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Materials Roadmap Enabling Low Carbon Energy Technologies

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1. INTRODUCTION

Materials are at the core of industrial innovation and enable it. New advanced materials are needed in developing better performing and sustainable products and processes. Such materials are a part of the solution to our industrial and societal challenges, offering better performance in their use, at lower resource and energy requirements, and improved sustainability at the end-of-life of the products. The discovery and development of new materials and the capacity to shape and utilise their properties enable scientists and engineers to develop energy technologies to power our economies and lifestyles. With the imperative to change our energy technology mix to respond to the challenge of decarbonisation and of the security of energy supply, the need for new materials and processing routes is overriding. We need new energy technologies – not just any low carbon technologies, but more efficient and cost-competitive low carbon technologies. Materials play a pivotal role in the solution, providing the means to generate and conserve energy in a more efficient and cost-competitive manner.

Materials research and control over materials resources is becoming increasingly important in the current global competition for industrial leadership in low carbon technologies. In response, the European Union has prioritised materials as a Key Enabling Technology (KET) to enable the transition to a knowledge-based, low carbon resource-efficient economy. As part of Europe 2020 strategy, the Union has set out a strategic agenda to ensure that materials will continue to support our industry and create economic opportunities. In particular, under the flagship initiative 'Resource Efficient Europe' of the Europe 2020 Strategy, the EU's Raw Materials Initiative and the Roadmap to a resource efficient Europe addresses the critical issue of scarcity of natural resources, as well as their sustainable and efficient use. The recent proposal of the Commission for the next Framework Programme for research and innovation – Horizon 2020 clearly emphasises the importance of advanced materials and the related technologies as key enablers and key factors in strengthening Europe's productivity and innovation capacity and ensuring Europe has an advanced, sustainable and competitive economy, global leadership in hi-tech application sectors and the ability to develop effective solutions for societal challenges such as for energy. Moreover, since 2007, the Strategic Energy Technology Plan (SET-Plan) provides the strategic frame between the Member States, Industry and the European Union to jointly invest on the development and market roll-out of more efficient, safe and reliable low carbon technologies, in which, materials play a major role.

The materials roadmap presented in this document complements and expands the technology roadmaps[1] developed in the context of the SET-Plan as the basis for its implementation. It puts forward key materials research and innovation activities to advance energy technologies for the next 10 years. It serves as a programmatic guide for research and development activities in the field of materials for energy applications for both the European Union's research and innovation programme and Member State programmes.

[1] *COM(2009) 519*

2. MATERIALS ROADMAP

2.1. Concept and methodology

The materials roadmap addresses the technology agenda of the SET-Plan by proposing a comprehensive European programme on materials research and innovation enabling low carbon energy technologies for the next 10 years. Its starting point is the sector's ambitions and technology challenges addressed in the SET-Plan initiatives (European Industrial Initiatives – EIIs- and European Energy Research Alliance - EERA). The energy technologies considered are: wind, photovoltaic, concentrating solar power, geothermal, electricity storage, electricity grids, bio-energy, novel materials for the fossil fuel energies sector (including carbon capture and storage), hydrogen and fuel cells, nuclear fission and energy efficient materials for buildings.

The individual materials roadmaps for these energy technologies are based on scientific assessments, produced by independent and renowned European materials scientists and energy technology experts from academia, research institutes and industry, under the coordination the SET-Plan Information System (SETIS), which is managed by the Joint Research Centre (JRC) of the European Commission. These scientific assessments, published together with the Materials Roadmap, provide an in-depth analysis of the state of the art and challenges of energy technology-related materials and the needs for research activities to support the development of energy technologies both for the 2020 and the 2050 market horizons.

Eleven hearings have been organised in the course of the roadmap development process with the participation of a wide pool of stakeholders coming from amongst others, energy technology and material platforms, associations, EERA Joint Programmes, to discuss and feedback on the scientific assessments prepared by the experts.

In developing the Materials Roadmap, attention has been paid to ensure added-value and complementarities with the SET-Plan technology roadmaps as well as with the other EU initiatives on energy and materials. In particular, this roadmap combines a large energy technology portfolio with a broad perspective on materials and processing innovation; and focuses on development and the proof of the technological usability of materials research outcomes to a scale sufficient for using materials for new low carbon technologies at industrial scale. Thus, a clear bridge is created for the integration of new material advances into commercial scale demonstration projects at system level as pursued in the SET-Plan EIIs. Hence, as a working premise, the commercial scale demonstration at system level has not been included in the roadmap.

2.2. On-going developments

This roadmap does not cover the full spectrum of energy technologies that will contribute to the decarbonisation of the European energy supply. To this end, the roadmap will be extended in the future to cover other technologies and avenues with great potential in line with the SET Plan future developments.

In particular, a roadmap is currently under development which will cover materials needed to develop ocean energy technologies with the potential to assist in new forms of power generation with reduced carbon emissions. Ocean energies such as tidal, current or wave energy offer truly zero-emission energies whose largely predictable nature can help accommodate other, more variable, energy sources. Materials issues are paramount. There is a need for reliable materials that can withstand corrosion, bio-fouling and fatigue to move these energies from demonstration to industrial production. Research activities should include laboratory scale innovative research into advanced material coatings and high stress drive-train components including gearing; pinions; plant bearings, lubrication systems, and anti-fouling materials in a high corrosion environment as well as a testing programme on MW scale capacity investigating cost reduction and improved survivability. A roadmap on marine technologies addressing specifically materials issues will be developed to extend the current roadmap in the first quarter of 2012.

Energy Efficiency is specifically addressed in the building sector and in all technologies considered in this document with actions proposed to improve the energy efficiency of the different technologies as well as to enhance the efficiency of materials resource usage and to promote their further recycling. Other technologies/sectors may be addressed in the future such as renewable heating and cooling. In addition, several material developments covered in the roadmap may be used for other applications, e.g., development of organic PV with optoelectronic applications. As such, dedicated cross-cutting cooperation and knowledge transfer with other sectors within and outside the energy field will be encouraged in the implementation of the roadmap.

2.3. Boundary conditions

The Materials Roadmap provides a detailed agenda of the efforts needed over the next 10 years on materials R&D for energy applications in the EU, based on the best available information today. In view of the large scope and dynamism of the field of materials research and its horizontal character, this Materials Roadmap needs to be seen in conjunction with and complementary to the detailed implementation plans of the SET-Plan and of other related initiatives of the EU, such as the Raw Materials Initiative. The key performance indicators (KPIs) included in the Materials Roadmap should be seen as the baseline to illustrate the level of ambition and vision of the Roadmap. These KPIs will be refined during the implementation phase and continuously monitored by SETIS against the state-of-the-art.

3. SET-PLAN MATERIALS ROADMAP ON ENABLING LOW CARBON ENERGY TECHNOLOGIES

The Materials Roadmap is built on a set of technology oriented roadmaps that focus on the specific needs of each energy technology. It is built around three main interlinked headings organised to reflect the timeline from discovery to market roll-out, as follows:

– Heading 1 - *Materials R&D and related product development* consists of a research programme that covers basic and applied research for materials design, manufacturing, including change in behaviour over different scales, characterisation and basic validation. It is organised in focus areas which represent key material objectives in the context of (a component of) a technology. One focus area for all technology oriented roadmaps is dedicated to novel materials solutions or novel combination of known materials to emerge beyond 2020.

– Heading 2 on *Materials integration and component technologies* includes pilot actions for materials processing at industrial scale (or at least to prove their scalability), bonding and joining technologies, materials and component testing for validation in an application context. The goal is to bring the knowledge generated under the first heading to industrial scale and to test it under real operating conditions. The proposed pilot facilities are considered to be consistent in their timing with the maturity of the materials research results for an industrial up-scaling within the next 10 years.

– Heading 3 on *Research Infrastructures* focuses on research-enabling platforms, which are needed to perform the activities under headings 1 and 2 and to permit the European industry to acquire the knowledge they need for innovation in the materials and product fields. Activities under this section relate to hardware and capacities e.g. modelling, testing etc.

These roadmaps are summarised in the following section.

3.1. Wind energy

The SET-Plan aims to improve the competitiveness of wind energy technologies, while fostering the exploitation of the wind offshore resources and deep water potential, and facilitating the integration of wind power with the grid. Wind turbines need to increase in size and operate in more demanding conditions and environments. The quest for low cost materials with improved mechanical performances and reduced weight is becoming paramount.

To this end, the materials roadmap for wind energy proposes a comprehensive research and development programme on blade materials such as fibre reinforced and sandwich core materials as well as bonding and joining technologies to improve the mechanical properties at reduced specific weight, to improve rotor performance and lifetime by intelligent use of materials and to reduce the manufacturing cycle times and production cost of blades; the development of new coatings for improved erosion resistance, self-cleaning and UV protection; the development of steel with enhanced properties for tower and support structures and related welding techniques, of concrete for mono-piles and gravity-based structures for deep water applications; the improvement of foundry technologies for dross-free ductile iron with high as well as lightweight composite structure to replace cast iron components. The roadmap focuses also on materials used in generator, power electronics and transmission (shaft, gears and bearing) with research efforts to substitute rare earth elements in permanent magnets and develop stronger, lighter magnets; to develop high temperature superconducting (HTS) generators, new materials for power electronics to increase the working limit of junction temperatures and metal alloys for transmission components to ensure an effective lifetime equal to the design lifetime. To scale-up the material development to industrial scales, the roadmap puts forward up to 4 industrial manufacturing pilots to develop and produce concept blades at MW scale, to develop, manufacture and demonstrate lightweight (composite) hub, bedplate or generator gearbox housing as alternative for cast iron components, to design, produce and test large blades with a length of over 100 m that allows the economic design of >12 MW turbines as well as automated production techniques in a MW scale blade production line; up to 2 technology pilots to test gravity based support structure for large water depth and demonstrate a HTS generator at full scale. Finally the roadmap proposes the creation of Trans-European research field network facilitators to accelerate industrial development and the up-take of research results as well as a test rig for the testing of large (> 10MW) drive train units.

