realized and their durability, quality and reliability demonstrated in the field. Innovative materials, cell and module concepts, as well as the corresponding production equipment need to be developed. Finally, real advantages must be realized in terms of energy yield improvement under real conditions, life-cycle environmental impact and economics compared to the current silicon-only technology.

SCOPE

Main scope of the proposal is the development and upscaling of materials, processes and equipment that are required for perovskite silicon tandem solar cells on an industrial level. These requires addressing the following aspects:
- Develop and upscale innovative materials, processes and equipment for the perovskite/silicon tandem technology
- Demonstrate materials and manufacturing innovations at pilot line level, targeting GW-scale, high-yield throughput and cost-effective industrial production of cells and modules
- Development of cell and module interconnection technologies
- Improve cell and module durability and reliability
- Demonstrate modules in operational environments
- Design for high energy yield and durability at specific locations on module level (adapted band gaps, layer thick nesses, etc.)
- Supporting activities to evaluate proof of concept
- Techno-economic analysis
- Societal techno-economic analysis, especially life-cycle analysis
- Industry value chain analysis

IMPACT

Proposals under this call are expected to achieve the following:
- Achieving efficiency targets above limits of existing individual PV technologies: 28% (in 2-5 years) to 30% (in 2030) with Perovskite on Si tandem solar cells (industrial size cells). This will ensure the continuation of LCOE reduction in the medium term as conventional c-Si technology is reaching its limits.
- Ensuring a product lifetime of Perovskite on Si Photovoltaics beyond 25 years.
- Strengthen and develop the PV value chain in Europe (notably materials suppliers, production tool suppliers, cell and module manufacturers) in this innovative technological area, hence creating new high-tech jobs and new business opportunities.
- Contribute to the transition towards a low-carbon economy.

SP4 – Materials and processes for advanced cost-efficient thin-film PV

TYPE: RIA
DRAFT LEADER: ALEJANDRO PÉREZ RODRÍGUEZ - IREC, EVA GUTIÉRREZ - TEKNIKER, ANA MILENA CRUZ - LEITAT

CHALLENGE

The main challenge of this call is the development of materials and processes for cost-efficient thin film PV technologies, achieving a better exploitation of their potential for reduction of manufacturing costs and allowing for a higher degree of flexibility for the development of competitive solutions better adapted to the different kinds of requirements imposed in grid distributed applications. The main goal is to contribute to a relevant decrease of LCOE to values in the range of ≤ 0.05-0.10 €/kWh, for the consolidation of technologies alternative and complementary to mainstream Si, as required for a mass-deployment of PV solutions with very low environmental impact for the production of electricity, including also the development of advanced thin film tandem device architectures for very high efficiency devices.
Proposals should address one or several of the following challenges:
- Increase large area (≥ 1 m2) single junction module efficiency to > 20% by 2030 (record commercial size CIGS module efficiency 17.5% in 2018)
- Develop cost efficient encapsulate and barrier processes compatible with flexible/light weight device applications (bending diameter ≤ 15 cm, module weight < 2 kg/m2) to improve device reliability (with a targeted lifetime > 35 year by 2030) with costs competitive with main glass/glass encapsulation processes (< 15 €/m2)
- Reduce/replace critical raw materials and toxic components, ensuring processes scalabilityto GW production level and compatible with targeted module costs ≤ 0.20 €/Wp (state of the art cost about 0.5 €/Wp) and reduced greenhouse gases emissions (CO2 emission < 10 g/kWh).
- Develop advanced device architectures based in thin film tandem concepts at cell and medium size module level on glass and/or light weight flexible substrates and compatible with very large (> 30%) efficiencies, demonstrating medium size (≥ 400 cm2) module devices with efficiency ≥ 25%.

SCOPE

Main scope of the proposal is the consolidation of a higher technological flexibility of competitive PV solutions, with the development of advanced cost-efficient sustainable technologies based in processes with very low environmental impact and allowing for a better adaptation to weight, shape, efficiency and customisation ability requirements involved in advanced grid-distributed applications.
Proposals should address one or several of the following innovation activities to address the challenges:
- Decrease environmental impact of production, materials and recycling processes, developing processes with potential lower environmental and climate impact on a life-cycle basis.
- Develop recycling processes to increase material yield and value retention (particularly to retrieve active material).
- Develop and demonstrate new materials, processes and strategies with improved recyclability for very high reliability encapsulation solutions for either rigid or flexible/light weight thin film modules with improved stability.
- Improve cell and module architectures to improve cost efficiency (including concepts as passivation layers, optical management, ultra-thin absorbers, innovative TCOs with improved transparency, electrical conductivity and stability, among others).

- Develop new module interconnection architectures for reducing the cell to module efficiency gap, including hybrid interconnection concepts involving improved laser and mechanical scribing processes with higher lateral resolution and low-cost printing processes of dielectrics and metallic grid interconnects.
- Improve/develop self-cleaning, anti-reflective, anti-soiling surfaces with long durability, including the development of tailor-made soiling and anti-soiling testing protocols for specific locations worldwide and the development of highly functional and durable anti-soiling coatings for PV applications.
- Develop large area, low cost and high throughput deposition processes scalable to GW production levels and compatible with production costs < 0.20 €/Wp.
- Develop innovative quality control and process monitoring methodologies suitable for advanced high throughput process control at different process stages
- Develop wide band gap chalcogenide and/or perovskite-based absorbers minimizing or eliminating critical raw materials with improved (semi)transparent contacts suitable for high efficiency and stable top cells in tandem device structures.

IMPACT

- Proposalssubmittedunderthiscallareexpectedtoachievethefollowingimpacts
- Consolidation of European leadership on Thin Film Technologies
- Increase the competitiveness of thin film PV industrial technologies
- Demonstration of the technological flexibility of advanced thin film technologies for very high efficiency and low-cost PV products very well suited for next generation PV integrated products and systems.
- Contribution to the increase of the level of penetration of PV for the production of electricity in grid distributed applications

SP5 - BIPV for opaque elements (incl. c-Si & thin-film)

TYPE: IA
DRAFT LEADER: MICHAEL DAENEN – UHASSELT, EVA GUTIÉRREZ – TEKNIKER, MICHAEL DEMEYERE – AGC

CHALLENGE

To significantly increase energy production of buildings it is mandatory to meet - zero-energy - building policies. Building integrated photovoltaic (BIPV) elements can play a leading role by using the envelope area of buildings as electrical energy generator. However, BIPV elements still need to overcome technical and economic barriers. Norms have to be developed compatible with building policies. Materials have to be adapted to fulfil building requirements. PV materials have to be adapted to building specific stress factors, i.e. increased temperatures, wind loads, mechanical safety in facades etc. Next to these challenges, architects have specific needs for materials that have to be integrated in facades, roof elements or shading elements. The aspects that need to be investigated are:
- Giving more freedom in design of custom shapes and dimensions for PV modules integrated in custom building elements up to 2 x 4 m2
- Colour ranges of the opaque elements must be adaptable: Foils and/or coatings have to be matchable for opaque, active and non-active parts of the building envelope. Standard RAL colours should be available.
- Visual intrusion has to be limited: No visible contacts or cabling. Cell edges indistinguishable from non-active parts, high colour uniformity or textures.
- Mechanical flexibility (radius) of PV elements: Active material has to be bendable to follow a specified radius (<50 cm) over 90 degrees, allowing flat production and bending afterwards or production on bent surfaces.
- Formability: Materials can withstand lamination process OR can be produced on 3D shaped surfaces. This for example in rooftile applications
- Lightweight modules: for roof replacement, maximum added weight by PV materials should be under 2 kg/m2 or total elements should be under the maximal added weight for roof replacement.
- Reliability and weatherability has to be improved: Lifetime of BIPV elements should be over 40 years for the building element functions and between 30 – 40 years for PV functionality
- Module efficiency has to approach grid centralized efficiencies while maintaining building specific functionality: >20%
- Additional cost for a building element with PV compared to without PV should be in the range of 40 – 80 €/m2 (depending on technology thin film or cSi)
• Reduction of Return of investment time to values < 10 years (short term target) and < 5 years (long term target, by 2030) (current value typically > 20 years)

SCOPE

Proposals are expected to develop a new generation of cost-efficient non-intrusive BIPV elements for both new and renovated buildings. The developed constructive elements will guarantee the building functions (regarding structural properties) while clearly contributing to energy generation. Aesthetic aspects should be considered to replace traditional constructive components as roofs, facades or shading devices. Research efforts should focus on delivering advanced materials active layers (including contacts) and innovative device architectures to maximise electricity generation with high stability and durability to warrant the lifetime of the active-constructive components. Typical service-lifetimes of building envelope components should be reached. For this, materials or innovative material combinations might be proposed. Solutions should include functional surfaces to increase durability and to lower maintenance costs or disturbing reflections. Besides that, these coatings should contribute to tune the visual aspect of the active constructive compo-

nents to minimise the visual intrusion of the PV element. Colour homogeneity should be warranted. Lightweight and flexible materials are considered of special interest.
Customizable module design and size should be proposed including strategies for cost-effective, durable and easy to install electric module interconnection. The interconnection concept should ensure high electricity yield also in case of partial shading.
The proposed solutions need to demonstrate their viability in terms of manufacturability and their economic competitiveness towards upscaling production.
Proposals should address one or several of the following Innovation activities:
- Improve and/or develop self-cleaning anti-reflective surfaces with long durability
- Replace glass plus frame with lightweight materials (front and back end) without lowering their service-lifetime (e.g. polymers. FRP)
- Mechanically flexible encapsulation barriers with high durability. The long-term stability of the diffusion barrier should be assessed.
- Develop hybrid interconnection (or modularization) strategies compatible with customizable module design
- Materials have to be characterized and optimized for CPR (EU construction product regulation) building functions
- Develop materials that can be easily incorporated in building elements
- Develop texture layers/coatings for advanced visual aspects and matchability while maintaining efficiency
- Work on active absorbent material to increase module service-lifetime/durability
- Mitigate shading effects (by e.g. printing bypass dye, using new bypass materials) in a cost-efficient way. Focus on partial shading.
- Thin flexible cells for cold-bended elements
- Back end process cut to size and modularize (p1 p2 p3), compatible substrate materials, while maintaining building standards

IMPACT

Impact
Proposals submitted under this call are expected to achieve the following impacts
- Development of a new generation of cost-efficient non-intrusive BIPV elements, eliminating one of the potential barriers for BIPV.
- Increase of level of penetration of BIPV in both new buildings and renovated buildings, contributing to an increase of the BIPV market to mass production levels
- Development of new production processes allowing a decrease in the gap between PV and building industry
- Contribution to the implementation of policies towards Zero-Energy Buildings
- Contribution to the development of standards and tests for BIPV to convince the market, architects and industry

SP6 - Materials and processes for next generation (semi)transparent BIPV

TYPE: RIA
DRAFT LEADER: ALEJANDRO PÉREZ RODRÍGUEZ - IREC, FRÉDÉRIC VANDERLINDEN - ENGIE, MICHAEL DEMEYERE - AGC

CHALLENGE

Proposals should address one or several of the following challenges for the development of materials and processes for the production of cost-efficient (semi)transparent non-intrusive BIPV elements with improved optical quality:
- Development of materials and processes for BIPV (semi)transparent modules with possibility to control the average visible transmission (AVT) in a wide range of values (depending on weather and environmental requirements of proposed BIPV application) up to a maximum value of 70% by 2030 (current AVT of commercially available BIPV modules up to about 30%)
- Improvement of optical quality of (semi)transparent elements for the development of colour neutral transmission and reflection components with improvement of a* and b* colour space indicators to slightly negative values by 2030
- Development of processes suitable for cost efficient production of (semi)transparent BIPV modules with customised shapes and scalable to large area (> m2) sizes (increase of maximum size from current valueof~1m2 to2x4m2 by2030)
- Decrease of added weight of the BIPV component in relation to the normal static glass component weight down to < 5% by 2030 (current added weight is < 20%)
- Improvement of module efficiency to a value > 10% (>12% at cell level) for 50% AVT devices by 2030 (current value > 5-6% at cell level)
- Improved Energy performance of (semi)transparent BIPV element with a selectivity value (defined as ratio between visible transmission and solar protection g value) of 1.7 (short term target) and 2.0 by 2030 (long term target) (current value 1.4)
- Improvement of BIPV module reliability to a lifetime ≥ 30 year by 2030 (current lifetimes of 10-20 years)
- Reduction of additional costs of BIPV elements to ≤ 50 - 100 €/m2 by 2030, in agreement with strategic targets indicated in the SET plan (https://setis.ec.europa.eu/system/files/integrated_set- plan/declaration_of_intent_pv.pdf)
- Reduction of Return of investment time to values < 10 years (short term target) and < 5 years (long term target, by 2030) (current value typically > 20 years)

SCOPE

Main scope of the proposal is the development of materials and processes that are required for the next generation cost-efficient and non-intrusive BIPV (semi)transparent elements. These are mainly based in the use of glass related substrates, and will involve processes with technological flexibility suitable for the design and production of customised elements and scalable to very large areas.
Proposals should address one or several of the following Innovation activities:
- Develop cost efficient processes and/or adhesion materials for incorporation of PV on (semi)transparent building elements compatible with glass industrial processes and with the production of customized sizes and shapes, scalable to areas > m2.
- Develop cell and module device architectures suitable for (semi)transparent devices with improved (neutral colour) optical quality allowing unhampered transmission of visible light with controlled visible transmission in a wide range of values (up to 70%)
- Develop materials and processes modelling & decision-making tools based on material characterisation with the focus reduction of material, material cost and added weight
- Develop textured layers/coatings for tuning visual aspect (including aesthetics and light transmission)

of BIPV element while maintaining efficiency
- Work on active absorbent and contact layers (transparent contacts) to increase lifetime/durability and aesthetics
- Develop innovative BOS components specifically adapted to (semi)transparent BIPV modules with 10% efficiency, including innovative solutions for junction boxes or pencil-type connectors, cabling and micro/nano inverters with the focus on cost reduction and additional weight
- Develop innovative components and design to improve the thermal control.
Projects are expected to bring the technology from TRL4 to TRL6IMPACT

IMPACT

Proposals submitted under this call are expected to achieve the following impacts
- Development of a new generation of cost-efficient non-intrusive BIPV elements, eliminating one of the potential barriers for BIPV.
- Increase of level of penetration of BIPV in both new buildings and renovated buildings, contributing to an increase of the BIPV market to mass production levels
- Development of new production processes allowing a decrease in the gap between PV and building industry
- Contribution to the implementation of policies towards Zero-Energy Buildings

SP7 - Materials and processes for silicon-based tandem photovoltaics with advanced top cell absorbers

TYPE: RIA (FOR INNOVATION IN THE TOP CELL MATERIALS)
DRAFT LEADER: BART VERMANG – UHASSELT, SIMON PERRAUD – CEA, SIMON PHILIPPS – FRAUNHOFER ISE

CHALLENGE

The dominant crystalline silicon wafer solar cell is converging to its theoretical efficiency limit. As efficiency improvement and cost reduction must proceed for successful power market development, approaches which can meet these needs are highly desirable. The most promising one to further improve efficiencies are multi-junction (mj) technologies with crystalline Si as bottom absorber, and with chalcopyrite, kesterite, lead-free perovskite, III/V semiconductors, or other advanced high-bandgap top absorbers.
For the next generation of silicon based tandem solar cells, materials, cell concepts and processes need to be developed to demonstrate very high power conversion efficiencies, while achieving high durability and low environmental footprint.

SCOPE

Main scope of the proposal is the development of innovative materials and processes that are required for the next generation of crystalline silicon based tandem solar cells. These requires addressing the following aspects:
- Develop stable, high transparency and high efficiency top cells based on tailored high bandgap inorganic thin film absorbers (such as chalcopyrite, kesterite, high throughout III-V, III-V nanowires, Pb-free perovskites etc.) that allow for >30% efficiencies and economically viable production processes.
- Develop monolithic interconnection methods
- Develop advanced characterization and modelling methods / tools dedicated to multi-junction devices and the novel materials to allow for knowledge driven optimization.
- Demonstrate potential for upscaling in a cost-effective way.
- Demonstrate reproducibility, reliability and stability
- Develop sustainable module solutions for multi-junction solar cells
- Design for recyclability and low environmental footprint
- Supporting activities to evaluate proof of concept
- Techno-economic analysis
- Societal techno-economic analysis
- Industry value chain analysis

IMPACT

- Achieving efficiency targets well above the limits of existing individual PV technologies: of 28% (in 2-5 yrs) to 30% (in 2030) with Si based tandem solar cells. This will ensure the continuation of LCOE reduction in the long-term.
- Strengthen and develop the PV value chain in Europe by providing innovative solutions that widen the option space of PV technologies and thus seeding future dynamic developments, hence creating new high-tech jobs and new business opportunities.
- Contribute to the transition towards a low-carbon economy.

SP8 - Advanced materials and coatings and innovative designs for durable and more efficient solar energy harvesting in Concentrated Solar Power (CSP)

TYPE: RIA
DRAFT LEADER: A. IGARTUA, E. ARANZABE, M. SANCHEZ (IK4), D. BOURDON, S. PERRAUD (CEA)

CHALLENGE

Advanced materials and coatings to reduce the LCOE of CSP systems to a new level by 2030, are needed to make solar energy generation competitive. Innovative materials, coatings and multilayers can increase the efficiency and lifetime of solar energy harvesting systems beyond that of the current solar technologies. This will require the application of enhanced materials and multilayer coatings able to work at higher temperature and under more aggressive environments, involving the complete solar system manufacturing chain to enhance lifetime, reducing the operation and maintenance costs.

SCOPE

Address the development of materials and coatings for sustainable CSP (mirrors, selective absorbers, diffusion barrier, heat transfer fluids, supercritical CO2, molten salts, high temperature resistance tube materials, materials for thermal or thermochemical storage ...). A sustainable increase in system durability should be clearly demonstrated including improved lifetime testing methods and protocols, taking into account a downstream end-user perspective. The proposed advanced materials and coatings should ensure resource availability, improving the long-term performance of the systems by extending the working conditions to more demanding environments (higher temperature, ambient air operation, corrosive media, soiling and abrasive conditions, mechanical loads...) is also requested. Bringing new opportunities of valorisation of the solar spectrum thank to smart coatings should be considered. The cost effectiveness, manufacturability, durability, sustainability and recyclability of the innovative technologies compared to the solutions currently available on the market should be quantified.
The high efficiency concepts should be explored for manufacturability, yield, technical, economic viability and developed to readiness for pilot manufacturing (TRL 4-6). Energy carriers could be electricity, heat or both, being possible to consider the levelized cost of heat, especially when integrating with industries that need energy or other alternative energies. Solar fuels are also to be considered as potential outcomes from solar energy.

IMPACT

The Research and Innovation Activities that are being called for are supposed to have a primary and secondary impact on three different levels:
- Technology Level
- Toincrease>20%installationefficiencyinrelationtostateoftheartonelectricalgenerationand storage
- Accelerated test protocols and standards for life-time prediction and durability validation adapted to new
- Economical level
- Decreasing the LCOE of solar energy technologies by increasing reliability of the systems, with the objective to reach a LCOE < 0.05€/kWh by 2030 in European locations
- Significant increased system durability to reach >30 years of performance by 2030 reducing 50% maintenance costs (OPEX).
- Social and environmental level

- To reduce the environmental foot print of the materials and the whole plant lifecycle including water consumption.
- To increase the valorized ratio of the collected solar flux through a mix of energy paths
To place the solar energy in a significant position on roadmap of energy generation technologies
- To contribute to strengthen the European position in the materials for solar energy conversion technologies Increase TRL from 4 to 6.

SP9 - Materials and processes for next generation cost effective MJ cells and arrays for CPV and Space

TYPE: RIA
DRAFT LEADER: G.TIMÒ (RSE)

CHALLENGE

MJ solar cells based on III-V compounds are the baseline components for space and CPV applications. The high concentrating PV technology (HCPV) offers a very low environmental impact, short energy payback time and reduced land area requirements in comparison to Si-based PV. Europe has excelled in the MJ solar cells, with world record efficiencies: however, new cost-effective solutions have to be developed for a more competitive technology.
For the next generation CPV MJ cells, materials, cell concepts and processes need to be developed to demonstrate, besides high conversion efficiencies, cheaper manufacturing processes. The potential for high efficiency four and five junction MJ cells in two or multi terminals configuration, as well as the environmental advantage of increasing the concentration factor, have to be investigated for a successful market deployment. In space photovoltaic applications, Europe has excellent capabilities; however, the new space wave is bringing a lot of challenges. Thus, for the next generation of space solar technologies, innovation is needed more than ever to stay ahead. R&D efforts should address end-of-life performances (W/kg, W/m2, W/m3) and cost. There are many requirements that can be gathered in the two following main domains:
- New very high performance solar array generator
- New cost-effective space commercial solar array
For the first domain, high conversion efficiency cell and array, four and five junction MJ cells solar cells, high radiation resistant, back contact MJ cells, flexible and lightweight cells and modules have to be developed. The second domain requires space proved MJ solar cells that can be manufactured at very low cost & fast, assembly/array concepts compatible with automated/optimized fabrication process, in order to match the big constellations specifications.

SCOPE

Main scope of the proposal is the development of innovative materials and lower cost processes that are required for the next generation of MJ solar cells both for space and terrestrial applications. This requires addressing the following aspects:
1. Development of new depositions and manufacturing technologies for low cost MJ solar cells, among these:
a. development of wafer bonded MJ cells with the utilization of cheaper substrates
b. development of monolithic MJ cells, with fully MOVPE grown MJ structures combining III-V and IV elements and improving the growth rate
c. development of MJ solar cells combining different growth methods (i.e InGaP/InGaAs/InGaNAs/Ge 4J or 5J solar cells with MBE and MOVPE)
d. Development of thin and flexible solar cells and solar cell assembly
2. Advanced characterization and modelling methods/tools dedicated to multi-junction devices and novel materials to allow for knowledge driven optimization.
3. Demonstrate reproducibility and reliability for cells and arrays
4. LCA studies for the evaluation of the environmental footprint
5. Supporting activities to evaluate proof of concept solar cell assemblies and/or modules, new functionalities
6. Techno-economic analysis

IMPACT

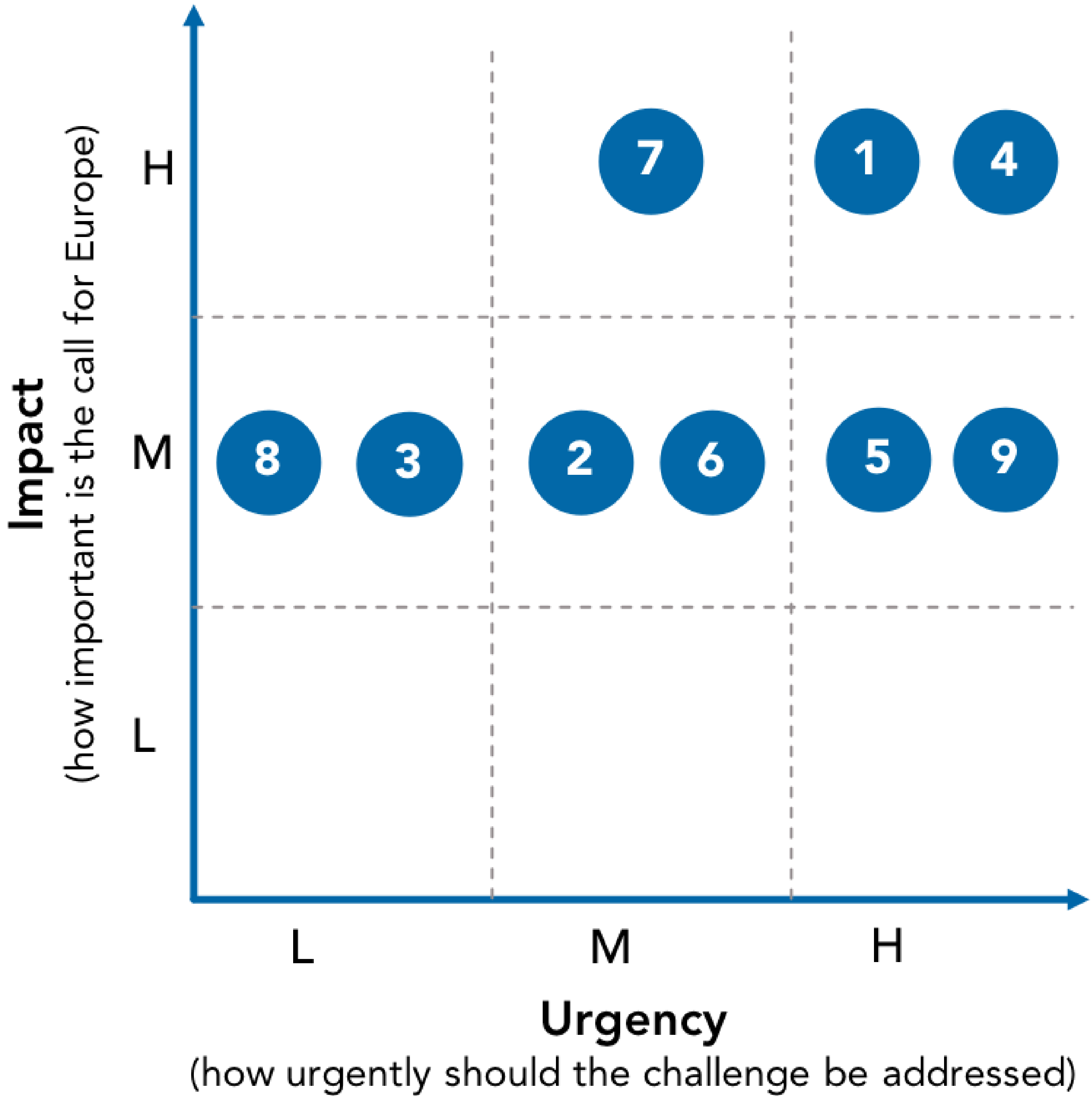
HCPV: Achieving efficiency targets of 46% (in 3-5 years) with cost effective MJ cells at concentration factor of 1000 sun. LCOE reduction. Strengthen and develop the CPV value chain in Europe by providing innovative and cost effective solu-

tions that widen the option space for the CPV technologies and thus seeding future developments, hence creating new high-tech jobs and new business opportunities. Contribute to the transition towards a low-carbon economy.
Space: Achieving efficiency target of 40% (in 3-5 years) BOL, AM0, 25°C and 33% in EOL.
Development of a thin and flexible solar cell and solar cell assembly for the new flexible solar arrays generation. Development of technologies to lower the production cost of solar cells and solar cells assembly, based on III-V compound keeping or improving the EOL behaviour. Development of methods for the qualification of flexible and low cost solar cells and arrays.

5. Wind energy harvesting

Call #	Theme	Lead	Contact
1	Advanced materials to reduce weight of wind turbines	Bent Sørensen	bsqr@dtu.dk
		Jens Kjær Jørgensen -	Jens.K.Jorgensen@sintef.no
		Philippe Thibaux	philippe.thibaux@arcelormittal.com
2	Advanced materials to reduce erosion and corrosion of structural parts of wind turbines	Philippe Thibaux	philippe.thibaux@arcelormittal.com
		Raquel Bayon	Raquel.bayon@tekniker.es
3	Advanced materials to reduce the content of critical raw materials in drivetrain components	Amaya Igartua	amaya.igartua@tekniker.es
		Ibon Ocaña	iocana@ceit.es
4	Advanced materials to improve durability of wind turbine blades	Bent Sørensen	bsqr@dtu.dk
		Jørgensen Jens Kjaer	Jens.K.Jorgensen@sintef.no
		Estibaliz Aranzabe	Estibaliz.aranzabe@tekniker.es
5	Advanced materials to improve durability of wind turbine drivetrains	Marta Hernaiz	marta.hernaiz@tekniker.es
		Raquel Bayon	Raquel.bayon@tekniker.es
6	Advanced materials to improve durability of off-shore wind turbine foundations	Jan Wielant	jan.wielant@engie.com
		Philippe Thibaux	philippe.thibaux@arcelormittal.com
7	Advanced materials to improve durability of cables and mooring of off-shore wind turbines	Raquel Bayon	Raquel.bayon@tekniker.es
		Onintze Matias	
		Elena Rodríguez	
8	Advanced material developments to increase circularity of wind turbines	Miren Blanco	miren.blanco@tekniker.es
		Jose Luis Viviente	joseluis.viviente@tecnalia.com
9	Advanced materials and material solution to increase the circularity of wind turbine drivetrains	Gérard Delette	gerard.delette@cea.fr
		Roland Gauss	roland.gauss@eitrawmaterials.eu
		Julien Frey	julien.frey@eitrawmaterials.eu

Priorisation matrix



W1 - Advanced materials and material solutions to reduce weight of wind turbine blades

TYPE: IA
DRAFT LEADER: BENT F. SØRENSEN - DTU, PHILIPPE THIBAUX -AM, JENS KJÆR JØRGENSEN - SINTEF

CHALLENGE

Wind turbine rotor diameter has been increasing steadily over the last few years, to enable harvesting of higher amounts of energy with a single wind turbine. Modern high production power (> 10 MW) wind turbine blades now can reach lengths of more than 100 meters, totalling diameters of more than 200 meters. Increasing the blade size poses significant challenges due to the high gravitational fatigue loads and blade deflexion, which are difficult to address with the current materials and blade design. To develop higher production power wind turbines, it is necessary to develop new materials and/or multi-material solutions of new or existing material with lower weight and better mechanical performance, which will enable realisation of larger wind turbine blades. Next to the materials, joining methods and concepts to fully utilise existing materials full capacity are also required.

SCOPE

The planned work should demonstrate new materials or material solutions that enable realisation of lighter wind turbine blade structures while still meeting the demands for mechanical performance (stiffness, fatigue life, ...), manufacturability, and cost-effective production. This can be addressed by:
- Enable the use of new materials in wind turbine blades - including materials used in other application but with low maturity for applications in wind turbine blades
- Innovative solutions to use new and/or existing materials in new configuration and combinations including joining technologies
Relevant modelling and testing methodologies suitable for incorporation of the developments in modern engineering and design processes should be addressed, next to the material development activities.
The processing/production and performance of the developed solutions should the demonstrated on a relevant scale from element to structural scale. Furthermore, the need for material and process standardisation should also be considered.
The positive environmental impact as well as the financial viability of the proposed solutions is expected to be demonstrated by means of LCA and LLCA.

IMPACT

Proposals submitted under this call are expected to achieve the following:
- At least 25 % weight reduction for a 10 MW blade with equal or improved stiffness and fatigue life compare with current state of the art
- Equivalent or reduced cost of 15 MW blades compared with scale up of current state of the art
- Improved design, test and modelling method enabling a minimum 30 % reduction in design safety factors.

W2 - Advanced materials to reduce erosion and corrosion of structural parts of (offshore) wind turbines

TYPE: RIA
DRAFT LEADER: PHILIPPE THIBAUX -AM, RAQUEL BAYON - TEKNIKER

CHALLENGE

Installation of wind turbines in Europe is has grown significantly in the last few years, and is expected to continue growing. Out of the new installations, a significant part comes from offshore wind turbines (25% CAGR in the years from 2012 to 2017, compared to 8% for onshore wind turbines [WindEurope, 2017]).
In the case of off-shore wind turbines, the substructures are exposed to harsh ambient conditions. Structure coatings should protect the metallic parts even at the locations where the cathodic protection is potentially ineffective, for example in the splash zone. Coatings are applied today, but it is well known that they can be damaged during transport and installation. In that case, a repair in offshore condition is necessary.
To improve such challenges, it is necessary to develop improved coating material to protect the metal structure of wind turbine blades.

SCOPE

- On steel with less treatment as possible
- Develop of testing protocols to test different previous properties, their efficiency and lifetime (2, 3)
- Develop connector materials and coatings (bolts, welds, screws, etc.) to reduce fatigue and fatigue corrosion mechanisms (2).
- To reduce thickness of protection scheme by increasing the durability of primers and paints
- To increase erosion/abrasion resistance at splash zone by developing to coatings based on ceramic nanoparticles additivation

Given the harsh ambient conditions that wind turbines operate at, there is a need for coatings protecting the offshore metal structure. The development is not limited to the factory applied coating, but also to the coating suitable for repair on-site. In the last case, the influence of the different environmental conditions and parameters (humidity, temperature, chlorine content...) during application should investigated.
For the structure, the coating should have a superior adherence and mechanical resistance to decrease the possible damages during installation and transport. The coating should protect in a more efficient way the splash zone and reduce potential corrosion. For the submerged part of the structure, a topcoat with an antifouling function is recommended to keep the structure in original conditions for longer periods of time. The coating should have an expected durability of more than 30 years. Coatings allowing a reduction of the release of chemicals or metals (e.g. zinc) in seawater should be favoured due to their lower impact on the environment.
It should be considered that the protective systems are also subjected to tribocorrosion conditions, but they are usually selected mainly to protect the structures and components from corrosion. Besides, 45% of the mechanical damage in coatings is mainly generated in transport and erection operations, which can considerably reduce their durability in life service. Therefore, the performance of these coatings should also be addressed in terms of tribocorrosion resistance. The selection of an adequate wear-corrosion resistant coating should also be a key issue in the design of offshore structures and components, to enhance the durability of coated systems against the large deterioration phenomena in marine environments.
Sensors or degradation markers embedded in the coating are also part of the scope, in order to generate an alarm when a loss of property occurs.
The development should prove by a validated methodology that the degradation over time is made realistically and should not only investigate the degradation of the coating but also the consequence for the protected part in realistic conditions. A methodology combining modelling and advanced testing is considered the most suitable.