3.2. Photovoltaic energy

The SET-Plan aims to further improve the competitiveness and ensure the sustainability of photovoltaic (PV) technology and to facilitate a self sustaining large-scale penetration in both urban areas and free-field electricity production units, as well as its integration into the electricity grid. Materials are key enablers in all PV systems. There is a need to design and manufacture PV systems that are both efficient and low cost enough to meet specific grid parity targets within the next few years. The materials supply chain needs to be able to supply sufficient quantities of the required elements, and thus, cost effective recycling solutions should be developed along with standardised performance testing and reliability/ageing test protocols needs to be developed to provide confidence (and so bankability) for PV devices employing newly developed materials in a wide range of operating conditions (from Europe to Sunbelt environments).

To this end, the materials roadmap for PV energy proposes a comprehensive research and development programme on the optimisation of materials usage through predictive modelling down to quantum devices at the nanoscale, the improvement of intrinsic performance and reduction in layer thickness of constituent materials for both inorganic and organic PV cells and modules, the development of alternative manufacturing processes for specific solar grade materials, the development of thinner, higher strength, conformal, lower cost glass as well as flexible, light weight, low cost, long lifetime and high barrier encapsulants and optical glues. The roadmap focuses also on materials for light management (anti reflective, anti soiling, anti abrasion coatings, light trapping / guidance, spectral conversion and optical concentrators materials); the development of high throughput, low cost manufacturing processes for film/layer deposition / thin film (epitaxial) growth; the development of materials for system-related devices such as inverters and trackers as well as the research into novel materials and processes. To scale-up the material development to industrial scales, the roadmap puts forward up to 3 manufacturing pilot projects on new solar grade materials, non vacuum deposition processes and PV high performance, thin, high strength glass; 1 field pilot to test new materials / device designs under real market conditions and to demonstrate the cost-effectiveness of combined High Concentrator PV and energy storage solutions for small-scale grid locations. This is complemented by the proposal to establish a Pan European open innovation network of PV research, modelling and test centres. Finally, a reinforcement of PV specific educational programmes will need to be achieved to ensure an adequate number of scientists and engineers for both research and industry.

3.3. Concentrating solar power

The SET-Plan aims at developing the competitiveness and readiness for mass deployment of advanced concentrated solar power (CSP) plants, through scaling-up of the most promising technologies to pre-commercial or commercial level. Achieving these objectives will require large-scale CSP plants with better technical and environmental performance and lower costs with increasing power availability through better storage systems and reduced water consumption. This necessitates materials with higher performance than those of today.

To this end, the materials roadmap for CSP proposes a comprehensive research and development programme on low-cost, spectrally selective, high mechanically stable absorber materials suited also for higher temperatures; and the development of higher reflectance and/or specularity, cost competitive, sustainable reflector materials. The roadmap focuses as well on heat transfer media to develop alternative synthetic fluids coupled with the improvement of molten salts and liquid metals to allow for higher temperatures, better heat transfer and better chemical stability; the development of more sustainable, reduced cost, corrosive-resistant structural materials such as steel, aluminium, fibre composites and the development of storage materials (heat storage materials and materials for thermo-chemical storage) to increase the performance and extend the operating temperature up to 600°C. To scale-up the material development to industrial scales the roadmap foresees up to 5 industrial pilot projects to manufacture absorber coatings, profiled multilayer tubes, high temperature synthetic heat transfer fluids, catalyst materials and heat exchangers of ceramics or alloys; up to 5 technology pilots to test and validate material performances under real market conditions in the areas of storage technologies, new molten salt mixtures, porous ceramic or metal structures for central receivers, fluidised bed materials as well as piping and tank structures. The roadmap puts also forward 3 test facilities (for coating technology, high temperature research and for advanced composites) to be developed in the framework of research infrastructure.

3.4. Geothermal energy

Geothermal power is a promising renewable energy source able to provide naturally a continuous base load power. Currently the exploitation of this technology remains limited to locations where geothermal heat is easily accessible, such as naturally occurring hot springs, steam vents or hot fluids at shallow depths. New technological developments are needed to further develop engineered geothermal systems (EGS) which involves deep drilling to exploit the heat from impermeable hot rocks. This could contribute to make geothermal sources more widespread available. To make these incentives also economically viable, innovative materials solutions and an improved understanding of the long-term interaction between the materials and their harsh environment is of key importance.

The R&D efforts proposed in the roadmap follow the different phases in the exploitation of a geothermal system. Focus is on innovative developments in accessing geothermal reservoir (including spallation drilling) that should work towards an increase of economic depth. An important contribution would come by researching lightweight materials for drill bits to extend their lifetime in highly abrasive and corrosive environments at high temperatures and developing site specific materials for proppants in conjunction with stimulation techniques. Improved monitoring of the downhole requires materials developments to make fibre optic cables and power electronics withstand the hostile environment they should operate in. When assessing the heat reservoir and the subsequent production phase, the accumulated deposition of material inside the pipes (scaling) and the extreme corrosion and temperature problems need to be tackled from a materials' perspective. This involves the development of corrosion-resistant materials for the pipes, equipped with protective outer coatings and insulation, and inner liners. Novel polymeric, ceramic or metallic membranes to separate and re-inject gases would make the operation of a zero emission plant possible. During the operation, continuous monitoring of the system should allow for early intervention thus reducing the risk of a fatal breakdown of a well too early in its exploitation life. Also the downtime due to replacement or maintenance of instrumentation such as downhole pumps could be reduced by selecting specific metal alloys. Although R&D is being developed at the laboratory scale, field tests on the materials and components listed above need to be conducted under long-term operating conditions. The establishment of research wells, one at supercritical conditions, one in over-pressured reservoirs, and one to improve EGS technology and stimulation materials are proposed as technology pilots. The roadmap furthermore contains several proposals for research infrastructures in realistic laboratory or even in situ conditions. Materials standardisation would be the topic of one facility. In a large scale autoclave heat exchangers and working fluids can be tested, while research wells are needed to test the structural materials for the drilling tools and well components.

3.5. Electricity storage

Electricity storage is an essential technology to improve the manageability and flexibility of the European power system. Today, most storage technologies are too costly and exhibit inadequate technical performances for a wide-spread deployment and integration at system scale. Materials are often the limiting but also the determining factor in making storage technologies affordable, efficient, and reliable options for a secure and dependable electricity grid. Bringing storage technologies to a stage of commercial maturity and accelerating the transition to mass commercialisation is an overriding priority.

To do so, the materials roadmap for electricity storage proposes a comprehensive research and development programme on low-cost, safe and sustainable electro-chemistry, electrolytes and structural materials with superior electro-chemical, thermal and mechanical properties under severe operating conditions and long cycle life, new and innovative cell/system design and manufacturing processes for both energy oriented technologies (e.g. lithium-ion batteries, red-ox batteries, compressed-air energy storage, pumped hydro-storage) and power technologies (e.g. electrochemical capacitors, superconducting magnetic energy storage and flywheels) of industrial potential at European level. This programme focuses as well on developing new electrochemical paths and proofs of concept for emerging technologies such as metal-air batteries, solid state batteries, liquid-metal systems etc. In parallel, the roadmap puts forward up to 4 industrial pilots to demonstrate at industrial scale high-speed and low cost manufacturing processes for electrical double layer capacitors, lithium-ion, flywheels rotor and motor as well as for materials for high temperature compressors and high thermal and pressure resistant media for thermal storage and containers with application in compressed air energy storage; up to 5 pilot projects to test and verify the reproducibility and durability of the performance of these advanced storage technologies including alternative to all vanadium red-ox systems at MW or above scale, under realistic operating conditions in different market environments. This is complemented by the proposal to establish trans-European research and innovation networks that pool industrial and research resources together on a wide range of technologies and research and innovation activities and to set-up a European network of safety testing organisations for stationary applications. Recommendation is also made to establish education and training centres in the field of electrochemistry and storage.

3.6. Electricity grids

The objective of the SET-Plan on electricity grids is to enable the transmission and distribution of up to 35% of electricity from dispersed and concentrated renewable sources by 2020 and a completely decarbonised electricity production by 2050; to integrate further national networks into a market-based truly pan-European network, to guarantee a high quality of electricity supply to all customers and to engage them as active participants in energy efficiency; and to anticipate new developments such as the electrification of transport. A pan-European network will be important for ensuring the quality of supply and the stability of the whole system, and the distribution network in particular will play a key role in the future energy system.

In response to these needs, the materials roadmap on electricity grids proposes a research and development programme on the development of high temperature superconductor materials (HTS) and manufacturing processes for DC and AC cables to ensure uniform critical current and enhanced magnetic field performance and to reduce cost at least by a factor of 10; the development of advanced composites for cables (including new carbon fibre and plastic core composite material and metal matrix composite) with enhanced mechanical, electrical and thermal performance; the development of polymer based insulating materials and their manufacturing processes for high voltage insulated cables, on line and station insulators; the development of wide bandgap semiconductor materials for 20 kV power electronics devices for high injection operation. The roadmap focuses also on the development of enabling structural materials for advanced packaging for power electronic devices at high temperatures as well as on the thermal behaviour of materials at cryogenic temperatures. In addition, to accelerate the transfer to market, the roadmap puts forward one technology pilot project to simulate, qualify and test new HTS materials and components and their interaction with the grid; and one pilot to improve significantly the manufacturing processes of HTS materials. This is complemented by the proposal to establish a European (or network of) grid testing facility on HTS and to set up a European research infrastructure for pre-stress application for advanced composites.

3.7. Bioenergy

The SET-Plan aims at accelerating the commercial deployment of bioenergy technologies for widespread sustainable exploitation of biomass resources in order to ensure at least 14% bioenergy in the EU energy mix by 2020, and at the same time to guarantee greenhouse gas emission savings of 60% for bio-fuels and bio-liquids. Achieving this objective will require the development and testing of a broad range of technology value chains flexible enough to operate with different feedstock quality and to produce a wide range of products.

To this end, the Materials Roadmap on bioenergy proposes a wide research and development programme covering 5 focus areas. In the first focus area, the emphasis is on high strength, wear- and corrosion-resistant structural materials such as steel, alloys and protective coatings, high durability polymers and ceramics to reduce the time to market and the life cycle costs of technologies and to improve their recycling. The second focus area covers the further development of catalysts, allowing for higher selectivity and yield, improved stability and functionality such as bi-/multi-functional catalytic systems. The third focus area includes the development of advanced ceramic, polymeric or metallic membranes for gas separation and separation of inhibitory or intermediary products from biomass pre-treatment. Also the efficient separation/recycling of enzymes, the immobilization of cells, and downstream processing in continuous separation of fermentation products needs materials solutions for advanced membranes. The roadmap focuses also on hydrolytic enzymes and novel microorganisms in a fourth focus area. Finally, advanced research in the domain of photosynthesis is presented in the fifth and final focus area. To advance the material and component development to industrial scales, the roadmap proposes up to 3 pilots: one pilot should develop the manufacturing of components with corrosion resistant steels, alloys and coatings; one on active coating application techniques and one on photosynthetic process materials. Testing the technology is proposed to happen in 4 pilots: one on testing fluidised bed materials under realistic operating conditions. A second pilot should test novel poisoning-resistant and long life catalysts. Testing the technical performance of polymeric, ceramic or metallic membranes and filters is proposed to be the topic of the third pilot. The last pilot is intended to test strains and vectors for screening and industrial scale production of strains and vectors for screening and industrial production of recombinant enzymes. In addition the roadmap proposes the creation of multi-disciplinary research centres of excellence and scientific networks to perform intensified research on a wide array of materials related topics ranging from pre-treatment technologies to the full life cycle analysis for biomass utilisation.

3.8. Novel materials for the fossil fuel energies sector, including carbon capture and storage

The SET-Plan aims, through research and innovation activities, to enable the cost competitive deployment of carbon capture and storage (CCS) technologies in the power sector by 2020 or soon after and to further develop the technologies to allow for their subsequent wide-spread use in all carbon intensive industrial sectors. Achieving this goal will necessitate the development and validation of new materials, manufacturing and testing processes. The capture of CO_2 requires functional materials that can separate efficiently CO_2 from a stream of flue and syn-gases. Increasing the efficiency of power plants, especially after the application of CCS, which is energy demanding, requires the increase of operating temperatures in boilers and burners, which in turn necessitates advanced materials that can operate in temperatures higher than those of today.

In response to these needs, the materials roadmap for the fossil fuels sector proposes a research and development programme that focuses on the optimisation of functional materials for post combustion capture, such as solvents and advanced solvents, high temperature solid sorbents, other solid absorbers and membranes that could separate CO_2 with a low energy penalty; the development of oxygen carriers and sorbents for chemical looping and pre-combustion technologies with lower cost per tonne of CO2 separated and of separation membranes with high permeability at high temperature and long lives; the development and optimisation of high temperature materials and protective and thermal barrier coatings with superior creep and oxidation resistance properties after long exposure at 800°C; the development of enhanced research capabilities to study and mitigate the influence of the harsh operating conditions on materials; the development of novel materials, such as refractory metals, metal composites, intermetallics and gradient materials, with superior performance at very high temperatures; and the development of materials for storage technologies. To accelerate the transfer to market of the research results developed above, the roadmap puts forward up to 4 industrial pilots to validate processing and manufacturing routes and the performance of high temperature materials and coatings under realistic operating conditions; up to 6 pilot projects to test advanced separation processes at industrial scale and a series of research infrastructures to model, test and standardise material/component performance evolution and to validate the outcomes of the pilot projects.

3.9. Hydrogen and Fuel cells

The Fuel Cells and Hydrogen Joint Technology Initiative aims to develop and test cost-competitive, high energy efficient fuel cell systems and sustainable hydrogen infrastructure technologies under real market conditions for transport and stationary applications. Achieving this goal will necessitate dramatic improvements in the economics, performance and reliability of fuel cells and hydrogen technologies. The need for new materials is overarching.

The roadmap for hydrogen and fuel cells proposes a comprehensive research and development programme for the development of low cost, high conductivity ionic and electronic conductors operating at a wide range of temperatures and pressures and stable under different chemical and mechanical conditions with long cycle life; the development of low-cost enhanced catalysts for both low and high temperature applications that withstand corrosion and exhibit a tolerance to impurities; the development of low-cost functional materials for hydrogen purification, storage and thermo-chemical cycles technologies with improved chemical and mechanical properties; the development of low cost, reliable and corrosion resistant structural materials for pressurised and cryogenic hydrogen storage, hydrogen transport, coal gasification, thermo-chemical cycles as well as sealant materials to maintain hydrogen tightness and to withstand thermal cycles. This programme focuses as well on developing novel materials with enhanced performances for electrolytes, catalysts, photo-materials and hydrogen storage materials. To reduce the time-to-market of these materials and associated manufacturing processes, the roadmap puts forward up to 4 industrial manufacturing pilots for proton exchange membranes and solid oxide fuel cells and water electrolysis applications, photo-electrochemical cells for hydrogen production and hydrogen storage tanks for automotive applications to demonstrate at scale and verify the reproducibility and durability of their performance, up to 3 industrial pilots to test and qualify the resulting manufactured components and systems in real operating conditions. These research and pilot activities are underpinned by the proposal of up to 3 (or network of) testing facilities at European level in the field of fuel cells for automotive applications, large scale hydrogen production by water electrolysis and hydrogen purification and storage materials. Cross-technology pilots and testing facilities are recommended for structural materials.

3.10. Nuclear fission

Nuclear Energy contributes to the SET-Plan objective to develop low carbon energy technology. In this framework, the SET-Plan aims to design and build over the next decade prototypes and demonstrators of fast neutron reactors, technologies for a more sustainable nuclear energy through a better resources utilisation and the reduction of potential impact of ultimate radioactive waste. These future reactors will have favourable safety characteristics by maximising inherent and passive safety features. On the other hand, the higher temperatures and irradiation levels as well as different coolants than Generation II/III reactors, foreseen for these systems, will require other materials to those used for Light Water Reactors.

In response to these needs the materials roadmap for nuclear fission proposes a research and development programme on commercially available material (steel and Ni-alloys) for the prototypes and demonstrators; and advanced materials for the industrial scale systems. The focus is put on cladding application (Oxide Dispersion Strengthened -ODS- steels for liquid metal fast reactor and composites, e.g. SiC_fSiC, for gas fast reactor an lead fast reactor) with the aim to improve high fuel burn-up capabilities and high temperature resistance; on coating technologies to enhance corrosion and erosion/wear resistance in liquid metal fast reactor and on novel materials based on Ti based alloys.

Based on the research results developed above, the roadmap puts forward up to 4 pilot projects to validate manufacturing routes of 9Cr steel heat exchanger, of fuel cladding tubes with ODS and SiC_fSiC and coatings pilot plant(s) to treat relevant components for liquid metal fast reactor; 4 pilot projects to test 9Cr steel heat exchanger out of pile, fuel cladding tubes with ODS and composites (e.g. SiC_fSiC) out of pile and possibly in pile, and to confirm wear resistance and corrosion resistance of large scale coated components. This is complemented by the proposal to refurbish and/or built a series of research infrastructure in support: irradiation facilities, hot laboratories, high temperature testing systems and large scale facilities for out of pile testing of components. In addition, a modelling centre would be of high relevance for the materials performance assessment in a multiscale approach.

3.11. Energy efficient materials for buildings

The roadmap on energy-efficient materials for buildings technologies aims at reducing the embodied and operational energy consumption of buildings over their entire lifetime. The construction sector is the largest raw material consuming industry, with a volume that in Europe alone exceeds 2 billion metric tons per year. The energy demand of buildings is about 40% of the global energy consumption. Even incremental improvements in the uptake of improved building materials by the sector could lead to a huge overall beneficial impact on the energy consumption as well as on the environment in general. Developing new materials for the construction of new buildings or – volume-wise certainly more importantly - retrofitting existing ones, thus certainly qualifies for the highest priority.

Given the extremely wide range of materials used and re-used in the building sector, this roadmap focuses on those areas where the highest savings in embodied and operational energy can be expected. A detailed research and development programme is proposed to cover structural elements (mainly innovative solutions to concrete and steel-based products), finishes and the envelope (mainly ceramic products and steel-based products), glased components for light directing elements, and insulation (from traditional to advanced bio-based). Focus is also on novel materials intended to feed selected advanced materials towards large-volume manufacturing and cost-effective developments of super-insulating materials, potentially reaching industrial up-scaling within the proposed 10-year time frame. In parallel yet shifted in time, pilots on carefully selected materials and materials production methods are proposed to demonstrate that bench-marked results of the research and development programme sketched above are viable for uptake by the industry. Although reducing the embodied energy while keeping a zero production cost increase remains the prime target, equal attention thereby goes to a pilot on manufacturing of advanced bio-based insulation materials. Because of the long lifetime of buildings, a pilot is proposed to develop methods to evaluate the durability of the proposed material solutions as well as their performance during aging. Research infrastructures are primarily needed to concentrate R&D efforts to adapt, test and introduce material developments from other technologies (e.g. nanotechnologies) into the building sector. A centre-of-excellence on energy-efficient ceramic materials should prevent fragmentation and enforce Europe's leading position in the world in this domain.

4. SYNERGIES

4.1. Materials and Manufacturing

The roadmaps address a large number of materials and processing activities. While being designed to address the specific needs of the technology, several materials are common to more than one technology. In addition, a broad range of activities proposed are of similar nature calling upon similar research and industrial capacities being developed to understand the fundamental nature of materials or processing technologies. Table 1 shows the research areas that are common to several technologies.

Leveraging these commonalities and synergies is of critical importance for the implementation of the roadmap. Economies of scale and scope can be realised and cross-technology knowledge can be pooled together at European level to accelerate the development and integration of innovative materials into low carbon energy technologies.