IMPACT

Proposals submitted under this call are expected to contribute to reducing the operating costs of wind turbines by reducing maintenance costs, which comes from increased durability and efficiency (e.g. through ease of application) of the coatings.
Furthermore, proposals are expected to contribute to reducing the degradation of structures (due to erosion and corrosion) by at least 30%, while maintaining current thickness (or reducing further if possible). This is expected to contribute to reduction of maintenance by 50%. The suggested material combinations are expected to minimize the use of toxic/harmful compounds. Furthermore, suggested solutions should aim at improved circularity, and making use of secondary raw materials when possible, to reduce environmental impact.

W3 - Advanced materials to reduce the content of critical raw materials in drivetrain components

TYPE: RIA
DRAFT LEADER: AMAYA IGARTUA -EUMAT-IK4, IBON OCAÑA -IK4

CHALLENGE

The ambition of the European Union to achieve a secure, competitive and sustainable energy system by 2050 has become a priority. Critical raw materials (CRM) can become a bottleneck to the supply-chain of the different technologies used in the drive train components for wind turbines with implications for materials demand under different scenarios described in the EU Energy Roadmap 2050.
Even if recycling rates for some of these materials could be optimized to the highest possible extent, the overall increasing demand for CRM urges the development of solutions requiring less amount of these CRM and, where possible, their substitution by less critical ones within the next decade.
This specific challenge is covered by the Priority Area “Substitution of raw materials” of the European Innovation Partnership (EIP) on Raw Materials, endorsed by the EIP’s High Level Steering Group on 25 September 2013.

SCOPE

Proposals should deliver innovative, sustainable and cost-effective materials solutions for the substitution of CRM (e.g. heavy rare earth elements used in permanent magnets) in drivetrain components. The potential of new manufacturing technologies (such as AM) to improve/change the architecture of the drivetrain components shall be explored. Along with them, the microstructural optimization of the material through (i) the development of specifically designed powders (geometry, oxygen content, chemical composition) to achieve the desired properties in the final part and/or (ii) the implementation of innovative manufacturing approaches (rapid solidification, fast consolidation, plastic deformation, additive manufacturing, nanoparticiple reinforcement, etc.) for the improvement of magnetic performance should be explored, including the possibility to modify material compositions or new materials for magnets.
In order to ensure the industrial relevance and impact of the research efforts in cost effectiveness, two main approaches might be considered:
- Substituting expensive rare earths (e.g. Nd, Pr, Dy, Tb) by cheaper ones (e.g. La, Ce)
- Minimizing the content of expensive rare earths (e.g. substituting bulk rare earth containing elements by thin layers)

The upscaling and commercial exploitation potential of the proposed solutions compared to state-of-the-art solutions currently available on the market should be convincingly assessed in the proposal.
The development of new techniques for recycling CRM including setting paths for the industrialization the recycling technologies, assessing the viability of using secondary materials, should be addressed.

IMPACT

Proposals submitted under this call are expected to achieve the following impacts:
- Reduce the technological risks related to lack of availability of CRM by reducing their use by 20%
- Improve the efficiency of the electrical machines by 20 % through the combination of more performant designs and the improvement of material characteristics
- Contribute to the increasing the competitiveness of the European industry in this field by demonstrating that the value chain (including manufacturing, use and recycling of drivetrains) for the suggested solutions is covered within Europe
- Increase societal awareness related to the use of CRM (scarcity, implication in third world countries, etc.)
- The reduction of overall Lifecycle environmental assessment of the production process of magnetic materials >20%

W4 - Advanced materials to improve durability of wind turbine blades

TYPE: RIA
DRAFT LEADER: BENT F. SØRENSEN – DTU, JENS KJÆR JØRGENSEN– SINTEF, ESTIBALIZ ARANZABE - TEKNIKER

CHALLENGE

Future wind turbines will have larger rotor diameters, generating larger speed at the tip of the blades. These higher speeds of particles (water droplets, sand, dust, etc.) impact the blades and possibly deteriorate their performance, eventually shortening their effective life. At the same time, the blades need to be as light as possible, which means that the weight of the coatings should remain as low as possible.
Durability of wind turbine blades is a key factor to reduce maintenance cost and increase lifetime of wind turbines. Damage development in composite materials used for wind turbine blades today is still insufficiently understood. This limits development of composite materials that fully utilise the potential of the constituent and possibly results in structural overdesign. The rotor blades of future wind turbines will be even larger than the blades of today and will be made as very large parts that it will not be possible to produce free of manufacturing defects at acceptable cost. In order to avoid great cost associated with repair on blades after manufacturing and in-service, the structures should tolerate larger defects without developing damages i.e. be more damage tolerant and damage predictable.

SCOPE

Activities undertaken by project proposals should aim at developing more durable, damage tolerant and damage predictable structural and coating materials, including structural adhesives, for wind turbine blades. The coating should exhibit a superior resistance towards erosion and also UV resistance, self-cleaning, anti-icing properties, anti-insects, anti-scratch, anti-slime, anti-fouling, resistant to erosion and rain erosion, with reduced friction for the blades, able to reduce aerodynamic noise.
Better understanding and control of damage mechanisms on micro and macroscale also taking into account the blade manufacturing process is required. Advanced modelling, characterisation and testing is expected to be required in the materials development and predictive damage models for the materials, and the necessary test methods for their qualification and model parameter identification should be developed. Modelling can include both materials and component production and processing, modelling of materials (micromechanical models), and modelling of macroscopic performance of design details and substructures. Improved testing methods for characterisation of materials to establish more accurate material laws, and for characterising damage evolution in sub-structure-like "elements", in order to test the accuracy of the model predictions should also be addressed.
There is a large statistical scatter in the actual lifetime of blades and many blades are likely decommissioned with large remaining load capacity. The technology developed should make a better assessment of actual damage state and residual life of older blades possible, thereby enabling safe life-extension of healthy old blades.

IMPACT

Solutions developed within projects submitted under this call are expected to increase the lifetime of wind turbine blades by 30%. Additionally, solutions should aim at reducing the time required for inspection and maintenance of wind turbine blades by 50% compared to existing solutions.
The suggested material combinations are expected to minimize the use of toxic/harmful compounds. Furthermore, suggested solutions should aim at improved circularity, and making use of secondary raw materials when possible, to reduce environmental impact.

W5 - Advanced materials to improve durability of wind turbine drivetrains

TYPE: RIA
DRAFT LEADER: MARTA HERNAIZ – TEKNIKER, RAQUEL BAYON - TEKNIKER

CHALLENGE

Durability of wind turbine drivetrains is limited by the failure modes of the critical components of the drivetrains (e.g. bearings, transmissions). This depends on the materials, surface coatings, finishing, lubricants. Typical failure modes are pitting, scuffing, micro pitting, but also WEC (White Etching Cracks) phenomena and hydrogen embrittlement might appear. Environmental factors like humidity, vibrations, electrical currents, etc. can affect durability. In order to increase the operational time and life of wind turbines, it is crucial to develop materials that address such issues.
Given the increasing number of wind turbines, another challenge that needs to be addressed is the development of renewable lubricants that do not require mining of raw materials. Furthermore, environmentally friendly, non-toxic lubricants will minimize contamination risk in case of accidental oil spills. At the moment bio-based lubricant solutions exist, but suffer from lower lifetime than fossil fuel derived solutions.

SCOPE

Proposals submitted under this call are expected to address one or more of the following issues:
- Development of advanced materials, hardening and surface treatments for bearings and transmission, with improved smoothness, cleanliness in order to increase the lifetime and minimize the typical failure modes for these components (e.g. pitting, scuffing, micro-pitting...)
- Development of drivetrain materials resistant to WEC and hydrogen embrittlement using innovative steel bulk materials, pre-treatments, hydrogen barriers, low friction multilayers or nanostructured wear resistant coatings.
- Development of high performance and low duration renewable lubricants able to reach extreme operating conditions (higher loads and velocities). The developed lubricants should be biodegradable and non-toxic in order to avoid risk for the environment in case of accidental spills.
- Development of technologies to regenerate the lubricant in-situ to extend maintenance downtime.
- Sensors for monitoring the health status of the materials and lubricants (e.g. vibration, noise, acoustic emissions, oil health and oil wear)
- Correlation between the information obtained from the sensors (vibration, noise, lubricants) when testing new materials and lubricant solutions at coupon level, component and system level
- Investigate by means of laboratory simulation the reproducibility of the failure mechanisms to develop ad-hoc testing protocols and specific laboratory test benches to validate experimentally the new materials/lubricants in relatively short time reducing as much as possible the time required prior to introducing a new product in the market.
- Advanced testing for wind components pitch systems, generator slip rings and brushes

IMPACT

Proposals submitted under this topic are expected to:
- Reduce OPEX costs by 20% (due to predictive/proactive maintenance using advanced on-line monitoring technologies and testing protocols)
- Increase 20% the lifetime of the components (by using new materials and surface treatments)
Furthermore, proposals are expected to achieve the following environmental impacts
- To increase the share of use of renewables lubricants in wind by 50%
- Sustain technological leadership by developing highly performant renewable technologies and their

integration in the EU's energy system to make wind energy more competitive
Finally, proposals are expected to achieve a positive societal impact as wind energy systems contribute to employment opportunities, ranging from system design, construction, equipment manufacturing, to the operation and maintenance. In other words, they create opportunities for the employment of people with different skills, from high-qualified jobs (data-analyst and system designers), medium-qualified ones (operation and maintenance) to the low-qualified jobs (construction). Moreover, many of these employment opportunities will be created locally, as large portion of the value chain (distribution, planning, installation, and maintenance) cannot be delocalized, assuring EU jobs.

W6 - Advanced materials to improve durability of off-shore wind turbine foundations

TYPE: RIA
DRAFT LEADER: JAN WIELANT - ENGIE, PHILIPPE THIBAUX - AM

CHALLENGE

Offshore wind turbine foundations are massive structures installed in seawater for a time of 20 to 30 years. They are loaded by large variable forces in harsh conditions. Therefore, they should be designed with the necessary conservatism, while keeping in mind that they should be in the long term decommissioned.
Under the general term "offshore", different environments are actually present depending on the soil and the biological activity of the specific offshore site. Offshore structures need to withstand different environments (atmospheric conditions, water splash, biological activity, soil, ...) which can be quite different from one location to the other. Consequently, the applied material combination for a structure should be robust for the different possible environments where offshore wind turbines are installed.
The base material of the substructure, mainly carbon steel, has a high level of recyclability, has a well- documented (corrosion) fatigue resistance and methods exist to protect them from corrosion, typically by cathodic protection or coating. The parts where the durability is often the lowest is at the level of component connection (e.g. welds and flanges) or when offshore conditions are underestimated or difficult to predict (seawater with cathodic protection). There is therefore a need to have materials and connections with superior durability (e.g. rapid anode consumption due to complex water hydrodynamics) sufficiently robust to operate in diverse offshore conditions.

SCOPE

The objective of this call is to propose and develop materials, surface protections and connections with superior resistance and robustness towards hydrogen embrittlement, fatigue cracking, pitting and microbially induced corrosion in different offshore conditions.
The considered connections include connections continuously localised below seawater level (often welded joints) and also parts in the tidal, splash and atmospheric areas (such as the flange connecting the substructure and the tower). The connections can be made by welding, bolts/screws, friction, glue, etc.
The components in the present scope are plates / tubes of the substructure, flanges, bolts, components of boat landings, ... The main degradation mechanism is a combination of corrosion, fatigue, abrasion, and eventually friction. The degradation mechanism and performance of developed technology should be considered in non-steady conditions and in different environments. The technology should be compatible with:
- cathodic protection (with interruption in the case of impressed current cathodic protection)
- (conventional) coating technologies and coating application methods
- marine biological activity
The research should propose solutions (materials, connectors, coatings) for the different conditions and demonstrate the performance level in standard and non-standard conditions. This should be supported by an understanding of the underlying mechanisms and a quantification (numerical and experimental) of their effects. The synergetic effects of the different degradation mechanism are a key issue to be investigated. To gain a better understanding, it is necessary to reproduce at lab scale the degradation phenomena observed in the field (hydrogen embrittlement, MIC, fatigue) and demonstrate the effectiveness of the newly developed techniques and solutions by these lab tests, compared to a benchmark solution.

IMPACT

Proposals submitted under this call are expected to reduce the cost of energy produced by wind turbines over their entire lifetime, enabled by (i) the reduction in maintenance cost, (ii) an increase of the necessary inspection intervals, and (iii) lifetime extension of the offshore structure. Furthermore, a significant part of offshore wind project costs is related to uncertainties. The uncertainty related to the different degradation mechanisms of the substructure during its life will be reduced, providing a cheaper access to funding for offshore wind projects. The materials should be presented in an embedded solution such that the solution allows a 20% faster installation and an/or extension of the life of the connected parts by 50%.- Reduce OPEX costs by 20% (due to predictive/proactive maintenance using advanced on-line monitoring technologies and testing protocols)

- Increase 20% the lifetime of the components (by using new materials and surface treatments)

Furthermore, proposals are expected to achieve the following environmental impacts

- To increase the share of use of renewables lubricants in wind by 50%
- Sustain technological leadership by developing highly performant renewable technologies and their integration in the EU's energy system to make wind energy more competitive

Finally, proposals are expected to achieve a positive societal impact as wind energy systems contribute to employment opportunities, ranging from system design, construction, equipment manufacturing, to the operation and maintenance. In other words, they create opportunities for the employment of people with different skills, from high-qualified jobs (data-analyst and system designers), medium-qualified ones (operation and maintenance) to the low-qualified jobs (construction). Moreover, many of these employment opportunities will be created locally, as large portion of the value chain (distribution, planning, installation, and maintenance) cannot be delocalized, assuring EU jobs.

W7 – Advanced materials to improve durability of cables and mooring of off-shore wind turbines

TYPE: RIA
DRAFT LEADER: RAQUEL BAYON - TEKNIKER; ONINTZE MATIAS, ELENA RODRÍGUEZ- VMI

CHALLENGE

The most employed mooring lines steel, usually mild or low-alloyed, easily corrodes in marine environment or submerged in seawater. These steels are relatively cost-effective, compared to other more corrosion resistant steels and alloys. High-Strength Low-Alloyed (HSLA) steels, for instance, are widely used due to their high mechanical properties, with yield strengths in the range of 460-960 MPa, and relatively low weight. The use of HSLA steels in offshore applications has increased from less than 10% to over 40% in less than a decade. They are used in the fabrication of mooring lines of semi-submersible structures, among others. The corrosion rate of mooring lines steel in seawater has been measured to be 250 microns per year. In some cases, depending on the location, this corrosion rate may be higher. This high dissolution rate involves elevated costs on maintenance and replacement of damaged surfaces, and what is worse, the risk of premature deterioration of infrastructures or components that can lead to catastrophic failures.
Mooring lines are also subjected to severe wear degradation in the connection between links and accessories, as consequence of the relative movement generated between components by waves, wind, and ocean currents.
In order to avoid or prevent such unpredictable failures, new coatings should be developed to minimize corrosion and wear losses in steel structures. The selection of the protective systems should consider the properties that it should provide the substrate with
The lack of knowledge in this field, along with the unpredictable behaviour of materials under the large amount of degradation phenomena occurring simultaneously in marine environments, lead to a slow progress in the development of offshore technologies. Up to now, the reliability of structures minimizing the risks of catastrophic failures has been achieved by oversized designs of structures and components. This, together with the high in-situ maintenance costs of metallic structures and protective coatings, entail high investments. Furthermore, the insufficient knowledge on real-time materials behaviour at different locations impedes the geographical expansion of offshore technologies, limiting the platforms and structure locations to low depths close to shore.

SCOPE

Offshore structures and their moorings are exposed to harsh environmental conditions, including high loadings coming from storms, waves, wind, ocean currents, marine growth, ice, and so on. Mooring lines can extent for several hundred meters undersea, and the weight of the catenary becomes very heavy. The environmental loads applied on the stationed unit are resisted by this high weight. When the unit is forced to move in one direction, the mooring line stretches in the opposite direction, lifting from the seabed, and adding more weight to the line. The lifting and dropping of the line in the thrash zone can cause wear and abrasion damage in the links, by rubbing them against the sand in the seabed. The sea behaviour results in cyclic loadings inducing the danger of fatigue. The combination of seawater with oxygen can generate considerable material loss of steel by corrosion. Therefore, mooring systems must withstand mechanical and environmental loads maintaining a stable position in the sea, ensuring the functionality of the FPS. Usually, mooring lines are designed for an operational life between 20 and 40 years, but the adversities in seawater environment can span the designed lifetime of these structures several years, resulting in unpredicted failures. Since moorings of fixed structures are not frequently inspected and repaired in dry conditions, periodic inspections are necessary nowadays to monitor the structural integrity of mooring lines.
The main objective of this call is to provide a closer insight into the complex behaviour of active structural steels in seawater. A better understanding at real time of this phenomenon could be used to improve the design of steel structu-

res, improve the integrity and extend the service lifecycle of the components of the mooring lines in extreme conditions, such as those in offshore applications.
This challenge can be achieved through a multidisciplinary approach, by fulfilling the following objectives:
- Evaluation and understanding of the synergies between different degradation phenomena occurring in active materials, i.e. HSLA steels used in mooring line systems.
- Development of enhanced wear-corrosion resistant coatings, able to protect mooring line steels from wear, corrosion, fouling attachments, etc
- Design of a suitable testing procedures to validate advanced materials and innovative protecting solutions, considering the influence of different test parameters, conditions and degradation mechanisms.
- Full scale testing of mooring lines components simulating the service environment.
- Development of advanced designs to evaluate the health of mooring lines components in offshore wind.
- Development of new designs to facilitate offshore operations of mooring lines components in offshore wind.
- Development of adequate modelling technics for the main degradation mechanisms and procedures based on integrity analysis.
- Research, development and characterization of advanced materials, able to withstand greater loads, enable weight reduction and improve properties of offshore wind mooring lines.

IMPACT

The project is expected to advance the knowledge and prove the technological feasibility of new materials, design and surface solutions during the service life of the mooring line. Beside this, the mooring line life will extend the service life based on predictions methods. The proposal should show its contribution towards establishing maintenance cost and demonstrate the performance and durability of the proposed materials/coatings solutions.
The proposed solutions are expected to contribute to strengthening the EU leadership on renewables.
The research in materials, designs, data analysis would allow to offer global solutions for the offshore wind projects at an international level and to diversify its market to cover future demand and to impact in the cost reduction offshore wind energy for the next generation offshore wind turbines, with improved performance in terms of degradation through new materials, designs and coatings.
The correlations between the degradation phenomena and the behaviour-life of mooring components, will allow the design based on real criteria, and test accuracy of predictions of theoretical models.
A synergy of work and knowledge will be achieved projects of high technological level and also to identify new R&D projects to accelerate the innovation cycle from the fundamental discovery for design and development of novel, high-performance, low-cost materials, that allows to reduce the cost of wind energy projects.
Large integrating projects facilitate effective consortia working on multi-disciplinary innovations due to the need for international wind energy R&D cooperation.
Increasing the durability of mooring lines by the use of coatings and advanced materials that will allow to obtain more wind energy, so the operational cost per GW will be reduced during the complete service life. Advanced materials will reduce the thickness of the components and weight between 20-25 %, therefore the cost will reduce as well at least this percentage. The use of less raw materials will reduce the CO2 emissions to the environment.
Increasing durability due to use more efficient materials and predictive models reduce the inspection, maintenance, repair and replace costs between 20 and 40 %. Mooring integrity assessment allow to a more efficient repair or replace operations reducing their environmental impact at 5-10 %.
The cost reduction of offshore wind energy will increase the market in different geographic zones all over the word, increasing the creation of jobs by 15 %.

W8 - Advanced material developments to increase circularity of wind turbine blades

TYPE: IA
DRAFT LEADER: MARCEL MEEUS – SUSTESCO; JENS KJÆR JØRGENSEN – SINTEF

CHALLENGE

The annual wind power capacity installed in Europe in 2016 attained 12.5 GW, bringing the use of FRP composites in blades to 150.000 - 186.000 tonnes, representing a significant economic value for recycling and reuse.
Novel Advanced Materials and sustainable processes dealing with the turbines at the end of their life are needed to maximise the environmental benefits of wind energy through a lifecycle approach. Most of the parts of a wind turbine such as foundation, tower, components of the gear box and generator are already recyclable and treated accordingly. Nevertheless, rotor blades represent a major challenge due to the complexity of their composition and materials used.
Turbine blades consist of different materials: fibre reinforced plastics made of carbon or glass fibres which are held together by synthetic resin, metal, wood, and plastic (used as core material and coating).
Wind turbine blades are the main end-use of GFRP (Glass Fibre Reinforced Polymers) and to a lesser extent of CFRP (Carbon Fibre Reinforced Polymers) and are expected to grow in size (and hence material usage) as turbine developments continue to evolve. The wind energy sector is expected to have a steady growth with a CAGR of 7% over the next five years.
Recycling composites remains a challenge due to several technical and legislative constrains. Currently landfill represents the cheapest option. However more evolved processes exist already such as Solvolysis, a chemical treatment, and Pyrolysis, a thermal recycling process which allows the recovery of fibre, and matrix in the form of ash. Other technologies include Mechanical grinding, Microwave pyrolysis, High voltage pulse fragmentation and Fluidised bed.
Pyrolysis and Solvolysis seem to be the most promising technologies but still have distinct shortcomings.
The praxis shows that the inherent nature of GFRP/CFRP makes it difficult to separate fibres and matrix. Retrieving fibres in their full length is very difficult. Moreover, recycling processes result in significant downgrading of the retrieved material, either due to damage to the fibres, reduction of size, or both. The value chain of blade recycling is quite complex and not fully established yet.
Another challenge is the coordination between the different value chain stakeholders (e.g. chemical companies that design the material, OEMs that design and manufacture the blades, and recyclers) in order to ensure that throughout the whole lifecycle of the application, measures are taken to increase ease of dismantling, separation and recycling, ensuring minimal value decrease of the recycled material.
Novel advanced materials are also needed to overcome the existing wind turbine blades recyclability limitations. As for resins, thermoplastics, although inherently more recyclable, they are relatively new engineering materials in this application and their circular economy practices are in their infancy compared to thermosets.

SCOPE

The objective of the call is to significantly improve the recyclability and correspondingly the circularity of wind blade materials by the use of novel Advanced Materials, new designs and optimized cost-effective recycling processes. The design phase is key when it comes to ensuring and optimising circularity.
Proposals to the call should focus on following Activities:
- Development of new recycling processes and materials allowing a total recovery of resins and fibres with minor loss of value;
- Further improvement of the recyclability of materials by focusing on making resins recyclable and reducing the loss of

quality for recycled fibres. For instance, modifications in the synthesis of thermoset resins can be made to improve their recyclability or by the use of additives (e.g. dispersion of Nano- particles during the material production phase, that can later help in the separation of the material layers);
- Minimising the number of material types used in blades can improve separation of materials and the effectiveness of recycling;
- The design phase is key when it comes to ensuring and optimising circularity
- Materials and technologies/practices, such as self-healing polymers or in-situ repair solutions, to extend the lifetime of wind turbines in an operationally and financially viable way
- "Smart" materials with embedded sensors to enable health monitoring and health forecasting capabilities, aiming at increasing maintenance intervals and overall lifetime

IMPACT

A significant improvement of the circularity of wind turbines should enable a recovery of at least 30% of functional fibres from EoL FRP wind turbine blades that could be re-introduced in fibre-reinforced applications, in wind turbine manufacturing or other high-value applications (and not as filler e.g. in concrete);
By re-using, re-purposing and recycling, decrease the amount of energy required to manufacture (selected parts of) wind turbines by 20% (compared to current practices based on raw materials extraction and processing); Furthermore, demonstrate reduction of the cost of recycling by 40% compared to existing solutions, considering the whole recycling value chain;
The most substantial impacts foreseen are both environmental and economic and are often interlinked. In the first place, circularity, by lowering the global cost of composites, would enable their incorporation in many other fields and applications. Also, due to their long-lasting quality, this would substantially contribute to the reduction of raw material extraction worldwide.
Circular economy has shown to boost local economy, create employment and reinforce the links between different European sectors and companies. This would be replicated in the composites sector with a >15% increase in employment foreseen in the recycling and waste management sector over the next 15 years.

W9 - Advanced materials and material solution to increase the circularity of wind turbine drivetrains

TYPE: RIA
DRAFT LEADER: GÉRARD DELETTE - CEA; ROLAND GAUSS, JULIEN FREY - EIT RAW MATERIALS

CHALLENGE

The main challenge is to reduce significantly the sourcing dependence on non-European Rare Earth Permanents Magnets (REPM) and to mitigate the shortage risk for European industry and end-users. Indeed, because of their reliability and lower maintenance costs, synchronous generators that are using REPM are often preferred to wounded rotor technologies, especially for offshore implementation. These drivetrains require up to 600 kg of permanent magnets per MW and all forecasts indicate that they will take a growing share of the market (12.5 GW of power installed across Europe in 2016), thus resulting in a larger demand for REPM. In the future, the amounts of magnet captured in this kind of wind turbines will hence represent several thousand tons per year of exploitable raw materials source.
From a quality perspective, these magnet modules are generally homogenous in their composition and geometry - a feature that strongly differs fr om other disposals (HDD for instance) - and provides a good prospect for recycling. Still, with RE-prices standing at commodity level, developing a viable economic alternative to disposal requires short recycling routes with high-added value. In that sense, a virtuous loop must preserve most of the magnet properties during dismantling, which would then require minimal remanufacturing of the magnet alloy, and in turn allow the resulting powders to be used for the production of new magnets.

SCOPE

To meet those challenges, the proposals to the call should favour multidisciplinary and interdisciplinary approaches starting from the diagnosis of end-of-life magnets. Depending on the damage state arising from corrosion, heat and cracks, different recycling routes could be pursued; either by reduction of magnets into powders, which opens different routes of valorisation, or by melting of magnets to produce fresh alloys as starting materials for powder metallurgy processes.
Within this frame, activities should support the maturation of existing technologies (from TRL 4 or above towards TRL 6) that are addressing the following items:
- Non-destructive pre- and post-dismantling diagnostic technologies to establish the level of degradation of magnets after long term operation (up to 20-25 years) and, more generally, their effective value for recycling
- Dismantling of magnets while preserving integrity of properties, avoiding contamination or oxidation of rare earth phases (C, O pickup less than 800 ppm).
- Recycling of magnets into powders to re-manufacture sintered magnets with at least 80% of the initial material properties. Besides, re-use plus milling should save up to 20% of the energy needed to manufacture permanent magnets
- After melting, reformulation of NdFeB-powders for innovative process such as additive manufacturing in order to manufacture complex parts for high-added value applications
Lastly, proposals should also take into account the inventory and the forecasted fluxes of end-of-life magnets across Europe.

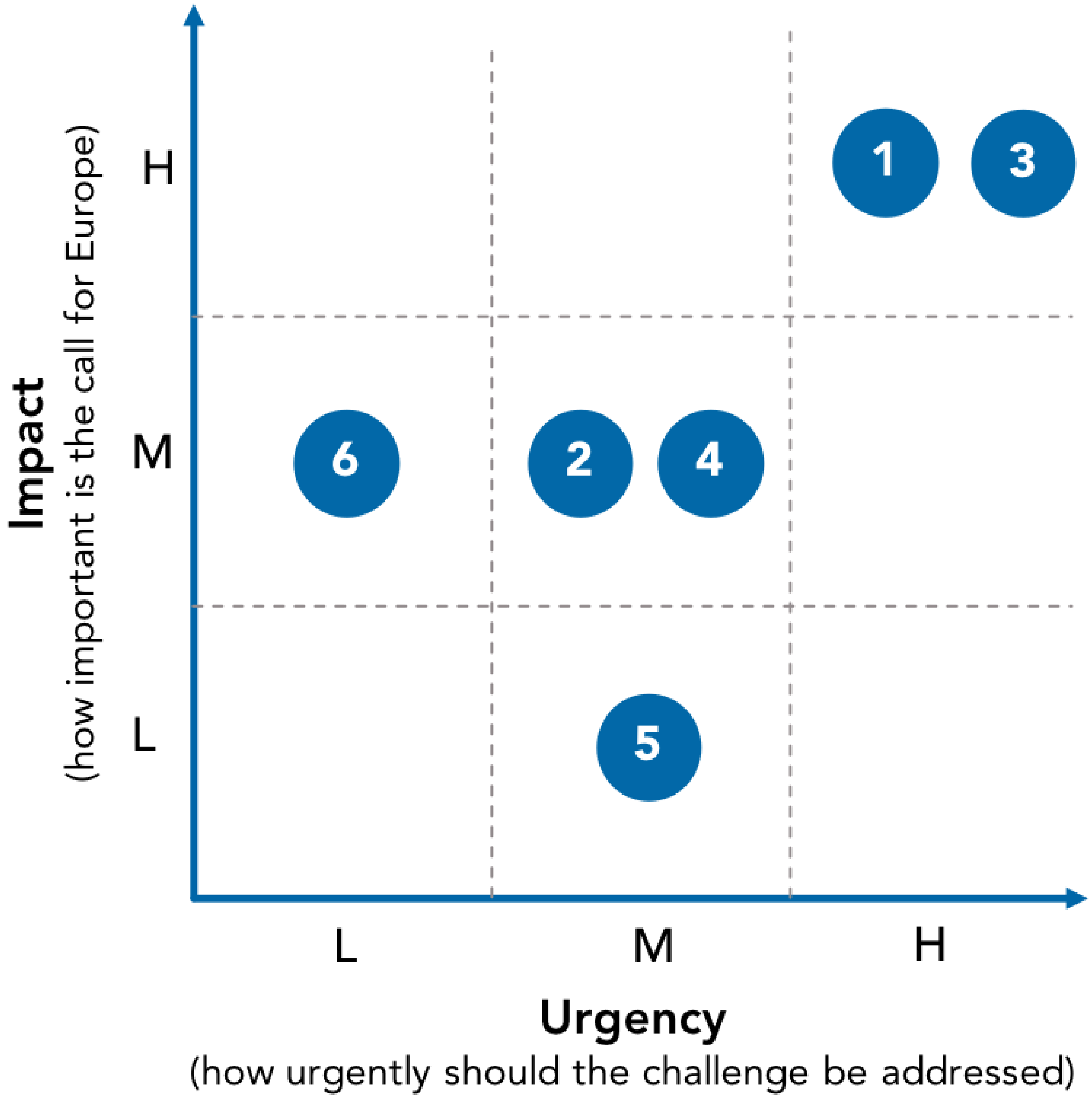
IMPACT

The short-loop circular economy proposed herein provides effective recycling options while satisfying the economic constraints imposed by the REPM sector. With this call, Europe aims to recover at least 70% of REPM materials used in wind turbines to re-manufacture new dense magnets. Noteworthy, this virtuous cycle will not only benefit to the wind energy sector but also support the emergence and/or growth of new European technologies (MRI and sensors), for which the lack of alternatives to source REPM remains a strategic issue and business risk.monstrate reduction of the cost of recycling by 40% compared to existing solutions, considering the whole recycling value chain;

6. Building energy performance

Call #	Theme	Lead	Contact
1	Development of advanced materials for thermal energy storage for district heating and cooling applications	Estibaliz Crespo	ecrespo@cicenergigune.com
		Stefania Doppiu	sdoppiu@cicenergigune.com
		Philippe Thony	philippe.thony@cea.fr
2	Advanced materials for lighting technologies (LEDs)	Jaap Lombaers	jaap.lombaers@tno.nl
		Eric Meulenkamp	eric.meulenkamp@tno.nl
3	Advanced materials for coating on glass	Hugues Wiame	hugues.wiame@eu.agc.com
4	Advanced materials for EC active dynamic glazing	Laurent Dusoulier	Laurent.Dusoulier@eu.agc.com
		VincentLieffrig	vincent.lieffrig@eu.agc.com
5	Advanced materials for insulation of buildings	Philippe Thony	philippe.thony@cea.fr
		Loriane Parisot	loriane.parisot@Dow.com
6	Advanced materials for lighting technologies (OLEDs)	Jaap Lombaers	jaap.lombaers@tno.nl
		Eric Meulenkamp	eric.meulenkamp@tno.nl

Priorisation matrix



BE1 - Development of advanced materials for thermal energy storage for district heating and cooling applications

TYPE: RIA
DRAFT LEADER: ELENA PALOMO, STEFANIA DOPPIU – CIC ENERGIGUNE

CHALLENGE

There is a need to develop new and improved thermal energy storage technologies with better performance, compactness, availability, durability, safety and not least, lower costs.
These new advanced storage technologies must contribute to the cost-effective integration of distributed and variable renewable energy sources and optimized use of waste heat, especially in new generations of district heating and cooling integrating a wide variety of energy systems (industrial waste heat, co-generation, incinerations plants, solar, PV, wind, etc.). About 50% of the final European energy demand is obtained from heat. A more efficient use of heat therefore holds a significant potential to reduced European energy consumption and CO2 emissions.
The innovative challenges are to develop advanced materials for thermal energy storage with significantly improved technical, economic and environmental performances compared to the state of the art.