Table 1: Research areas common to several technologies

	Wind energy	Photovoltaic	Concentrated Solar Power	Geothermal energy	Electricity storage	Electricity grids	Bioenergy	Carbon capture and storage	Hydrogen and fuel cells	Nuclear fission	Buildings
Structural materials											
Fibre reinforced materials	X		X			X			X	X	
High temperature, low temperature and corrosion-resistant materials	X		X	X	X		X	X	X	X	
Structural steel components and related joining techniques	X		X	X	X		X	X		X	X
Advanced concretes	X			X			X			X	X
Functional materials											
Separation membranes				X			X	X	X		X
Catalyst and electrolytes					X		X	X	X		
Solid catalyst, sorbents and O2 carriers					X		X	X	X		
High temperature superconducting materials	X					X					
High temperature heat storage materials			X		X				X		
(High temperature) insulating materials			X	X		X		X		X	X
Materials for power electronics	X	X		X		X					
Heat transfer fluids			X	X						X	
Manufacturing techniques											
Coatings and coating techniques	X	X	X	X	X		X	X	X	X	X
Condition monitoring techniques	X	X		X	X		X	X	X	X	

4.2. Research Infrastructures

Research Infrastructures such as simulation and modelling capacities (supercomputing) and advanced characterisation techniques are critical tools for exploring complex phenomena, designing advanced materials and predicting and testing their functionalities and performances before manufacturing and throughout their lifetime. All technology-oriented roadmaps have prioritised the need for such leading research infrastructures in Europe and stressed the importance for dedicated cross-cutting efforts and implementation. Furthermore, results from advanced experimental characterisation techniques should be closely coupled with advanced modelling in order to enable detailed understanding of experiments.

4.2.1. Simulation and modelling

Materials design

Materials that are highly functionalised will have to be modelled according to various approaches based on elementary physical and chemical principles but also from macro to micro scale in order understand the correlation between atomic-level structure and function, between materials architecture and the mechanical, chemical and physical properties etc. This is crucial for the materials design where optimised sets of functions will guarantee the highest added value of new materials solutions. The development of ab-initio methods for the modelling of materials with catalytic, electrochemical, electronic or photonic functions, simulation methods for modelling mechanical properties and architectures will require joint efforts across Europe in order to be competitive with cutting-edge activities of other international players. The integration of materials and their functions into components requires more and more complex numerical simulations. This concerns the interfaces from material to material and the functions of different materials within the component. Large scale numerical simulations integrating wide ranges of chemical, physical and electronic processes are required. At the European level, the joint development of methods has to go hand in hand with the necessary access to the computational power required. To this respect, the activities carried out on supercomputing in the frame the European Strategy Forum on Research Infrastructures (ESFRI) will be instrumental.

Materials modelling of aging mechanisms

The expected lifetime of energy facilities typically exceeds ten years and is often in years range of 50 years. A key to predict the behaviour of materials on these very long time scales is the understanding and modelling of material aging processes that accumulate damage ultimately leading to the failure of the component. Chemical degradation mechanisms like corrosion can go hand-in-hand with mechanical fatigue and components may fail due to the simultaneous action of such processes. In addition to the development of models for single damage processes these interactions have to be included. The development of complex models for damage and lifetime predictions often exceeds the capability of single institutions. Means and models to predict materials behaviour and lifetime would enable European industry to optimise their products and to issue warranties that are more competitive on the international scale. A European initiative on predictive modelling of energy materials aging mechanisms is a possible means of support.

4.2.2. Materials characterisation

The development of new materials requires a combination of characterisation methods at difference scales to understand and to design the relationship between materials structure and function. Characterisation of the functions at atomic level as e.g. in the case of ion transport through membranes the lattice distortion in new materials has to be measured. Catalytic, photonic and electrochemical processes with high time resolution are required. At the mesoscopic level, the entire nano-scale has to be covered by suitable characterisation methods. Properties at macro-scale such as for composite materials needs to be investigated down with testing methods that allows high magnification observation of internal architecture, defects and damage evolution. Often only large to very large scale cutting edge facilities can fulfil these characterisation requirements like dedicated microscopes with subatomic resolution, particle beam analysis methods, synchrotron radiation based methods, including 3D hard X-ray tomography, neutron based methods, etc.

At the European level a range of facilities exists, but these are often not fully exploited for the development of new energy materials. A close coordination with the energy materials science community would lead to an optimised exploitation of these opportunities. The formation of a European network/platform of "cutting edge" characterisation facilities and the definition of access schemes to these facilities will greatly help academic institutions as well as industry to improve and advance their materials development activities. Missing methods that are not sufficiently available at the European level could be established by a joint effort, for instance, in the frame of ESFRI.

4.3. Multi-disciplinary research

Another important aspect for the implementation of the roadmap is the need to conduct multidisciplinary research, also exploiting the potential of converging technologies, and to bring to operational successes the cooperation between industry and research organisations fostering the transfer to market of research results across the EU. European research efforts currently suffers from being too dispersed and insufficiently coordinated to fully realise its performance potential and ensure long term EU leadership on low carbon technologies. To this end, the roadmap proposes a set of recommendations to establish scientific and cross-technology European open innovation networks and clusters based on national capacities that would ensure cross-access to researchers, industry and resources.

4.4. International Cooperation

Materials and energy technology markets are global by nature. All over the world, investments in materials research and innovation activities are being intensified. Europe needs to seize these opportunities. International cooperation can speed the deployment of materials for clean and efficient energy technologies. This includes long term, pre-competitive research and innovation, including pre-normative research, but also on large-scale research infrastructures such as characterisation, simulation and modelling facilities, standardisation and the sustainable supply of resources, in particular of critical materials. Building international alliances and partnerships can also support the EU Industry to access the global materials and energy technology markets for energy applications; strengthening the EU position in the global energy materials sector.

5. CROSS-CUTTING ACTIVITIES

Beyond the technology-specific actions envisaged in the Materials Roadmap, additional cross cutting activities need also to be considered, which will ensure the successful implementation of the Roadmap.

- Standardisation: Standardisation of and common regulations for material specifications, products and testing procedures need to be further promoted to ensure the access of European products to the European and world markets. In this respect, collaboration with international standardisation bodies need to be further strengthened.

- Information: Benefits that will come about from the installation of low carbon technologies and the related materials must be clearly and actively communicated to consumers to instigate change of behaviour and more sustainable choices. This activity is closely linked to labelling but also to other actions related to advertising and marketing of products and services related to the materials specified in the present Roadmap. To improve information provisions, Europe needs to consult with other large economies (e.g. within the G20 group) and other international organisations such as the OECD, the World Bank and the UN.

- Supply of critical raw materials: Many low carbon energy technologies rely on rare raw materials, such as rare-earth metals, which are by and large imported in Europe[2]. The Raw Materials Initiative of the European Union and in particular the recent strategy on non-energy raw materials[3] and the proposed Materials Innovation Partnership, aim at ensuring the fair and sustainable supply of raw materials from international markets, at fostering sustainable supply within the EU and at boosting resource efficiency and promote recycling. It is thus essential that these initiatives be implemented to secure and improve access to raw materials for the EU.

- Resource efficiency and sustainability of materials. Activities related to assessing the sustainability of materials, the impact of their production, use, recycling, disposal or substitution on a broad range of resources in line with the approach of the Roadmap to a resource efficient Europe, are essential for the further development of energy technologies. Aspects related to recycling, at manufacturing as well as at end-of-life, and design for recycling/cradle-to-cradle approach are an integral part of the proposed developments. Furthermore, activities that will establish the environmental footprint of products and processes, through full life cycle analysis and other methods, need to be established. To this end, further reinforcing the work of the European LCA platform[4] and the complementary work on the energy and carbon footprint of the information and communication technologies (ICT) sector[5] will be a meaningful step in the right direction.

- Market side measures: the market up-take of sustainable and resource efficient materials and technologies requires a conducive environment. To this end, it is

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2 European Commission / JRC : Critical Metals in Strategic Energy Technologies: Assessing Rare Metals as Supply-Chain Bottlenecks in Low-Carbon Energy Technologies, R.L.Moss, E.Tzimas, H.Kara, P.Willis and J.Koorosh, EUR 24884 EN, 2011.

3 COM(2011)25

4 http://lct.jrc.ec.europa.eu/

5 http://ec.europa.eu/information_society/activities/sustainable_growth/ict_sector/index_en.htm

important that the regulatory framework, demand side instruments etc. support the up-take of research and innovation outcomes and further stimulate innovation.

- Education and training: The expansion of European capacities to innovate in the area of materials through the continuous advancement of the quality of skills of materials scientists and engineers are essential for the continuous advancement of knowledge on materials and for ensuring technological development. This can be achieved through the improvement of existing related education and training programmes and the encouragement of the development of new ones offering both basic skills and advanced training, thus addressing research and innovation, tailored to the current and future needs of our society.

6. NEXT STEPS

The Materials Roadmap presented in this document is intended to contribute to and promote coherence and synergy among the research and innovation activities launched by the all concerned stakeholders.

The Materials Roadmap will be implemented in the context of the SET-Plan. The next steps are to detail further the defined actions for implementation within a strategy-led approach; the timing of commitment of resources needs to be aligned to priorities and availability of funds; key performance indicators need to be further elaborated and agreed; and concrete projects have to be identified for rapid implementation.

The roadmap puts forward a comprehensive research and innovation package on a Key Enabling Technology for the SET Plan. It emphasises the need for a value-chain perspective in its implementation. To this end, support will be provided at European level to the roadmap from the different parts of the Union's Framework Programme.

The Commission will also put the emphasis on implementing it jointly with Member States and industry e.g. through the SET-Plan mechanisms the European Industrial Initiatives (EIIs) and the European Energy Research Alliance (EERA) Joint Programmes, as well as relevant Public Private Partnerships. This can also be complemented with support that may be provided by national or regional authorities under the Cohesion Policy funds within the framework of their innovation strategies for smart specialisation.

Close links will be ensured with other European Initiatives on energy and materials such as the Raw Material Initiative to ensure a comprehensive coverage of the roadmap proposals and effectiveness and efficiency of the EU intervention.