SCOPE

Proposals should develop advanced materials for thermal energy storage including all of the following elements:
- Thermal energy storage up to 250 °C, to cover a temperature range where there is currently a gap;
- Flexibility to adapt to different storage conditions, with for instance easy tuning of melting points or equilibrium temperatures;
- Characteristics allowing to avoid or to reduce at maximum the heat exchangers, which usually are one of most costly elements of the storage system; with this regard, materials compatible with most commonly used heat transfer fluids (encapsulated materials, coated materials etc.) are expected;
- Improved durability (including deeper understanding of degradation in normal operation conditions) and chemical compatibility (with most commonly used construction materials for vessels and heat exchangers) and thermal conductivity (> 10 W/mK by 2030);
- With respect to overall storage system, the materials should demonstrate the potential to reach volumetric energy density at least two times higher than that of most commonly sensible heat-based technologies and investment cost below 30 €/kWh;
- Proven safety and environmental sustainability (energy for manufacturing, recyclability, 2nd life opportunities and design for manufacturing) of chemistries and processes achieving all the above.

Proposals submitted under this topic should include multidisciplinary approach that includes material science, system engineering and socio-economic knowledge to achieve possible production-readiness by two to three years after the end of the project. The whole storage system performance has therefore to be addressed as well as advanced performance parameters critical to customer acceptance (low cost per unit of energy and power capacity, safety, durability), environmental sustainability (energy-efficient manufacturing, recyclability and 2nd life usage) and aspects for large scale manufacturing solutions.
The proposed solutions should demonstrate technological readiness and safety through prototypes in accordance to the required TRL levels (from TRL3-4 to TRL 5-6)

IMPACT

Research and innovation activities will bring European industry to a stronger position on the world market having the technological knowledge and be prepared for a fast implementation to launch competitive next generation of thermal energy storage solutions in Europe.
Proposed solutions are expected to result in improved volumetric energy densities - above 150 kWh/m3 - as well as decreased costs - below 30€/kWh at system level.

BE2 - Advanced materials for lighting technologies (LEDs)

TYPE: IA
DRAFT LEADER: JAAP LOMBAERS, ERIC MEULENKAMP - TNO

CHALLENGE

LEDs cost of ownership has led to significant adoption of solid-state lighting over the past years. Indeed, all lighting applications in buildings can be addressed with LEDs, and major energy savings can be achieved. State-of-the-art LED lighting reaches about 150 lm/W. However, there is room for further improvement to around 250 lm/W by 2030, which is seen as the practical limit. This increased efficacy will drive down levelized cost of lighting (LCoL, in €/lm) by close to a factor of two. An additional factor of 2-3 in LCoL is sought, in order to realize close to 100% penetration of solid-state lighting by lower upfront investment cost.
Next to core performance and cost, the second challenge is the development of form factors and integration concepts that enable new ways of integrating lighting into the built environment in a more human-centric way. For example, partial replacement of overhead (ceiling) lighting by lighting embedded into office furniture increases the utilization of generated lumens and makes personalized light settings easier to achieve, aiding further lowering of lighting energy consumption. Particular challenges to overcome are very long-life solutions at system level, since buildings and furniture can have economic lifespans of 10-30 years before refurbishment.

SCOPE

The main remaining efficacy loss mechanisms in white LED lighting are well-understood. Significant improvements can be made by development of narrow-band red, green and amber phosphor materials, with Full Width at Half-Maximum smaller than 30nm, leading to higher lumen efficacy and increased spectral purity. These new phosphor materials should have at least today's quantum efficiency of broader-band phosphors, and show <10% efficiency loss and >100,000 hr operational lifetime under high-temperature (high-power LED) operating conditions.
At chip and lamp level, optical losses can be reduced by development of high-refractive index optical materials for improved light extraction and beam shaping. Various materials with optical properties that span a range of transparency, translucency, and nano- or micro-structures and refractive index >1.8 are required, that also show very good stability, i.e. not limit product lifetime, under multi-stress conditions (temperature, photon flux) as they apply in high-power LED packages. Materials and material formulations that integrate optical and other functionality (encapsulation, thermal management) are of particular interest as these can lead to lower overall cost and miniaturization.
Novel form factors and integration, making use of the unique attributes of solid-state lighting, require concepts and materials that connect the objects and elements in buildings with LED light engines in non- traditional ways. Development should target either 'sealed-for-life' approach with up to 30-year reliability, or 'replacement' approach with to-be-standardized interfaces. Critical elements in both approaches are robust and reliable electrical and mechanical connectors that can be integrated seamlessly in e.g. desks and walls. Furthermore, concepts and materials are needed to integrate lighting in novel ways without compromising the performance of either the lamp or the building object. For example, integration of lighting in a facade window puts additional requirements on UV and temperature stability, as well as on mechanical strength of the window system.
A generic aspect that can be integrated into projects related to the themes mentioned above, but which can also be the sole objective of a project, is sustainability. Increased use of recyclable or reusable materials and concomitant LED lamp or luminaire designs, more efficient use of materials, application of materials with smaller environmental footprint, and reduction of the amount of Critical Raw Materials (CRM) are examples of eligible topics.
LED-based solid-state lighting has relatively high maturity. Therefore, this Call considers an Innovation Action the appropriate mechanism. Projects should start at least at TRL4 and end at TRL6-7. Demonstration of the improved materials in market-realistic prototypes must be included in the project, as well as evaluation of the LCoL showing a feasible path to lower cost as quantified.

IMPACT

Proposals should demonstrate a sizeable step towards the quantified targets and demonstrate the material and technology capability to achieve these targets after further (industrial) development to higher maturity level. Successful development of new materials will strengthen the European materials manufacturers in the lighting value chain and create new options with regard to re-use and recycling.
Novel integration of lighting will lead to new value chains that connect the very strong European lighting industry with leading European players in building and office materials, components and equipment. The efficacy and reliability targets will lead to substantial lower energy consumption and CO_2 emissions. Light sources with better light utilization and personalization will contribute to increased well-being of building residents.

BE3 - Advanced materials for coating on glass

TYPE: RIA
DRAFT LEADER: HUGUES WIAME - AGC

CHALLENGE

Europe has a leading position in the components development for façade envelopes. Its leadership is based on the use of high efficient materials among which glass is playing a key role when building (free) energy management together with light comfort are considered. It is indeed demonstrated that the inhabitant wellness is directly correlated to the light level and the light purity inside the building, should it be an office or a private house.
The CO2 emissions of the building may be reduced by increasing the thermal insulation of the windows. In order to keep a comfortable ambiance in rooms largely glazed, it is important to let the light pass inside while reflecting the heating (IR) part of the sun radiation. The thermal insulation as well as the selectivity between the light part and the energetic part of the sun radiation are both obtained thanks to thin multistacks of coating. The most performing stacks integrate a noble metal (most currently Ag) embedded between oxides layers (Zn, Ti, binary alloys, ...). The nature as well as the morphology of the layer on which the noble metal will grow during its deposition phase are crucial for its final properties (electrical conductivity, spectral reflectivity, adherence ...) and the stack performances.
The next generation of glazing for buildings will require new performances that do not exist today and their dynamic control e.g;: the light transmission, the humidity and the CO2 concentration inside the building, the intensity of the bluish light for wellbeing, the control of the electromagnetic radiations (antennas, 5G), etc. These new performances require to combine various functionalities on glass and the development of new materials that are transparent and conductive, transparent and porous, transparent and staying cool, transparent and filtering wavelength, transparent and realising water vapour, ...
Nowadays, the high complexity of the nanoscale material interactions limits the speed development of new stacks. Modellisation has shown an obvious interest but is still not able yet to quickly simulate complex layer compositions with a user-friendly interface. The launch on the market, at a fast pace, of new materials requires a structured methodology.

SCOPE

The market launch of better performing coating for window application requires the following activities:
- Development of transparent multi layers stack by fast atomistic modelling of macroscopic properties. Projects are expected to reduce the computation time of clear relation between properties like electrical conductivity, mechanical stability, adhesion, chemical resistance to alkali,
from several days down to some hours
- Development of in-situ plasma analysis to transpose working conditions from lab-scale devices to industrial large-scale coaters. Particularly, projects are expected to:
- Reduce costs from around 30 k€ per probe in lab-scale down to < 2 k€ for a usage in industrial-scale applications
- Combine probes response
- Have a link between plasma analysis and layer, stack properties
- Deliver a process regulation based on macroscopic properties rather than film thickness (only parameter used today).
- Development of fast prototyping for material/alloys/stacks. Projects are expected to develop an approach to validate in a short period of time (3 months) and more accurately the materials identified by an atomistic modelling pre-screening (e.g. ternary alloys).
- Development of low cost flexible layer deposition technologies (PECVD or other plasma source) on large area (3 m) with high throughput and uniformity < 2% able to deposit alloys, dielectric compound and metallic film material

IMPACT

Proposals are expected to offer new and lower cost materials leading to new product properties transferable in a large range of applications at a high pace including other market segments such as transparent conductive coating for electronic devices. Furthermore, proposals should decrease building energy consumption and / or increase citizens wellness based on new materials produced by clean technologies.
Finally, proposals should contribute to increasing competitiveness of European solutions thanks to lower costs and faster design tools, defining the correct coating for a given macroscopic property avoiding trial and error approach. In turn, this would ensure that European building material producers remain in the frontend position.

BE4 - Advanced materials for EC active dynamic glazing

TYPE: RIA
DRAFT LEADER: LAURENT DUSOULIER, VINCENT LIEFFRIG – AGC

CHALLENGE

Besides the high-end glazings with sputtered coatings (solar control or lowe) that keep constant properties whatever the external climate, Electrochromic (EC) technology allows building occupant to dynamically adjust the natural light level windows or skylights let into the building. In excessive sunny conditions, the EC technology can moderate the light transmission of the glazing as well as, by correlated effect, the energetical part of the sun radiation.
While maintaining a comfortable and healthy interior light ambiance, this dynamic sun radiation management can reduce the energy consumption of the building by up to 20%, hence its CO2 emissions.
EC glazings available on the market show the following typical performances: light transmission range (65 % – 2 %), total solar energy transmittance range (45 – 5 %), the time needed to switch from the extreme state to the other (3-15 min), the colour neutrality in transmission (b* index > 6) and a selling price above 500 €/m^2.

SCOPE

Proposals are expected to contribute to increasing light transmission rate to 75 % - 0.1 %, total solar energy transmittance range to 50 % - 1.3 %, switching time (from one extreme state to the other) of 1 minute, and colour neutrality in transmission b* < 2.
Meeting the targeted performances requires the following activities
- Formulate ionic conductor with higher ions mobility to obtain a fast switching time (< 1 min)
- Develop high conductivity oxides to ensure uniform aesthetics during the switching phase (difference of colour between edges and centres)
- Develop ionic layer and anode/cathode less sensitive to photoreaction to avoid ageing under UV exposure (yellowing, ...)
- Develop materials that selectively filter IR and/or visible ranges and reflect IR instead of absorbing them
- Improve the aesthetics by decreasing blueish aspect at dark state or decrease the light reflection (<15%)
- Develop lower cost components
- Design of new methods for scale-up processes and industrial production lines
- Design of new materials and instrumentations necessary for the technology development

A dynamic glazing with less wiring or even no cabling should have a competitive advantage. Proposed solutions should be easy to use in existing environments, without the need for special frame designs.

IMPACT

Proposals under this call are expected to achieve impact on several domains.
- Regarding cost, reduce the sales price for EC glass to less than €200/m2
- Regarding human well-being, contribute to generating healthier living/working conditions thanks to the management of high quality light
- Contribute to the reduction of CO2 emissions further due to better lighting and energy/heat (IR radiation reflection) management in buildings
- Contribute to the creation of new supply chains including raw material producers, machinery producers, traders, and construction companies. Additionally, proposals should contribute to and consider extension of the applications to new market sectors such as automotive and agriculture.

BE5 - Advanced materials for insulation of buildings

TYPE:
DRAFT LEADER: LORIANE PARISOT – DOW, PHILIPPE THONY – CEA

CHALLENGE

Heating and cooling of residential and industrial buildings account for half of the EU's energy consumption. Given the average EU energy mix, this energy demand significantly contribute to climate change and temperature rises.
An important challenge of the European building sector is to accelerate the renovation rate of the European building stock, so as to limit the GHG emissions. More specifically, the challenges that need to be addressed are:
- Reduce energy and environmental impact at construction/renovation phase
- Reduce energy consumption during building exploitation phase (thermal resistance) by more efficient insulation technologies and practices for walls, windows, and other building elements
- Ease deconstruction phase and enhance recycling or re-use possibilities

In order to achieve wide-spread uptake of such technologies, it is crucial to ensure safety of occupants for any building usage (VOC, fire retardancy), ensure occupant comfort (address secondary effects of efficient insulation, e.g. condensation due to temperature and humidity differences and development of bacteria), and reduce costs.

SCOPE

To address the above challenges, proposals are expected to work on the following domains:
- Reduce the cost of heating and cooling of building envelopes by providing solutions for thermal bridges reduction, and overall increasing performance
- Provide retrofittable solutions for active heat management in buildings such as autonomous dynamic glazing or advanced window film technologies able to actively control the heat transfer through windows.
- Reduce the environmental impact due to material extraction and processing by developing and/or incorporating new materials such as bio-based, materials with long lifetime (considering the lifetime of buildings) and easy to dismantle capabilities, as well as designing for circularity
- Improve safety and comfort of occupants by ensuring that developed solutions are adaptable to provide comfort throughout the year, and throughout the day and night, provide zero risk of fire (propagation and ignition), zero VOC, high air quality
- Ensure ease of on-site installation by developing materials and processes for fast and low cost installation, easy-to-control materials and processes, and limitation of failures in thermal high performing envelope
- Reduce the cost of insulation, maintenance and installation, while if possible developing multi-purpose material to further decrease the cost of building envelope

Proposals could include (but not limited to) aerogels, cement foams, PCMs, vacuum panels, coatings, insulation for windows (e.g. vacuum/PCMs between window glazings), dynamic windows (e.g., electrochromic, thermochromic), window/wall interface, and roof insulation.
If need be, the proposals could have a different scope for residential and commercial applications. Environmental performance should be demonstrated with LCA comparing with existing state-of-the-art solutions, while similarly cost efficiency (which contributes to higher market adoption) should be demonstrated by means of LCA.

IMPACT

Proposals are expected to achieve the following impacts:
- Reduce environmental impact, especially carbon content of building stocks and GHG emission (>30% improvement by 2030)
- Reduce the total energy used for building heating and cooling by X%

BE6 - Advanced materials for lighting technologies (OLEDs)

TYPE: RIA
DRAFT LEADER: JAAP LOMBAERS – TNO, ERIC MEULENKAMP – TNO

CHALLENGE

OLED lighting bears great promise for human-centric lighting. Because of its relatively low surface brightness, it is especially suited to lighting applications in the immediate surrounding of people, often with direct line of sight into the light source, where design aspects also play a major role. However, market uptake is limited by cost (€/lm) and performance (lifetime, efficacy). The efficacy of white OLEDs today is around 60-80 lm/W. A target of 180 lm/W by 2030 should be achievable, but will require great strides to overcome several important loss paths. Lifetime depends strongly on brightness and currently ranges from approximately 10,000 to 50,000 hr. An operational lifetime of >100,000 hr at maximum brightness is desired, together with 20- to 30-year shelf lifetime. Cost per lumen should go down by a factor >20x to be close to cost of medium- to high-end LED solutions at system level. This is particularly challenging since OLEDs are an area source and the lumen output per surface area cannot be increased significantly due to the proximity of the lamp to people.
The second challenge is the development of robust materials and technologies for integration of OLED lamps into luminaires and into building and office elements. Since OLEDs will be ultra-thin and flexible and be located in places where people can often touch or handle the light source, many new materials and integration concepts will be required to enable reliable products and practical integration of OLEDs in the everyday building environment.