Materials, including critical materials are a priority area of cooperation between the EU and US under the US EU Energy Council. The Commission will propose a transatlantic workshop with the US in 2012 to boost further cooperation initiatives and actions with added value, including coordinated research, lab to lab cooperation and other efforts to foster greater research cooperation. Cooperation with other strategic partners to the EU will also be explored in parallel when mutually beneficial.

The information system of the SET-Plan (SETIS) will support the monitoring of this Materials Roadmap and the further definition of the Key Performance Indicators to measure progress.

ANNEX
The technology oriented roadmaps

Materials Roadmap for Wind Energy[1]

1. MATERIALS R&D AND RELATED PRODUCT DEVELOPMENT

1.1. Focus Area 1: Blade materials

1.1.1. Fibre-reinforced materials

- Materials modelling from micro-scale via phenomenological and subcomponent approach to full-scale modelling and extension of current databases with test specimen data and subcomponent data. Special emphasis has to be put on the uncertainty of material testing, to bring down the standard deviation of test results;

- Development of new/improved materials that combine high strength, stiffness, toughness and fatigue resistance for the production of very light blades;

- Development of recyclable materials for blades such as thermoplastics as well as natural fibres and biopolymers.

1.1.2. Sandwich core materials

- Development of cost competitive, very light weight core materials that perform at least as good as the currently used balsa wood and PVC foams and that can be recycled and produced in an environmental sustainable manner.

1.1.3. Adhesives and joining/bonding materials

- Development of adhesives and joining/bonding materials suited for the newly developed structural blade materials;

- Material characterization and modelling of adhesives and bonding materials to enable state of the art strength and fatigue analyses

1.1.4. Coatings

- Development and testing of blade coatings to increase the biofouling erosion and UV light resistance, the self cleaning capability and the ice shedding efficiency;

- Development and testing of blade coatings to reduce the detectability of static or rotating wind turbines by radars ("stealth" materials).

[1] The effective and sustainable use of resources is critical for the further development of energy technologies. Aspects related to recycling, at manufacturing as well as at end-of-life, and design for recycling/cradle-to-cradle approach are an integral part of the proposed developments.

1.1.5. Condition monitoring techniques

- Development of condition monitoring and other non-destructive testing techniques to monitor the blades during their life time and during full scale testing of blades.

1.1.6. Manufacturing techniques

- Systematic research into the influence of blade manufacturing methods with the aim to investigate the influence of the production process, resin infusion technology and/or prepregs technology on the material properties and to speed up production cycles and to ensure a reliable production.

KPIs:

Research areas	KPI
1.1.1	The blade material properties (stiffness, tensile strength, etc) over weight ratio must be increased by >30% at the same or lower blade costs
1.1.2	Core material at least 30% lighter than currently used balsa wood and PVC foam with the same or better mechanical properties at competitive costs
1.1.3	Development and characterization of bonding materials has to be in line with the developments of the fibre reinforced materials
1.1.4-a	The developed coatings must protect the blades against erosion both for on- and offshore conditions and increased blade tip speeds up to 100m/s during the entire lifetime of the blade
1.1.4-b	The developed coating must reduce blade detectability by radar
1.1.5	The condition monitoring components must have a lifetime that equals the life time of the monitored components (indication: for most components 20 years), and provide information on the components consumed lifetime
1.1.6	Blade production cycle times must be reduced to 50% of the current state of the art cycle times. (indication: up to 1 day for blades of 2-3 MW turbines)

1.2. Focus Area 2: Tower and support structure materials

1.2.1. Material developments and related joining technologies

- Development of high strength, heavy gauge, steels (thickness above 30 mm), with high toughness down to -50°C and with well suited welding technology;
- Development of high efficient, in terms of productivity, welding techniques as submerged arc welding, laser welding and non-vacuum electron beam welding and hybrid-friction stir welding;

- For onsite joining of parts the development of automatic or robotised gas metal arc welding procedures and the further development of bolted flange and friction connections;

- Application of coatings and development of new protection methods for towers and substructures to reduce erosion, oxidation and biofouling.

1.2.2. Concrete

- Development and application of drilled concrete monopiles and gravity based support structures for deep water applications.

KPIs:

Research areas	KPI
1.2.1	Steel yield strength > 355 MPa, facture toughness K_{JC} > 100Pam^{½} at -40°C. Welded joints must sustain high cycle fatigue loads above 90-100 MPa. Toughness guarantee in HAZ even for welding with very high heat input (above 5kJ/mm)
1.2.2	Drilled concrete monopiles and gravity-based support structures feasible up to 50m water depth.

1.3. Focus Area 3: Cast iron components

1.3.1. Foundry technology

- Development of foundry technology for dross-free ductile iron with high strength and high wall thickness;

- Development of foundry technology that allows the designer to define the geometry instead of the foundry technology.

1.3.2. Material development/manufacturing process

- Better control of metallurgy and mechanical properties through controlled casting (gating, flow of melt, mould material), allowing for a uniform internal structure or a better designed internal microstructure tailor made for the operational loads.

1.3.3. Composites

- The development of light weight composite structures that can replace cast iron components, as fibre reinforced light weight metal structures or complete fibre reinforced structures.

KPIs:

Research areas	KPI
1.3.1	Weight reduction in cast components >25% compared to current technology
1.3.2	Uniform internal structures/ designed microstructures tailor made for applied loads
1.3.3	Targeted weight reduction: 50% compared to cast iron

1.4. Focus Area 4: Generator materials and power electronics

1.4.1. Permanent magnet materials

- Reduction of use and substitution of rare earth elements in permanent magnet generators;
- Development of stronger, lighter magnets with improved key magnet parameters including intrinsic coercivity and remanence.

1.4.2. High temperature superconducting materials

- Development of high temperature superconducting (HTS) generators for the application in large MW wind turbines;
- This includes the development of robust, reliable and low maintenance cryogenic techniques required for generator cooling;
- Reduction in the price of superconductor wire.

1.4.3. Power electronics and power converters

- Development of new/adapted materials to increase the working limit of junction temperatures.

KPIs:

Research areas	KPI
1.4.1	• Rare earth content (in mass) at equal magnetic density: neodymium (31 % currently, 28 % by 2015, 25 % by 2020 and 20 % by 2030), dysprosium (2.3 % today, 2 % by 2015, 1.8 % by 2020) • Power density range increasing from 270-422 kJ/m^3 in today's most performing magnets, 360-500 by 2020 and 460-535 kJ/m^3 by 2030

1.4.2	• Superconducting wire cost - 300 €/kA-m today to 30-40 €/kA-m by 2020 and below 15 €/kA-m by 2030 • Superconductor temperature - 70 K today to 85 K by 2015 at laboratory level and by 2020 in the market.
1.4.3	Power electronics • Increase in junction temperatures of commercially-available devices, e.g. for IGBTs from today's 150 ºC raising to 200 ºC by 2015, 225 ºC by 2020; • Current rating to 330 A by 2013, 500 A by 2020; • Voltage: from today's low voltage raising to 6 kV by 2013; 15 kV by 2020, 25 kV by 2030. Power converters • Medium-voltage converters with voltage levels of 6, 15 and 25 kV as above; • Medium-voltage switches and cables without a significant price increase or loss of performance; • Topologies: 3-level converters and other more developed structures.

1.5. Focus Area 5: Transmission materials (main shaft, gears, bearings)

1.5.1. Metal alloys

- Development and production of steels with low non-metallic inclusions;
- Development of measuring and detection techniques for bearing behaviour and damage, and detection techniques for exogenous inclusions on gear blanks;
- Determination of the influence of various grinding and finishing techniques on the topography of gear teeth and rolling element bearing surfaces and the degree of surface finishing required for the required service life;
- Development of new surface coatings such as PVD coatings, nitriding treatments and laser treatments to improve teeth properties.

1.5.2. Non –metal issues

- Development of new durable, stable, non corrosive, environmentally-friendly lubricants; specific requirements for hot and cold climate conditions need to be addressed in these developments.

- Determination of the solid contaminant influence on lubricants;
- Development of components, sealants, paints, complying with environmental legislation.

KPIs:

Research areas	KPI
1.5.1	The effective lifetime of the transmission components must be equal to the design lifetime maintaining same total costs (manufacturing + maintenance costs) - indication: nowadays mostly 20 years.

2. MATERIALS INTEGRATION AND COMPONENT TECHNOLOGIES

2.1. Manufacturing

Pilot 1: Development and production of concept blades at MW scale (Start of design activities T0).

The development of very cost efficient and light weight blades, needs to be stimulated through the design, manufacturing and testing of concept blades where, irrespective of costs, new materials and manufacturing techniques can be developed and demonstrated at MW scale.

KPIs: Weight less than 50% of state of the art light weight blade. Costs reduction up to 25% (material +production). Size MW scale. Inclusion of distributed control devices is optional.

Pilot 2: Development, manufacturing and demonstration of light weight (composite) hub, bedplate or generator-gearbox housing as alternative for cast iron components. (Start of design activities T0).

KPI: Weight reduction > 50% compared to cast iron alternative. Costs less or at least at same level (material and production). Size MW class.

Pilot 3: Design, production and testing of large blades with a length of over 100 m that allows the economic design of 10-12 MW turbines.

Keywords: new structural design solutions, high strength materials, light weight sandwich foams.

KPI: Blade length +100 m.

Pilot 4: Automated production techniques in a MW scale blade production line.

Keywords: fast curing resins, automated positioning of fibre fabrics, improved resin infusion, etc.

KPIs: Blade production speed-up of 50% and reduced production costs.

2.2. Technology

Pilot 1: Development and demonstration of a gravity based support structure for large water depth (T0 + 3-5).

KPIs: Water depth 40-50 m, turbine size >5 MW.

Pilot 2: Demonstration of a HTS generator (T0 + 3).

KPI: Weight reduction > 50% compared to PM generator. Size MW class.