SCOPE

Efficient, long-lifetime blue light emission continues to be one of the core OLED challenges. Today's commercial materials are singlet emitters with intrinsic <25% quantum efficiency (QE). Emitter systems with >90% internal QE are required, based on TADF- or triplet emitters. Secondly, narrow-band red emitters are looked for, with Full Width at Half-Maximum <30nm, to maximize the lumen efficacy. The biggest single loss mechanism in OLEDs is poor light extraction. Typical extraction efficiency is below 50%. Cost-effective light extraction materials that are compatible with (low-temperature) flexible substrates are essential to bring OLED efficacy >120 lm/W. The challenge is exacerbated by relatively strong light absorption in standard stacked (tandem) OLED lighting cells. Materials and OLED designs leading to >70% extraction efficiency (external QE/internal QE >75%) can bring a breakthrough on this topic.
To bring out the unique design and integration features heavily relies on the development of ultra-thin, flexible lamps with thickness <0.2-0.3 mm. A key challenge in this respect is a flexible, robust, encapsulation material (stack) that serves as water and oxygen barrier. Projects should pay particular attention to cost, which should not exceed 1 €/m2 at commercial scale. The second major design aspect is transparency. Technologies and materials are required that can deliver >70% transparency, with no haze, without compromising lifetime or uniformity. Light extraction efficiency should be >50%.
Making use of the unique attributes of OLED lighting requires concepts and materials that connect the objects and elements in buildings with OLED light engines in non-traditional ways. Development should target either ‘sealed-for-life' approach with up to 30-year reliability, or ‘replacement' approach with to-be-standardized interfaces. Critical elements in both approaches are robust and reliable electrical and mechanical connectors or mounting that can be integrated seamlessly in e.g. desks and walls. Furthermore, concepts and materials are needed to integrate lighting in novel ways without compromising the performance of either the lamp or the building object. For example, integration of lighting in a facade window puts additional requirements on UV and temperature stability, as well as on mechanical strength of the window system.
A generic aspect that can be integrated into projects related to the themes mentioned above, but which can also be the

sole objective of a project, is sustainability. Increased use of recyclable or reusable materials and concomitant OLED lamp or luminaire designs, more efficient use of materials, application of materials with smaller environmental footprint, and reduction of the amount of Critical Raw Materials (CRM) are examples of eligible topics.
OLED-based solid-state lighting has not yet reached high maturity. Therefore, this Call considers a Research Innovation Action the appropriate mechanism. Projects should start at least at TRL3 and end at TRL5-6. Demonstration of the improved materials in market-realistic prototypes must be included in the project, as well as evaluation of the LCoL showing a feasible path to lower cost as quantified.

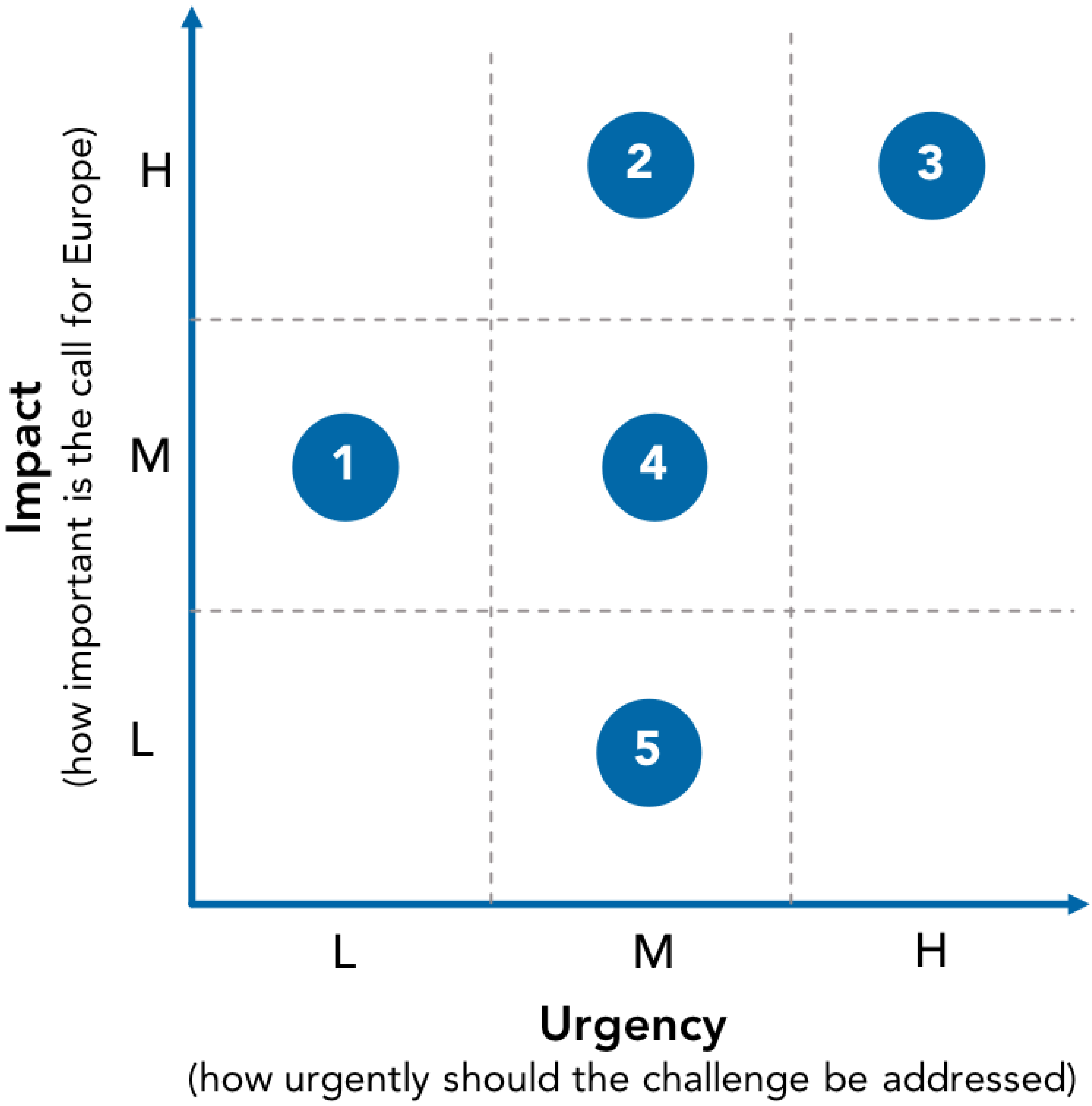
IMPACT

Proposals should demonstrate a sizeable step towards the quantified targets and demonstrate the material and technology capability to achieve these targets after further development and optimization. Successful development of new materials will sustain the leading position that European OLED materials manufacturers have in various materials classes and create new options with regard to re-use and recycling. Important side benefits can be expected towards the very large OLED display industry.
Novel integration of lighting will lead to new value chains that connect the very strong European lighting industry with leading European players in building and office materials, components and equipment. The efficacy and reliability targets will lead to substantial lower energy consumption and CO2 emissions. Light sources with better light utilization and personalization will contribute to increased well-being of building residents.

7. Lightweight technologies

Call #	Theme	Lead	Contact
1	Develop and/or upscale resource (energy, consumables) and cost efficient processing and manufacturing technologies	Dag Mortensen	dag.mortensen@ife.no
2	Develop materials with inherent properties, and efficient recycling technologies, to increase the quality (in terms of properties) and quantity of materials retrieved from recycling	Knut Marthinsen	knut.marthinsen@ntnu.no
3	Develop lightweight materials with improved performance, improved manufacturability, and substitute hazardous and scarce raw materials with safer and more abundant ones	Ana Fernandez	afernandez@azterlan.es
		Amaya Igartua	amaya.igartua@tekniker.es
		Otto Lunder	Otto.R.Lunder@sintef.no
4	Develop technologies (materials, processing, joining) to enable multimaterials and multifunctionality	Thilo Bein	thilo.bein@lbf.fraunhofer.de
5	Develop the tools and know-how necessary to gain a better understanding of the cradle-to-cradle performance (environmental, mechanical properties, cost, social) of the materials		

Priorisation matrix



LT1 - Develop and/or upscale resource (energy, consumables) and cost efficient processing and manufacturing technologies

TYPE:
DRAFT LEADER: DAG MORTENSEN – IFE

CHALLENGE

Lightweight technologies are today available for many applications, but in order for these technologies to have a real impact on the future energy and material use in the transport sector the cost of the new materials and components has to be lowered. With lowered costs the lightweight solutions will enter the automotive mass market to a larger degree resulting in significant energy savings in the future fleet of vehicles. The processing of new/improved lightweight materials has to be done efficiently (lower cycle times, scrap rates, and energy consumption) and therefore existing manufacturing will need to be adapted, or new ones will have to be developed. The new technologies that are developed must have the full life cycle of the materials/components in focus. It is the combined effects of materials production, manufacturing, usage and recycling over several generations of the materials that will be focused.

SCOPE

The total energy and material consumption to produce a final component in a transport vehicle are dependent on several process steps. In order to reach significant savings, the full value chain has to be addressed. Starting from the raw materials improved furnace and moulding technologies or novel process technologies for producing the materials have to be developed. The new technologies will be based on better understanding of the physical and chemical processes involved by advanced monitoring and modelling through the use of digital twins. Large amounts of energy in the further processing of the materials are related to the change of state of the material (gas, liquid, solid) as well as the mechanical forming processes, this has to be done as efficiently as possible by improving near-net shape technologies and thereby reducing scrap and energy consumption in the forming of the components. Further cost savings are possible by the introduction of hybrid manufacturing technologies utilizing the combination of new technologies like additive manufacturing combined with established production technologies. Upscaling of new technologies from lab to pilot scale will be supported. Overall this call seeks also to enhance cooperation and knowledge transfer through the value chains which is necessary to gain the ambitious goals.

IMPACT

Successful projects under this call are expected to achieve the following impact:
Contribute to reducing the complete life-cycle emissions for lightweight solutions through reduced energy consumption in the production
Achieve a cost of lightweighting of €2/kg saved or lower
Contribute to reducing the total cost of ownership
Simultaneous production of hybrid structural and powertrain components combining strength and ductility
Contribute to increasing use of lightweight solutions in at least 3 different sectors
Reduce production scrap by 30%
Facilitate recycling of at leas 30% of the EoL component mass to produce high quality materials for transport applications.

LT2 - Develop materials with inherent properties, and efficient recycling technologies, to increase the quality (in terms of properties) and quantity of materials retrieved from recycling

TYPE:
DRAFT LEADER: KNUT MARTHINSEN - NTNU

CHALLENGE

Increased use of lightweight materials like aluminium, high strength steels and FRP, in the transport sector have significant potential to provide low carbon mobility solutions and to decouple growth in transport demand from an increase in CO2 emissions. The share of such materials in transport vehicles been increasing, and with that, the need for making sure that there is a viable and sustainable scenario for their End-of-Life treatment.
In order to increase sustainability potential of such components, it is important to develop technologies and practices that can be employed throughout the whole lifecycle, addressing various circularity priorities. From more durable materials that last longer, efficient repair and re-manufacturing solutions, designs that facilitate second life use and ease of sorting recycling, to materials with inherent recycling properties, to further improvement of recycling technologies.

SCOPE

An important factor to strongly promote more recycling is to move from a material-centric to a product-centric approach, in an End of Life perspective that facilitates maximum re-use and re-cycling. In order to achieve this, proposals are expected to address at least three of the following points:
Develop materials with inherent properties that facilitate separation, sorting and recycling
Within this focus area, work is mainly expected on improving the material's inherent sorting, separation and recycling capabilities, paired with the necessary processing technologies if necessary. Main activities expected are:
Develop materials that facilitate adequate identification in sorting processes, e.g. by modification of the material itself or through the introduction of markers into the material
Develop materials that facilitate an adequate separation of its constituents (e.g. fibres and resin in reinforced plastics)
Improve the inherent properties of recycled materials that facilitate their use in transport applications or facilitate recycling by minor separation operations
Develop improved materials which degrade less during recycling processes
Reduce the diversity of material compositions (e.g. metal alloys or polymer blends) in order to facilitate sustainable and scalable recycling processes
Develop technologies and practices that facilitate separation and recycling of multi-material products and components
Develop design approaches and/or new component designs that facilitate separation of multi-material products
Develop new joining technologies that facilitate material separation, such as reversible adhesives.
Develop new "recycle friendly" metal alloys
Develop new metal alloys based on recycled material sources that employ compensational metallurgy (i.e. taking advantage of certain impurities of secondary material to cancel/compensate the detrimental effects of other impurities that are introduced by recycling).
Develop new aluminium alloys produced directly from recycled metal
Develop new more scrap tolerant alloys
Develop new or improved sorting, separation and recycling processes
Develop automated dismantling processes for multi-material products and components.
Develop cost efficient and sustainable recycling processes for the recovery of various reinforced plastics, avoiding downgrading of the retrieved materials.
Simplified and cost-effective re-melting process of metals and technologies to facilitate separation of undesired elements.
Develop improved recycling processes that reduce the need for sorting and/or pre-processing or further develop promising sorting and separation technologies
Advance on recyclability/compatibility modelling for EoL products

Develop harmonised standards and certification for recycled materials and re-usable components
Comprehensive and detailed documentation of the properties of recycled materials and reusable components.
Develop solutions for postponing the End-of-Life
Improve understanding of failure mechanisms of components and products based on recycled materials (e.g. fatigue, wear, corrosion).
Develop efficient repair and re-manufacturing solutions (including in-situ), e.g. by employing additive manufacturing techniques.
Develop modular product design to facilitate re-use.
Develop surface treatments and/or cladding that enhance the durability of recycled materials without sacrificing recyclability.

IMPACT

Successful projects under this call are expected to achieve the following impact:
Contribute to reducing the energy consumption of a vehicle by >15% (for a lightweighting of ~15%) at a cost of lightweighting of €2/kg saved or lower
Contribute to increasing recycling of material from the targeted sectors by at least 30%
Decrease the overall energy consumption during the EoL phase (material collection, sorting, separation, recycling, ..., post-processing) by at least 20%
Contribute to reducing the total cost of ownership Contribute to increasing the potential of multi-material components

LT3 - Develop lightweight materials with improved performance, improved manufacturability, and substitute hazardous and scarce raw materials with safer and more abundant ones

TYPE:
DRAFT LEADER: ANA FERNANDEZ - IK4-AZTERLAN, AMAYA IGARTUA, IK4-TEKNIKER, OTTO LUNDER, SINTEF

CHALLENGE

Lightweight technologies are today available for many applications, but in order for these technologies to have a real impact on the future energy and material use in the transport sector the cost of the new materials and components has to be lowered. With lowered costs the lightweight solutions will enter the automotive mass market to a larger degree resulting in significant energy savings in the future fleet of vehicles. The processing of new/improved lightweight materials has to be done efficiently (lower cycle times, scrap rates, and energy consumption) and therefore existing manufacturing will need to be adapted, or new ones will have to be developed. The new technologies that are developed must have the full life cycle of the materials/components in focus. It is the combined effects of materials production, manufacturing, usage and recycling over several generations of the materials that will be focused.

SCOPE

Proposals are expected to support the wider adoption of lightweight materials primarily in the transportation sectors (but as an extend to other sectors as well) by addressing the following aspects:
Develop leaner and cheaper lightweight materials
Lightweight materials have an extra cost in comparison to conventional (heavy) materials which hinders their spreading in wider transport applications. The reduction of the content of certain expensive or critical alloying elements/additives or their substitution by alternative lower price chemical elements, and the use of recycled materials will facilitate the introduction of these lightweight solutions in transport and energy applications. In addition, leaner metallic alloys, polymers or fibre reinforced materials with simplified manufacturing processing and/or waste reduction capabilities will enhanced productivity. To find suitable replacements, the analysis of the performance of the new light materials should be assessed.
Improve fatigue performance of structural parts
The fatigue performance of lightweight structural parts is the master combination of an optimized design, chemical composition of the material and an advanced manufacturing processes (forming, casting, moulding, injection, joining, machining and assembly) to obtain high-performance structural parts. To improve fatigue wear or corrosion performance, different strategies can be proposed, such as improving the design, the material itself and/or the manufacturing process. In such cases, covering the whole value chain with an enhanced cooperation between all the stakeholders is crucial for achieving results. Solutions of modifying specific alloying elements and/or coating chemistry, fine tuning surface condition of stress hot-spots, new tooling technologies to facilitate direct quenching in hot stamping, application of innovative heat treatments, improvement of welding and other joining processes to reduce fatigue concentration, development of new process such as VPDC (Vacuum Pressure Die Casting), plastic injection (using recycled or bio-based plastics), new sensing capabilities in tooling or during processing, etc.
Develop material that can withstand higher operating conditions
In order to reduce CO2 emissions and reduce weight, internal combustion engines designs require more severe mechanical stress an improved creep strength at >300[Símbolo]C. Aluminium casting technology is very suitable for engine components because it masters the best combination of high geometry complexity, good mechanical properties of the parts and medium manufacturing cost for serial production with a reduced weight. Different solutions such as combination of alloying elements and manufacturing processes needs to be optimized for obtaining the desired thermal and mechanical properties at the new engine operating conditions to strengthen components or reduce their residual stresses.
Improve performance of bio-based and elastomeric materials (e.g. natural fibres, bio-based polymers, seals)
Natural fibres and bio-based materials are being introduced as alternative raw materials for transport and energy components. Compared to glass and carbon fiber reinforced plastics (GFRP, CFRP), NFRP provide beside other advantages lower density, less energy consumption during manufacturing as well as excellent acoustic and mechanical damping

properties. Despite the significant efforts in improving bio-based materials, several challenges still hinder wider adoption. Most important drawback of NFRP is the higher uptake of moisture compared to that of GFRP and CFRP, which can lead to reduced mechanical properties and microbial attack. Additionally, most of available bio-based and biodegradable polymers are currently not used in technical applications due to their weakness in impact strength, heat distortion temperature as well as their resistance against hydrolytic and thermo-oxidative degradation, which are reduced compared to most conventional engineering plastics and some of the commodities. Ageing due to temperature and/or use needs to be better controlled in order to reach equal performance to fossil-based materials. Finally, constant supply of bio-based materials (both fibres and matrices) is necessary.