3. RESEARCH INFRASTRUCTURE

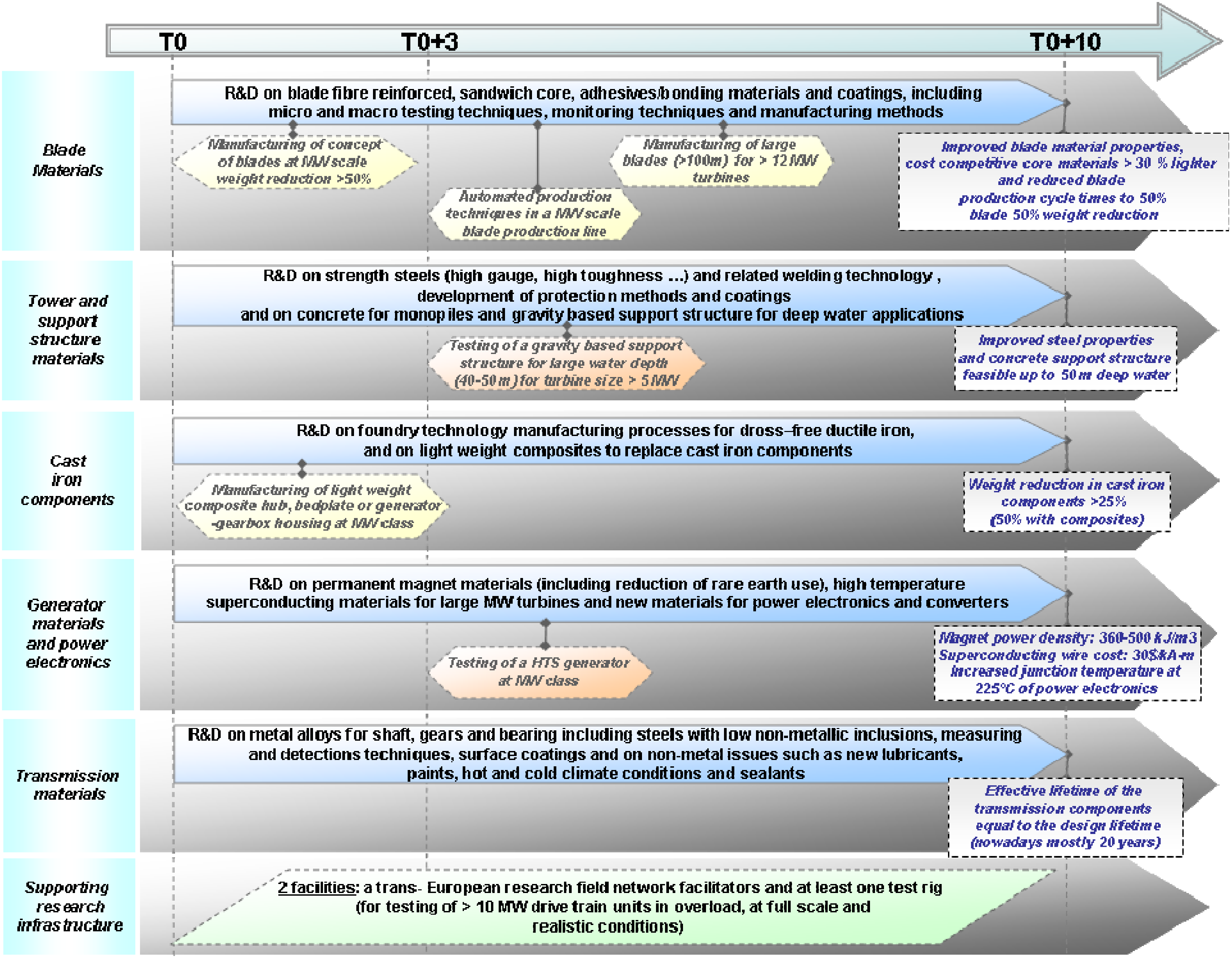
Facility 1: Trans-European research field network facilitators (Start T0)

Establishment of trans-European research field network facilitators as a contact point for R&D organisations and industrial parties to coordinate R&D activities with respect to:

- Fibre reinforced materials:
  - wind turbine blade materials;
  - light weight alternatives for castings and heavy steel plate structures;
- Gearbox and bearing materials including lubrication aspects;
- High strength castings and forgings, material as well as manufacturing aspects;
- High strength materials for towers and support structures, including welding aspects;
- Generator materials as REE usage, alternative materials and recycling, HTS materials.

Facility 2: Drive train test rig (Start T0 + 5 years)

At least one test rig for the testing of large > 10MW drive train units (gearboxes, generators and other transmission components) in overload, at full scale and under realistic, including cold climate and offshore, conditions. The test rig must be able to simulate the transverse and axial loadings on the main shaft.


T0
T0+3
T0+10
Blade Materials
R&D on blade fibre reinforced, sandwich core, adhesives/bonding materials and coatings, including micro and macro testing techniques, monitoring techniques and manufacturing methods
Manufacturing of concept of blades at MW scale weight reduction >50%
Automated production techniques in a MW scale blade production line
Manufacturing of large blades (>100m) for > 12 MW turbines
Improved blade material properties, cost competitive core materials > 30 % lighter and reduced blade production cycle times to 50% blade 50% weight reduction
Tower and support structure materials
R&D on strength steels (high gauge, high toughness …) and related welding technology, development of protection methods and coatings and on concrete for monopiles and gravity based support structure for deep water applications
Testing of a gravity based support structure for large water depth (40-50 m) for turbine size > 5 MW
Improved steel properties and concrete support structure feasible up to 50 m deep water
Cast iron components
R&D on foundry technology manufacturing processes for dross–free ductile iron, and on light weight composites to replace cast iron components
Manufacturing of light weight composite hub, bedplate or generator -gearbox housing at MW class
Weight reduction in cast iron components >25% (50% with composites)
Generator materials and power electronics
R&D on permanent magnet materials (including reduction of rare earth use), high temperature superconducting materials for large MW turbines and new materials for power electronics and converters
Testing of a HTS generator at MW class
Magnet power density: 360-500 kJ/m3 Superconducting wire cost: 30$/kA-m Increased junction temperature at 225°C of power electronics
Transmission materials
R&D on metal alloys for shaft, gears and bearing including steels with low non-metallic inclusions, measuring and detections techniques, surface coatings and on non-metal issues such as new lubricants, paints, hot and cold climate conditions and sealants
Effective lifetime of the transmission components equal to the design lifetime (nowadays mostly 20 years)
Supporting research infrastructure
2 facilities: a trans- European research field network facilitators and at least one test rig (for testing of > 10 MW drive train units in overload, at full scale and realistic conditions)

Materials Roadmap for Photovoltaic Energy[1]

1. MATERIALS R&D AND RELATED PRODUCT DEVELOPMENT

1.1. Focus Area 1: Optimised materials usage

1.1.1 Development of predictive behavioural material models (down to the quantum and nano scale - grain interfaces, impurities, crystal defects, opto-electronic properties, transparency, conductivity, layer thickness, layer interfaces, device architecture (especially multi junction), ageing effects;

1.1.2 Improvement of performance of materials (for both inorganic and organic PV), processes and devices for thinner layers, wide band gap gradiented absorber layers and device characteristics; buffer layers with no toxicity; lead-free solders; transparent indium-free conductors; silver-free metallisation conductors; T0-T10 (This will be an ongoing requirement to improve performance of all types of solar cells/modules);

1.1.3 Applied research on manufacturing processes for specific solar grade materials – Alternative refining and manufacturing processes for specific PV grade materials. The materials in question can be but not limited to polysilicon, crystallisation and wafer cutting, CIGS, CdTe and organic compounds. Sections 1.1.1 will support the efforts needed to develop such new processes;

1.1.4 Development of thinner, higher strength, conformal, lower cost glass through new glass compositions, novel tempering, novel inter layers, module re-design;

1.1.5 Basic and applied research on encapsulants and optical glues - Flexible, light weight, low cost and high barrier encapsulants and optical glues materials with life times of 40 years by 2030. This should also include the development of appropriate ageing tests.

KPIs:

Research areas	KPI
1.1.1	Availability of robust proven predictive modelling tools
1.1.2	Layer CdTe <1,5µm / CIGS <1,0 µm; Wider total layer band gaps than current (e.g. TFPV 1,7-1,8 eV; multi junction 2,2 eV); Elimination of all toxic substances in PV devices; Non indium containing TCOs with adequate performance; Low Silver / silver free metallisation. The combined effect of all improvements should lead to a reduction by 50% of the LCOE by 2020 and >65% by 2030 compared with 2011
1.1.3	Robust definition of adequate solar grade material; Lower cost solar grade material manufacturing process (e.g. polycrystalline Si 10-20 €/kg); high yield mono-casting ($V_{mono\text{-}Si}/V_{total}$ >90%) and wafer separation (loss<1g / Wp

[1] The effective and sustainable use of resources is critical for the further development of energy technologies. Aspects related to recycling, at manufacturing as well as at end-of-life, and design for recycling/cradle-to-cradle approach are an integral part of the proposed developments.

	lower energy input for manufacture; lower GHG footprint
1.1.4	Glass thickness reduction - <1mm by 2020
1.1.5	Life time40 years; cost reduction 75%; (Based on a validated life time prediction model)

1.2. Focus Area 2: Light management

1.2.1 Development of anti reflective coatings (ARC), anti soiling coatings (ASC), anti abrasion coatings (AAC) with improved performance coatings to maximise the amount of light entering a device;

1.2.2 Basic and applied research on light trapping / guidance - Improved light capturing and management in the device through surface texturing , structuring and photonic structures for spectrum splitting and light guidance for single and multi junction PV cells with active layers <1 µm;

1.2.3 Basic and applied research on spectral conversion - Up and down conversion of light frequency through specially developed phosphor or rare earth materials to increase the quantity of light energy suitable for conversion. Some of these materials may qualify as novel materials as they will only be available post 2020;

1.2.4 Development of new materials development, lens design and production processes of optical concentrators to enhance the optical concentration especially at high sun values with resistance to high UV-doses.

KPIs:

Research areas	KPI
1.2.1	ARC - Improve module efficiency by 0,7%; ASC - Transmittance >96%; Reduction of soiling loses by >50%
1.2.2	Surface texturing applied to absorber layers of <1µm as well as for bulk materials
1.2.3	Layer cost <0,05€/Wp (module cost 0,5€/Wp); 10% of current efficiency improvement
1.2.4	Contribute to HCPV system efficiency >39%; Lifetime 40 years

1.3. Focus Area 3: High throughput, low cost film/layer deposition / thin film (epitaxial) growth

1.3.1 Improvement of existing vacuum based processes through the further optimisation and development of for example rotary sputtering targets through a more thorough understanding of the influence of process conditions and tool design on film integrity;

1.3.2 Development of non vacuum processing in the case of thin films, epitaxial growth of for example thin crystalline silicon layers (to replace current mechanically produced wafers). Ultrathin functional layers (surface passivation and isolation layers). Development of alternative lower cost processes to replace the current front and back metallisation of crystalline silicon cells.

KPIs:

Research areas	**KPI (targets are indicative of scaled production conditions)**
1.3.1	In the case of TCOs: ITO – Cost 6€/m2, Sheet resistance 20Ω/sq, VLT 95% AZO– Cost 5€/m2, Sheet resistance 5Ω/sq, VLT 88%
1.3.2	For new deposition processes, the exact KPIs need to be established case by case, but in each one they should aim for reduction in Capex >70%, Materials usage >90% without loss in device performance compared with vacuum deposited materials

1.4. Focus Area 4: Novel materials

1.4.1 Basic and applied research on alternative materials systems to TFPV (cf. CIGS) that do not require scarce elements such as indium (e.g. Kesterites (CZTS), sulphur based salt systems, etc.) including a deep understanding of the chemistry, formation of homogeneous layers, and doping techniques;

1.4.2 Development of new conductors – New materials systems for highly transparent or reflective conductors that do not rely on scarce materials such as indium or silver. Such materials (copper, aluminium) need to have high optical and electrical performance, long-term reliability and be cheap to manufacture and deposit;

1.4.3 Development of non vacuum processing materials – the first examples of non vacuum processing will normally have been demonstrated prior to 2020, but continuing efforts for high performance cheap materials will be required that will run on into post 2020 (Absorber, buffer, conductors, encapsulants, etc);

1.4.4 Basic and applied research on Plasmonic effects, in particular development of metallic nano particle synthesis techniques with close control over size, geometry and functionalisation;

1.4.5 Basic research on quantum structures - Similarly as for 1.5.4 for other forms such as quantum wires, “q-dots” and q-wells that will expand the efficiency envelope of PV devices. Work will be required on deposition technology, nano particle synthesis, metallic intermediate band bulk materials, morphological and opto-electronic characterisation.

KPIs:

Research areas	KPI
1.4.1	CZTS module efficiencies circa 15% (2020), >15%(2050); No (or very low) usage of scarce materials.
1.4.2	These will need to be considered on a case by case basis due to the diversity and the probable trade offs between lower costs but lower performance compared with the status quo.
1.4.3	These will need to be considered on a case by case basis due to the diversity and the probable trade offs between lower costs but lower performance compared with the status quo.
1.4.4	Layer cost <0,05€/Wp (module cost 0.5€/Wp); 10% of current efficiency improvement
1.4.5	The cost of manufacturing will need to be compatible with a module cost target of <0,5 €/Wp

1.5. Focus Area 5: Materials for peripheral devices – inverters, trackers

1.5.1. Inverters

Power electronics – development of lower cost, low power loss materials based on chemistries such as SiC and for longer term GaN. Lower thermal losses enable smaller devices and possibility for module integrated inverters. Development of passive components (capacitors and inductors) with improved lifetime T0-T3

Magnetics – Lower cost materials based on amorphous composites and for longer term nano composites T0-T5

1.5.2. Development of new low cost materials / design of trackers especially for CPV trackers. T0-T3

KPIs:

Research areas	KPI
1.5.1	Power electronics - 30% Cost reduction - >30% (2020), >50% (2030); Switching frequency - 50kHz (2020), 100-200kHz (2030), Power losses 1,5% (2020), <1,0% (2030) Magnetics – Cost Reduction >50% (2020), >70% (2030); Switching Frequency – 50kHz (2020), 100-200 kHz (2030)
1.5.2	Life time - 40 years by 2030 and 50 years by 2050

2. MATERIALS INTEGRATION AND COMPONENT TECHNOLOGIES

Pilot1 Industrial piloting of new solar grade and PV materials and processes

Build pre-commercial pilot lines and operate to develop accurate forecast of future industrial production costs and will allow the definition of the optimal design of a full industrial scale production line of new PV material and processes as developed under headings 1.1.2 and 1.1.3.

The main drivers are a) higher efficiency devices b) lower cost devices c) materials availability. Points “a” and “b” are interrelated to achieve lowest cost of electricity production in a given context whereas “c” is independent but can be of equal importance.

Point “c” will need to be judged according to the incumbent material’s expected future availability (with strong PV growth of circa 120 – 160 GWp/year by 2020 – 2025 period, as of now we can anticipate stress on the materials supply chains for indium (CIGS), tellurium (CdTE) and silver (c-Si) depending on which PV technology predominates). This is however an ever changing situation as new reserves are discovered and become economically viable, so the priority will need to be re-validated at the appropriate time.

T3-T8 (Could be T0-T5 for processes that have already been developed at lab scale)

KPIs: The performances required will depend on the material, but those indicated in section 1.1.3 are relevant. For example, for solar grade polysilicon: manufacturing cost of 10-20 €/kg; lower energy input for manufacture; lower GHG footprint.

For materials and processes, whose performance can only be evaluated on a functioning device, typical of 1.1.2, the materials and device designs for points “a” and “b” above will need to be judged on their likely relative contribution (based on lab results) in meeting the overall KPIs for PV devices as indicated in the PV performance table below. This is however a constantly changing situation and reference to the latest PV SRA at the appropriate time will be advisable.

KPIs:

PV performance targets		2020	2030	2050
Typical electricity generation costs in Southern Europe (2011 Euros/kWh) (1)		0.10	0.06	0.03
Typical turn-key price for a 100kW system (2011 €/Wp, excl.VAT) (2)		1.5	1.0	0.5
Typical PV module efficiencies (%)	Crystalline Silicon	18-23%	30%	>30%
	Thin Films (inorganic)	10-18%	20%	>20%
	Thin Film Silicon	13-14%	16%	>16%
	Thin Film CIGS	16-17%	18-21%	>21%

	Thin Film CdTe	16%	>16%	>16%
	Thin Films (organic)	>10%	16%	18%
	HCPV	40-50%	50-60%	<60%
	DSSC	10%	>10%	>10%
Inverter life time (years)		>25	>25	>25
Guaranteed performance output (years) (3)	Inorganic	35-40	40	40
	Organic (OPV)	10	>20	>30
System Energy Pay-back time – Southern Europe (years)		<0.5	<0.5	0.25

Source: Implementation plan for the strategic research agenda / SEII May 2010 – EU PV Technology Platform / EPIA – AT Kearmey / PV SRA-2011

(1) Exact LCOE varies with financing cost and location. Southern EU locations considered range from 1500kW/h² (e.g. Toulouse) to 2000 KWh/m² (e.g. Syracusa).

(2) Price of system depends on technology improvements as well as market maturity (Industry infrastructure and admin costs)

(3) Refers to highest performance guarantees required from the industry but actual figures required will be application dependent.

Pilot 2: Industrial piloting of non vacuum deposition processes:

Demonstrate and test non vacuum processing in the areas of thin films, epitaxial growth of for example thin crystalline silicon layers and front and back metallisation of crystalline silicon cells as developed under heading 1.3.2. Develop accurate forecast of future industrial production costs, confident design of a full industrial scale production line. T3-T7 (Could be T0-T4 for processes that have already been developed at lab scale).

KPIs : CAPEX reduction of >70% and materials usage of >90%.

Pilot 3: Demonstrator line for PV high performance, thin, high strength glass at the lowest cost glass.

Develop accurate forecast of future industrial production costs, confident design of a full industrial scale production line, T3-T7.

KPIs: Glass thickness less than 1 mm by 2020 and reducing material usage by weight of >50% / watt.

Pilot 4: Field demonstrator projects for small scale combined HCPV and energy storage

For small grid locations e.g. islands located in southern Europe with limited land availability but high irradiance (DNI > 1800 kWh/m^2/year). Suitable demonstrator size would be 10 MWp, T0+ 5.

KPIs: HCPV system efficiency >30% DC (CSOC; concentrator standard operating conditions based on aperture area); Reduction of the median absolute deviation of the power production during daytime by >50% with respect to a CPV power plant without storage.