Develop material and manufacturing processes to optimise hardness and ductility

Alloy-manufacturing process selection for a lightweight design is a very complex process that requires several functional properties, such as yield strength, ductility, wear, corrosion and fatigue response and fracture toughness. Specifically, yield strength has been a driving factor since the early ages of aerospace engineering in the development of high strength aluminium alloys. The main drawback is that their ductility in aged condition is rather low, what becomes, for example, a technological problem for shaping the material to the desired design. Different combination of innovative alloys and manufacturing process can result to new combinations of hardness and ductility of lightweight materials. For example, hot stamping is an innovative technology with several successful applications in HSLA steels for High Strength aluminium processing and VPDC allows to produce a wide range of different yield strength/ductility properties in very thin castings.

Substitute Pb, Li and Co in aluminium alloys

For every 1% by mass of lithium added to aluminium the density is reduced by 3% and the stiffness increased by 5%, both properties are very useful for optimized lightweight designs. Cobalt is also a material being used in high strength aluminium alloys. The main drawback of these alloys is the rising price of Li and Co due to their use in batteries. For example, Al-Li alloys are 2-4 times more expensive than basic Al-alloy. Thus, alternative aluminium alloys with similar performance are strategic to extend the use of lightweight solutions with a reduced amount of Li or Co and/or enhanced use of secondary alloys.

The use of lead as alloying element in aluminium is typical to improve machining performance. However, lead has to be removed for toxicological reasons. Several candidates are under research such as tin and bismuth, but further research is necessary to assess their processability like formability, precipitation hardening, machining and coating behaviour to protect against wear and corrosion.

Develop materials and coatings to decrease air-borne emissions

Ultrafine particles can be emitted in passenger cars from brakes with emission factors of 4-10mg/km/vehicle. For this application, it is necessary to develop materials and surface coatings with enhanced durability that can minimize the nanoparticle release. Understanding of the effect of the microstructure, durability and nanoparticles release should be further studied. Also, nanoparticles release depends on testing conditions, common methodologies to measure and control the emission of nanoparticles, are needed.

Any new materials developed are expected to make use of existing or upcoming manufacturing and process technologies.

IMPACT

Successful projects under this call are expected to contribute to the development of the next generation of lightweight technologies which combine improved performance, manufacturability, and sustainability. This in turn is expected to contribute to the following widespread impacts:

Reduction of the vehicle weight by 15 % at a cost of lightweighting of €2/kg saved or lower

Reduction of fuel/energy consumption of 15% with no compromise on vehicle safety and performance attributes

Reduction of tailpipe particle and CO2, as well as airborne emissions

Contribute to the creation of more relevant jobs for the future in Europe

LT4 - Develop technologies (materials, processing, joining) to enable multimaterials and multifunctionality

TYPE:
DRAFT LEADER: THILO BEIN - FRAUNHOFER LBF

CHALLENGE

One of the key societal challenges of today is the decarbonisation of our daily live particular of our transport system. Within this context, advanced lightweight materials and designs play a crucial role. Significant weight reduction in mass production can not only be realized by cost-attractive lightweight solutions but exploiting secondary measures such as reduced number of parts, high integration of functions like haptic, optic or acoustic. Within this context, a multi-material design as well as a high degree of function integration resulting in a multifunctionality have already proven to offer high potential in weight savings and CO2 balance over the life-cycle. However, the implementation of a consequent multi-material design in combination with a desired multifunctionality is currently limited by either the insufficient performance of highly integrated functions through multi-material design or too high additional costs for mass market applications. Furthermore, functional materials are applied where their impact on health and safety in production, over the use phase and at End-of-Live (EoL) is not well understood.

SCOPE

Besides material and design driven lightweight design, function integrated lightweight design shows the highest potential for reducing significantly the weight of technical structures and thus contributing to the targets of decarbonisation and energy efficiency. Function integrated lightweight design addresses the integration of passive or active functions into one single, structural component. In this context, passive functions are measures to ensure defined properties without additional energy like crashworthiness or NVH performances but also corrosion protection or other measures enhancing the endurance of a structure. The overall aim is to reduce the number of components or materials used in a structure and thus to reduce weight. On the contrary, active functions requires additional energy but extending the overall functionality of a structure like monitoring, noise and vibration or shape control. Active functions are mostly used either to realise weight savings or to extend the life-time of a structure by reducing operational loads, by controlling and understanding the usage of a product or by decreasing safety margins. Besides, new functions are addressed which cannot be realised in a traditional way but are desired e.g. under harsh environments, in IoT applications or just for competitive reasons.
However, a consequent function integrated lightweight design requires new, advanced materials, advanced concepts for multi-functional, multi-material systems, manufacturing processes allowing to produce and handle multi-material systems, as well as the necessary joining technologies. Besides, the interfaces between the material pairs applied must be fully understood and controlled over life-time to ensure reliably a function integrated lightweight design based on multi-functional multi-materials.
From material point of view, the work under this call is expected to focus on the following aspects:
materials and designs with cooling capabilities,
materials with inherent sensing capabilities,
materials and designs with fraud protection (of the material composition/micro-structure),
materials and coatings with self-healing properties,
materials enabling enable local material and/or part properties and
materials enabling tailored haptic, optic, acoustic, and smell properties (mainly for interior applications)
Since the implementation of those materials will have a significant impact on the manufacturing, novel technologies are needed such as:
advanced tooling facilitating multi-material processing,
automated handling and processing of highly dissimilar materials,
function integration through additive manufacturing
optimisation of hardness and ductility of multi-material systems

joining technologies to enable multimaterial joining in a cost-efficient way, while not hindering recycling (i.e. facilitate easy disassembly and separation)
Above mentioned manufacturing challenges are non-exhaustive, all technologies needed to process multi-materials and to realise affordable, reliable function integrated designs are sought for.
Besides, materials and processing technologies focussing on optimising the interfaces between the highly dissimilar material pairs are included.

IMPACT

Successful projects under this call are expected to achieve the following impact:
20% weight reduction through reducing number of components and/or materials used as well as through reducing safety margin in designs, which will enable >20% energy consumption reduction, achieved at a cost of no more than €2/kg saved Reduced energy consumption over life-time through controlling operational loads and usage of a product
Improved resource efficiency through extended life-time
Improved competitiveness of multi-material solutions through additional functionality (demonstrated by the potential of application in multiple sectors)

LT5 - Develop the tools and know-how necessary to gain a better understanding of the cradle-to-cradle performance (environmental, mechanical properties, cost, social) of the materials

TYPE
DRAFT LEADER:

CHALLENGE

Advancements in several technological fields have enabled the introduction of improved, or completely new materials over the last years. Although these novel materials come with improved performance in one or more domains (mechanical properties, cost, ...), their full potential is not always utilised as on the one hand there is limited understanding of their properties by end users, and on the other hand many industrial processes have over the years been optimised for a specific type of material, and therefore it is difficult to adapt to a completely new material with different properties and requirements (e.g. car manufacturing is heavily focused around steel – from design principles to manufacturing, to repair – making it difficult to adapt to a completely new material such as FRP).
Additionally, in many cases such new materials are developed to address a specific challenge – e.g. mechanical performance – but at the same time create additional challenge(s), such as difficulty in maintenance and repair, in recycling, etc.
In order to ensure that such materials are fulfilling their potential, and that they have an overall positive impact on all aspects, it is crucial to develop the necessary tools and know-how to better understand their cradle to cradle performance on all aspects.

SCOPE

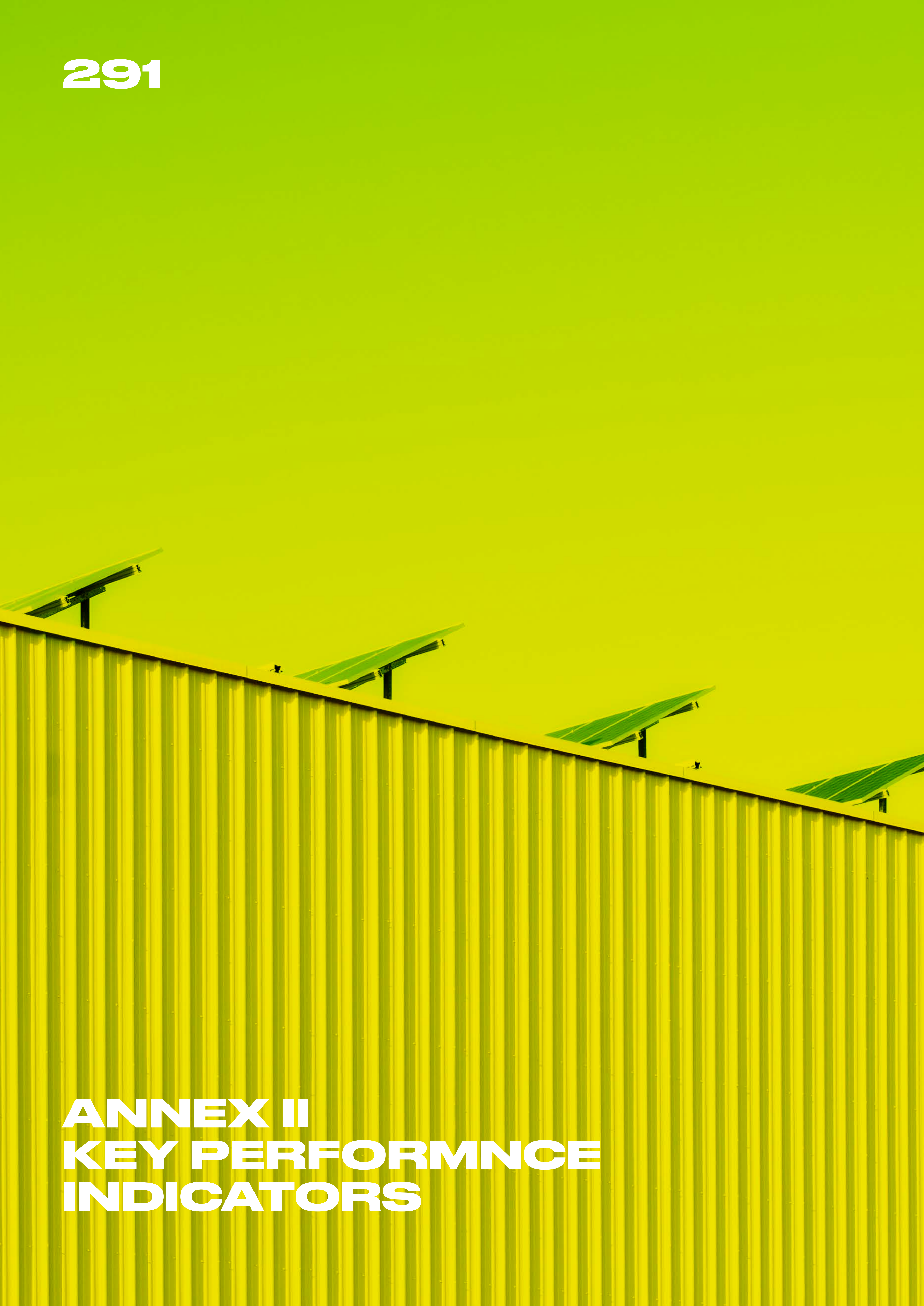
Proposals submitted under this call are expected to develop the necessary tools and know-how to better understand - and therefore take advantage of the full potential of novel material - such as:
lifecycle cost assessment, with adequate granularity as to the costs attributed to each phase (extraction and production, use, EoL), and each activity (e.g. materials, machinery, energy, personnel, logistics...)
lifecycle environmental assessment, with adequate granularity as mentioned above, especially for processes occurring outside the boundaries (e.g. environmental impact of extraction of raw materials outside EU). Tools are expected to be able to assess not only climate change impact (GHG, GWP, kg CO2eq), but other impacts such as human toxicity, resource depletion, acidification, etc.
impact on human health and well-being (strongly related to environmental assessment)

Proposals are expected use a number of case studies to demonstrate the credibility of their methodology, spanning different materials and vehicle components. Results should be benchmarked with a number of different scenarios (e.g. reuse, recycling, landfill).

Given the proven difficulty of acquiring credible industrial data to provide high accuracy assessments, proposals are urged to find a solution to this issue, either by developing credible databases, suggesting a framework for industrial partners to share (competitive) data, or bypassing the topic of data acquisition completely.

IMPACT

Successful projects under this call are expected to achieve the following impact:
Give input to other tools and practices such as design methodologies
Decrease the time from when a new material technology reaches market maturity (TRL9) until it is implemented in medium/high volume transportation applications
Improve the understanding of end users (e.g. automotive engineers and designers) of the novel materials, and therefore enable better and higher use in the overall vehicle
Improve the understanding of the cradle to cradle performance of novel materials on multiple aspects (environmental, cost, ...)
Improve the overall performance of novel materials (considering multiple aspects)



ANNEX II
KEY PERFORMNCE INDICATORS

1. Battery energy storage

2018/2019

System / Component / Sub-component	#	KPI	Unit	Stationary: Na-ion domestic ● (B1S)	Li-ion domestic ● (B2S)	Flow utility ● (B3S)	Metal-air utility ● (B4S)	Li-ion commercial ● (B5S)	Li-ion utility ● (B6S)	Mobility: 3b HV-P ● (B1M)	3b HC-E ● (B2M)	4a ●● (B3M)	4b ●● (B4M)	4c HV-P ● (B5M)	5 ●● (B6M)	ZSM HP ● (B7M)	SuperCaps HP ● (B8M)
Battery Pack	1	OPEX	€/kWh/cycle	0.15	0.15	N/A	N/A-	0.4-0.6	0.4	N/A	0.15	N/A	N/A	N/A	N/A	0.15	N/A
Battery Pack	2	CAPEX (pack out of plant)	€/kWh	N/A	400-600	150-2000	N/A	500-800	500-600	150-300	150-300	N/A	N/A	N/A	N/A	N/A	N/A
Battery Pack	3	Calendar life @25 °C	years	N/A	15	20	N/A	15	15	N/A	15	N/A	N/A	N/A	N/A	15	15
Battery Pack	4	Fast recharge time (80% SOC)	minutes	N/A-	60	N/A-	-	60	60	N/A	60	N/A	N/A	N/A	N/A	N/A	-
Cell	1	Gravimetric Power density	W/kg	N/A	200-2000	<100	N/A	200-2000	400	300-400	300-400	N/A	N/A	N/A	300-600	-	1000
Cell	2	Volumetric Power density	W/l	N/A	-	-	-	-	-	700	700				300-650	-	2000
Cell	3	Gravimetric Energy density	Wh/kg	120	100-200	<50	200	100-200	100-200	150-200	90-250	N/A	N/A	N/A	200-400	100-200	<50
Cell	4	Volumetric Energy density	Wh/l	200	250-400	10-30	200	250-400	400	250-450	200-650	N/A	N/A	N/A	200-450	-	-
Cell	5	Lifetime (cycling)	cycles	1000	2000	10000	100-1000	2000	2000	1500-2000	1500-2000	N/A	N/A	N/A	50-150	-	>15000
Cathode	1	Potential vs Li/Li+	V	-	3.8-4.2	-	-	3.8-4.2	3.8-4.2	3.8-4.6	3.8-4.2	3.8-4.2	-	-	-	-	-
Cathode	2	Nominal capacity	mAh/g	-	120-180	-	-	120-180	120-180	140-200	140-200	-	-	-	-	250	-
Anode	3	Potential vs Li/Li+	V	-	0-0.2	-	-	0-0.2	0-0.2	0-0.3	0-0.3	-	-	-	-	-	-
Anode	4	Nominal capacity	mAh/g	-	374	-	-	374	374	374	374	-	-	-	-	-	-
Electrolyte	5	Electron conductivity	S/cm	-	$<10^{-9}$	-	-	$<10^{-9}$	$<10^{-9}$	$<10^{-9}$	$<10^{-9}$	N/A	N/A	N/A	$<10^{-9}$	$<10^{-9}$	-
Electrolyte	6	Ionic conductivity	S/cm	-	$>10^{-3}$	-		$>10^{-3}$	$>10^{-3}$	$>10^{-3}$	$>10^{-3}$	$>10^{-3}$					
Charging Infrastructure	1	Power	kW	22-50													
Charging Infrastructure	2	Recharge time	minutes	60													

2030

System / Component / Sub-component	#	KPI	Unit	Stationary: Na-ion domestic ● (B1S)	Li-ion domestic ● (B2S)	Flow utility ● (B3S)	Metal-air utility ● (B4S)	Li-ion commercial ● (B5S)	Li-ion utility ● (B6S)	Mobility: 3b HV-P ● (B1M)	3b HC-E ● (B2M)	4a ●● (B3M)	4b ●● (B4M)	4c HV-P ● (B5M)	5 ●● (B6M)	ZSM HP ● (B7M)	SuperCaps HP ● (B8M)
Battery Pack	1	OPEX	€/kWh/cycle	<0.050	<0.050	<0.050	<0.05	<0.050	<0.050	<0.05		<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
Battery Pack	2	CAPEX (pack out of plant)	€/kWh	100-200	100-200	100-500	<100	100-200	100-200	75		75	75	75	75	<300	<100
Battery Pack	3	Calendar life @25 °C	years	>20	>20	>20	>20	>20	>20	20		20	20	20	15	20	15
Battery Pack	4	Fast recharge time (80% SOC)	minutes	30-	30	-	30	30	30	12		12	12	12	12	12	-
Cell	1	Gravimetric Power density	W/kg	>500	>1000	<100	>500	>500	>500		700	>500	>500	>500	>500	>1500	2000
Cell	2	Volumetric Power density	W/l		>500	-	-	400-500	400-500		>1500	>700	>700	>700	>700	>3000	4000
Cell	3	Gravimetric Energy density	Wh/kg	180	200	<100	200-400	>200	>200		350-400	>400	>500	>500	>500	>150	200
Cell	4	Volumetric Energy density	Wh/l	500	500	>50	800	>500	>500		700-1000	1000	1000	>1000	>1000	>300	150
Cell	5	Lifetime (cycling)	cycles	6000	15000	>15000	2000-5000	>6000	>10000		3000	3000	3000	3000	>800	>15000	50000
Cathode	1	Potential vs Li/Li+	V	-	3.8-4.2	-	-	3.8-4.2	3.8-4.2	3.8-4.8	3.8-4.6	3.8-4.3	3.8-4.3	3.8-4.8	-	-	-
Cathode	2	Nominal capacity	mAh/g	-	200-300	-	-	200-300	200-300	250-300	250-300	250-300	250-300	250-300	250-300	250-300	-
Anode	3	Potential vs Li/Li+	V	-	0-0.3	-	-	0-0.3	0-0.3	0-0.3	0-0.3	0-0.3	0-0.1	0-0.1	-	>250	-
Anode	4	Nominal capacity	mAh/g	-	1000	-	-	1000	374-1000	1000	1000	1000	4000	4000	-	>250	-
Electrolyte	5	Electron conductivity	S/cm	$<10^{-9}$-	$<10^{-9}$	-	-	$<10^{-9}$	$<10^{-9}$	$<10^{-9}$	$<10^{-9}$	$<10^{-9}$	$<10^{-9}$	$<10^{-9}$	$<10^{-9}$	$<10^{-9}$	
Electrolyte	6	Ionic conductivity	S/cm	$>10^{-3}$	$>10^{-3}$	$>10^{-3}$	$>10^{-3}$	$>10^{-3}$	$>10^{-3}$	$>10^{-3}$	$>10^{-3}$	$>10^{-3}$	$>10^{-3}$	$>10^{-3}$	$>10^{-3}$	$>10^{-3}$	
Charging Infrastructure	1	Power	kW	>350													
Charging Infrastructure	2	Recharge time	minutes	<5													

• Power Applications
• Energy Applications

2. Hydrogen for mobility

System	Component	Sub-component	#	KPI	Unit	2018/2019 PEM Low Temperature	2018/2019 PEM High Temperature	2018/2019 Storage	2030 PEM Low Temperature	2030 PEM High Temperature	2030 Storage
FCEV			1	TCO	€/km	0.55-8*		-	0.3**		-
			2	CAPEX	€/kW	100**,[a] / 1000-1500***,[a]			40 **,[a] / 600 ***,[c]		<75[b]
					€/kgH_2	1000[a]			300[a]		
			3	Power density	W/kg	650		-	650		-
			4	Consumption	kg/100km	1.2-34		-	1-28		-
	Stack		1	Gravimetric Power density	kW/kg	0.77		-	2.3		-
					Wt%	-		5	-		6
			2	Volumetric Power density	kW/l	4		-	8		-
					gr H_2/l	23			35		
			3	Cost	€/kW_{net}	26		-	15		-
			4	Durability	h	4000** / 12,000***			7000** / 30,000***		
			5	Max operating temperature	°C	60-95	>120	-	100	>160	-
			6	Cost (storage)	€/kg H_2	-		1000-1500	-		<800
			7	Refilling times (storage)	kg H_2/minute	-		>1	-		<1
		Catalyst	1	Pt loading	mg/cm²	0.3-0.35		-	<0.1		-
		MEA	2	Durability with cycling	h	2500		-	>7000		-
			3	Performance @0.8V	mA/cm²	240		-	>300		-
		Membrane	4	Mechanical durability (cycles until >15mA/cm² crossover)	cycles	23,000		-	>40,000		-
			5	Through-plane proton aerial resistance (@80°C, 100%RH)	mΩ cm²		10	-		6	-
		Bipolar Plates	6	Weight	kg/kW	< 0.4		-			-
			7	Electrical conductivity	S/cm			-	>100		-
		GDL	8	Thermal conductivity	W/m·s	0.4-0.7		-	5		-
			9	Electrical resistance (in-plane/through-plane) @1MPa	mΩ cm²	1-5 / 8-20		-	0.5 / 2		-
			10	Contact resistance	mΩ cm²	3-30		-	0.5-2		-

* from light duty (0.55) to heavy duty vehicles (8)

** passenger / light duty vehicles

*** heavy duty vehicles

[a] 100,000 units/year

[b] 50,000 units/year

[c] 900 units/year

3. Hydrogen for Stationary Applications and Carbon Capture and Utilisation

Area	System	Component	Sub-component	#	KPI	Unit	2018/2019		2030	
							PEM	SOE	PEM	SOE
H_2 Production				1	OPEX	€/kWh/year	40	80	6	20
						%/year of CAPEX	4		2	
						€/(kgH_2/day)/year*	58	600	21	75
	H_2 Production Facility			2	CAPEX	€/kW	1200	2000	500	1000
						€/kgH_2/day**	12,000		1500	
				3	System efficiency	kWh/Nm³ H_2	5.2 - 5		5 - 4.8	
						%	60-80	80 - 90	>80	>90
				4	H_2 purity***	%	99.9		>99.95	
		Electrolyser		1	Consumption @nominal capacity	kWhe/Nm³	5.8	4.1	5	3.7
				2	Ramp-up time (cold)	sec	120		10	
				3	Ramp-up time (idle)	sec	10		1	
				4	Output pressure	bar	<200	30	<200	60
				5	Degradation rate	%/1,000h	0.25	2.8	0.12	0.5
				6	Availability	%			99%	99%
				1	Lifetime	h	40,000		60,000	
			Stack	2	Operating temperature	C	60 - 100	700 - 1000	60-100	700-1000
				3	Current density	A/ cm²	2		2.5	
			MEA	4	CRM content	mg/cm²	5	-	0.4	-
			Electrolyte	5	Max H_2 crossover	vol % of H_2 in O_2	<0.8	<0.8	<0.5	<0.5
			Bipolar Plates	6	Electrical conductivity	S/cm			>100	
				7	Interconnect lifetime	h		40,000		>100,000
CCU	CC			1	CO_2 capture rate	%	85		95 - 99	
				2	Cost of CC and purification	€/CO_2 tn		<50	<20	
	CCU			1	Lifetime	h			1000	

* operation and maintenance including potential stack replacements over the first 10 years of operation; does not include electricity costs

** assumed for production volume of 100MW in steady state operation, availability 98%, for a 10-year system lifetime; end of life is defined as 10% increase in energy required for hydrogen production; does not include building construction

4. Solar Energy Harvesting

System	Component	Sub-component	#	KPI	Unit	2018/2019							2030						
						Crystalline silicon							Crystalline silicon						
						Multi-crystalline (BSF, PERC/PERT)	Mono-crystalline (BSF, PERC/PERT)	Heterojunction	Back contact	Multi-junction	HCPV-Multi-junction	Thin films	Multi-crustalline (BSF, PERC/PERT)	Mono-crystalline (BSF, PERC/PERT)	Heterojunction	Back contact	Multi-junction	HCPV-Multi-junction	Thin films
Solar System			1	LCOE	€/kWh	0.02-0.06				N/A		0.2-0.06	0.015-0.04						
	Module		1	Average stabilized module efficiency*, **	%	16-17	17-18	19	20	N/A	33	14-16	18-19	19-21	22	23	>25	38	17-19
			2	Average module power*	Wp	280-290	290-310	325	340	N/A			310-330	330-360	370	390	>420		N/A
			3	Module degradation rate	%/year	0.7%				N/A		~1%	<0.5%						
			4	Expected lifetime of antireflective coating on module front sheet	years	15				N/A		15	25						
		Cell	1	Average stabilized cell efficiency	%	19-20	20-22	23	24	28 [a]	43	N/A	20-22	22-24	25	26	>29	46	N/A
			2	Silicon bulk recombination current	fA/cm²	160	90	20	20	N/A		N/A	50	20	10	10	10-50		-
			3	Silicon surface recombination current	fA/cm²	90	90	20	20	N/A		N/A	20	20	10	10	10-20		-
			4	Limit of cell thickness in module technology	µm	150				N/A		N/A	90						-
			5	Polysilicon utilisation	g/wafer	16-19	15-18			15-19		N/A	13-17		12-16		12-17		-
			6	Front side metallization finger width	µm	40				N/A		N/A	20						
			7	Silver content	mg/cell	90				N/A		N/A	40						
			8	Silicon recycling rate in wafering process	%	0				N/A		N/A	20						-

* industrial size: 60 cell module for c-Si technologies; few mm² for CVC technologies

** indicated for cell size of 156 x 156 mm²

[a] 1cm² perovskite/Si (monolithic) record cell, Oxford PV, 2018

5. Wind Energy Harvesting

System	Component	Sub-component	#	KPI	Unit	2018/2019 On-shore	2018/2019 Off-shore	2030 On-shore	2030 Off-shore
Wind Farm			1	LCOE	€/kWh	0.04-0.07	0.06-0.08	0.03-0.06	0.03-0.06
			2	CAPEX	€/kW	900-1200	3000-3500	700-1000	2100-3200
			3	OPEX	€/kWh	0.017	0.025-0.040	0.016	0.02-0.03
	Turbine		1	Lifetime	years	20-25	20-25	25-30	25-30
			2	Power coefficient	%	88	88	90	90
			3	Capacity factor	%	20-45	35-60	20-45	35-60
			4	Audible noise	dB	90-107	90-107	90-107	90-107
		Blades	1	Lifetime	years	20-25	20-25	25-30	25-30
			2	Length	m	37-100	45-100	50-90	50-120
			3	Use of recycled secondary materials	% by mass	<10	0	30	
		Coating	4	Erosion and corrosion resistance	corrosion class*	C4 (C3 interior) C5 (C4 interior) **	CX (C4 interior, Im4 submerged parts)	C4 (C3 interior) C5 (C4 interior) **	CX (C4 interior, Im4 submerged parts)***
			5	Toxic compounds content		Compliance		Compliance	
		Drivetrain	6	Overall efficiency (axis to axis)	%	95	95	97	97
			7	Average power of installations	MW	3.5	8	5	10-15
			8	Use of CRM** (magnet)	% by mass	30		15-20	
		Foundations	9	Maintenance interval (WEC, lubricant, bearings, vibration)	months	6-12	12	12-24	
			10	Fatigue resistance, biofouling	years	20-25	15-20	25-30	20-25

* according to ISO12944 standard
** when the structure is located in coastal areas
*** test duration should be at least 50% longer than the minimum duration as defined in ISO19244-6-2018

6. Building Energy Performance

System	Component	Sub-component	#	KPI	Unit	2018/2019		2030	
Building			1	Airtightness	l/m²s@75Pa	0.6			
	Window	e-glass	1	U-Value	W/m²K	0.28		0.25	
			2	Emissivity		0.02		0.01	
			3	Visible light transmittance		0.64		0.55	
			4	Solar heat gain coefficient		0.27		0.24	
		Dynamic Glazing	5	Range of switching/light transmission (clear state)	%	65		>75	
			6	Range of switching/light transmission (dark state)	%	1		<0.1	
			7	Cost	€/m²	500		<200	
			8	Aesthetics in transmission (clear state)	b*	>6		<2	
			9	Switch speed/responsivity	sec	1-600		1-60	
			10	Energy consumption	W/m²	0.3-0.5		<0.2	
			11	Durability (period to maintain above properties)	years	10-20		>25	
	Insulation		1	Air tightness	l/m²s @75Pa	0.6			
			2	Cost	€/l	2-3			
			3	Thermal conductivity (λ) (25mm thickness at 20°C)	mW/mK	15			
			4	Durability	years	20-25		>40	
			5	VOC emissions	μg/cm³	0.1		<0.1	
Type of storage technology						**PCM**	**TCM**	**PCM**	**TCM**
	TES		1	LCOE	€/kWh	50		10	
			2	Volumetric capacity	kWh/m³	100	250	200	500
			3	Gravimetric capacity	kWh/tn	100	250	200	500
			4	Thermal conductivity	W/mK	5		>10	
			5	Operating temperature	°C			100-250	
Type of lighting technology						**LED**	**OLED**	**LED**	**OLED**
	Lighting		1	Efficacy	lm/W	140 - 160	60 - 80	250	180
			2	LCOL	€/lm	0.01 - 0.1	0.2 - 0.5	0.002 - 0.02	0.01 - 0.02
			3	Durability	h	50,000	40,000	100,000	100,000
			4	Operational lifetime	years	10		20	10

7. Lightweight Technologies for Mobility

System	Component	Sub-component	#	KPI	Unit	2018/2019 Automotive	2018/2019 Aviation	2018/2019 Shipping	2030 Automotive	2030 Aviation	2030 Shipping
Vehicle			1	Energy consumption	kWh/pkm	0.5	0.55	0.05	0.3-0.35	0.35-0.4	0.04
Vehicle			2	Weight reduction *	%	25	10-15	30-40	35	15-20	40-50
Vehicle			3	Cost of lightweighting	€/kg saved	3	>10	<3	1.5	10	1
	Vehicle Module		1	Lifecycle performance **	gr of CO_2eq/pkm	100	250	N/A	75	190	-
	Vehicle Module				kWh/pkm	0.5	1.5-2	N/A	0.35	1-1.5	-
	Vehicle Module		2	Recycling	%	80-85	30-35	80-90	>95	>60	>95
	Vehicle Module		3	Cost of Ownership ***	€/100kg 1000km	0.1-0.2		N/A	0.02-0.05		-

Sub-component	#	Material technology	2018/2019 Steel	2018/2019 Aluminium	2018/2019 Magnesium	2018/2019 FRP	2018/2019 Ceramics	2018/2019 Polymers	2018/2019 Glass	2030 Steel	2030 Aluminium	2030 Magnesium	2030 FRP	2030 Ceramics	2030 Polymers	2030 Glass
Mono-material Part	1	Cost compared to steel part	1	1.5-2.3	N/A [a]	7-9	N/A [a]	1-10	N/A	1	1.2-2	3-5	3-7	<10	1-7	N/A
Mono-material Part	2	Degree of downcycling ****	4-5 [b]	4-5 [b]	4-5 [b]	1-3 [c]	1-2	1-5 [d]	4-5	5	5	5	4-5	3-4	4-5	5

* financially viable reduction that can be achieved compared to a conventional vehicle

** includes emissions from production, use, and EoL treatment

*** includes cost of raw materials, production, and use (cost of use if the cost of energy needed for carrying the part throughout the vehicle's lifetime); includes production and use costs, divided by the total mileage and module weight

**** using commercially available recycling technologies; scale of 1-5 where 5 is no downcycling, 1 is complete loss of material properties

[a] not enough comparable applications

[b] although metals can theoretically be recycled endlessly without degradation of properties, in some alloys, volatile alloying elements might be lost during the process

[c] depending on the type of fibre and matrix; TP matrices facilitate better separation of matrix and fibre and therefore lower degradation

[d] lower degradation for TP polymers, significantly higher for TS polymers

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