3. RESEARCH INFRASTRUCTURES

Facility1: EU testing facility of new materials / device designs

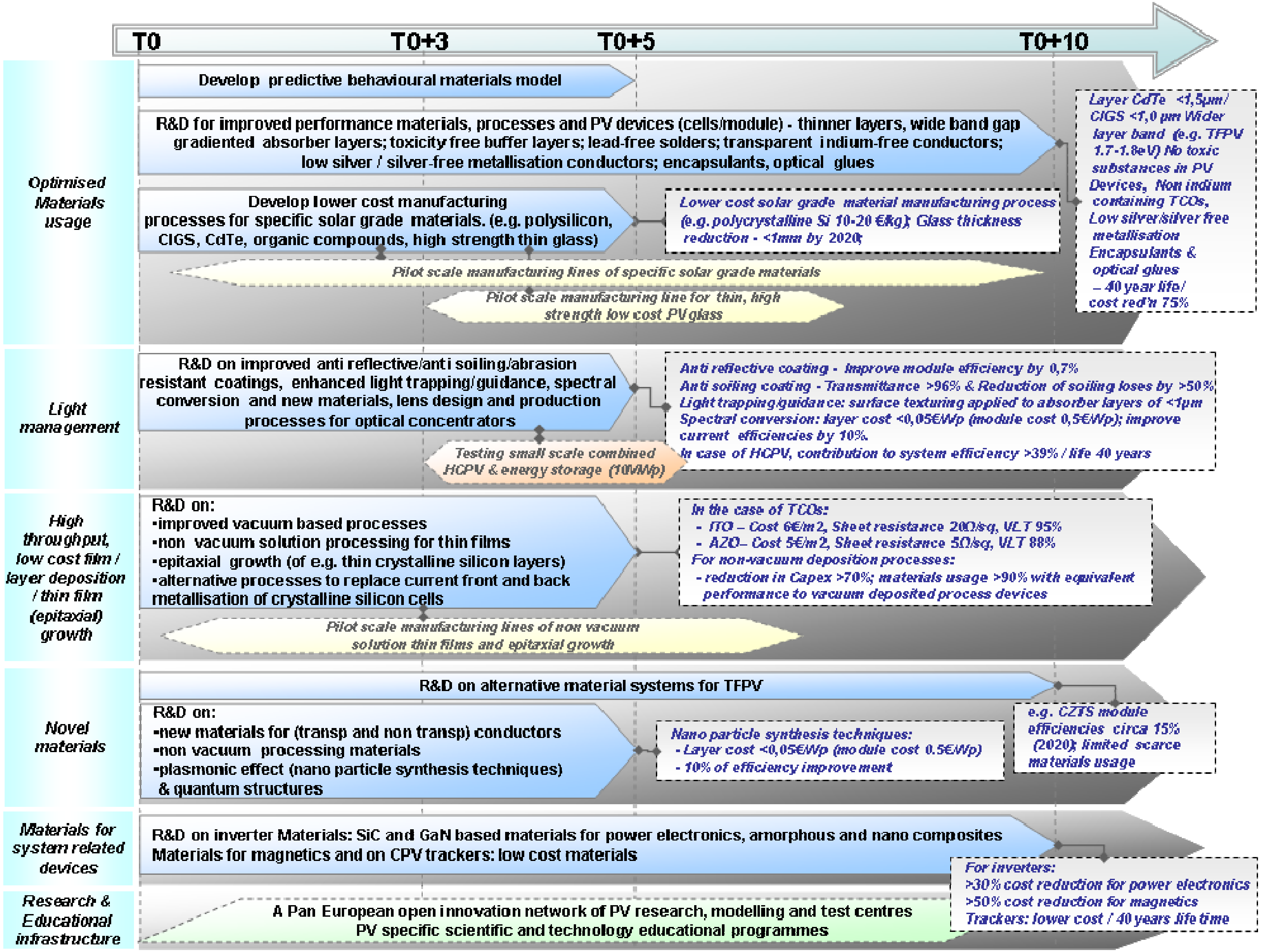
This Integrated EU facility or network of facilities will host research and testing infrastructure to test in both the lab and the field the performance and reliability of materials and devices developed under 1.1.2, 1.1.3, 1.1.5, 1.2 and if appropriate 1.4 produced by relevant pilot industrial lines under real operating conditions. This facility will be based on a joint public and private partnership, with open access to EU industry and research community based on rules to be agreed. The purpose would be twofold:

- Establish standardised and recognised testing data that will indicate the actual field performance and reliability of devices;
- Where appropriate establish the link and influence of production process parameters on the field performance and reliability of devices.

Facility 2: A Pan European open innovation network of PV research, modelling and test centres

The scope should cover testing centre(s)/networks for materials and devices as covered in section 1 that will apply the standardised protocols referred to in 4.1, the modelling network of excellence as referred to in 1.1.1 and a programme that will link production parameters to device field performance as referred to in 2.4. The logical structure would be for clusters of excellence that reflect the focus areas of section 1. There would be liberal cross-access to researchers and resources to best meet research goals. This should be seen as a simplified one-stop shop for guaranteed research excellence on a specific theme with working modalities that are attractive for industrial participation. The joint vehicle should also include contributions from Universities as well as the major research centres. They will need to be structured around some form of joint vehicle with a formal governance structure and legally binding agreements that define:

- Financial aspects
- IP (Foreground and Background)
- Valorisation


T0
T0+3
T0+5
T0+10
Optimised Materials usage
Develop predictive behavioural materials model
R&D for improved performance materials, processes and PV devices (cells/module) - thinner layers, wide band gap gradiented absorber layers; toxicity free buffer layers; lead-free solders; transparent indium-free conductors; low silver / silver-free metallisation conductors; encapsulants, optical glues
Layer CdTe <1,5µm / CIGS <1,0 µm Wider layer band (e.g. TFPV 1.7-1.8eV) No toxic substances in PV Devices, Non indium containing TCOs, Low silver/silver free metallisation Encapsulants & optical glues – 40 year life / cost red'n 75%
Develop lower cost manufacturing processes for specific solar grade materials. (e.g. polysilicon, CIGS, CdTe, organic compounds, high strength thin glass)
Lower cost solar grade material manufacturing process (e.g. polycrystalline Si 10-20 €/kg); Glass thickness reduction - <1mm by 2020;
Pilot scale manufacturing lines of specific solar grade materials
Pilot scale manufacturing line for thin, high strength low cost PV glass
Light management
R&D on improved anti reflective/anti soiling/abrasion resistant coatings, enhanced light trapping/guidance, spectral conversion and new materials, lens design and production processes for optical concentrators
Anti reflective coating - Improve module efficiency by 0,7%
Anti soiling coating - Transmittance >96% & Reduction of soiling loses by >50%
Light trapping/guidance: surface texturing applied to absorber layers of <1µm
Spectral conversion: layer cost <0,05€/Wp (module cost 0,5€/Wp); improve current efficiencies by 10%.
In case of HCPV, contribution to system efficiency >39% / life 40 years
Testing small scale combined HCPV & energy storage (10MWp)
High throughput, low cost film / layer deposition / thin film (epitaxial) growth
R&D on:
•improved vacuum based processes
•non vacuum solution processing for thin films
•epitaxial growth (of e.g. thin crystalline silicon layers)
•alternative processes to replace current front and back metallisation of crystalline silicon cells
In the case of TCOs:
- ITO – Cost 6€/m2, Sheet resistance 20Ω/sq, VLT 95%
- AZO– Cost 5€/m2, Sheet resistance 5Ω/sq, VLT 88%
For non-vacuum deposition processes:
- reduction in Capex >70%; materials usage >90% with equivalent performance to vacuum deposited process devices
Pilot scale manufacturing lines of non vacuum solution thin films and epitaxial growth
Novel materials
R&D on alternative material systems for TFPV
e.g. CZTS module efficiencies circa 15% (2020); limited scarce materials usage
R&D on:
•new materials for (transp and non transp) conductors
•non vacuum processing materials
•plasmonic effect (nano particle synthesis techniques) & quantum structures
Nano particle synthesis techniques:
- Layer cost <0,05€/Wp (module cost 0.5€/Wp)
- 10% of efficiency improvement
Materials for system related devices
R&D on inverter Materials: SiC and GaN based materials for power electronics, amorphous and nano composites
Materials for magnetics and on CPV trackers: low cost materials
For inverters:
>30% cost reduction for power electronics
>50% cost reduction for magnetics
Trackers: lower cost / 40 years life time
Research & Educational infrastructure
A Pan European open innovation network of PV research, modelling and test centres
PV specific scientific and technology educational programmes

Materials Roadmap for Concentrating Solar Power[1]

1. MATERIALS R&D AND RELATED PRODUCT DEVELOPMENT

1.1. Focus Area 1: Novel materials – Absorber Materials

- Applied R&D to develop improved spectrally selective absorber coatings stable both in vacuum and air. The coatings should have an increased absorptance, lower emittance and better resistance to higher temperatures; the interaction of the coating with the substrate properties should be taken into account;
- Development of porous ceramic and metal absorber structures for central receivers with higher mechanical stability and better performance, suited also for higher temperatures;
- Improve properties of high temperature metals to reach long-term resistance to corrosion at elevated temperatures and increase upper temperature limit for operation to allow for an increase of the process temperature and thus lower the cost;
- Glass/alloy tubing for direct steam generation: Resist high temperature, pressure and thermal cycling;
- Applied research to develop fluidised bed materials with high performance, abrasion resistance, high heat transfer;
- Insulation materials: Improved resistance to environmental loads;
- Transparent tower receiver cover: Allow for high temperature closed receiver/reactors at >800 °C;
- Development of accelerated ageing testing for different applications, i.e. substrate/coating durability, optical properties, abrasion resistance etc.

KPIs Absorber Materials

Technology / Material parameters	Current performance	Target performance 2020/2030	Target performance 2050
Absorber coatings	α=0,95, ε=0,1 τ> 0,96 Tmax=400 °C	α>0,96 ε=0,09 (400 °C), 0,10 (450°), 0,14 (580°) τ> 0,97 Tmax=600 °C	Tmax =700°C
High temperature metals and alloys	600°C (Stirling) 560° (molten salt)	650 °C (Stirling) 600°C (molten salts) 500°C/120 bar (direct	700°C molten salt

[1] The effective and sustainable use of resources is critical for the further development of energy technologies. Aspects related to recycling, at manufacturing as well as at end-of-life, and design for recycling/cradle-to-cradle approach are an integral part of the proposed developments.

		steam)	
Porous ceramic and metal structures	540°C (steam cycle) 800°C (Brayton)	600°C (steam cycle) 1000°C (Brayton)	700°C (steam cycle) 1200°C (Brayton)
Transparent receiver cover	Only prototypes	800°C (cycle temperature)	1200°C (cycle temperature)

1.2. Focus Area 2: Novel materials – Reflector Materials

- Applied R&D for higher reflectance and/or specularity, cost reduction, sustainability;
- Applied research to further develop low-lead solutions towards "Zero Lead" mirrors with long term corrosion protection against weathering;
- Develop advanced mirror protective coatings with anti-soiling function and high abrasive resistance;
- Improve resistance of non-glass mirrors to surface degradation in different climatic conditions and under abrasion; develop improved accelerated ageing tests;
- Applied research for low-iron glass with reduced transmission losses; method for recycling process, method for treatment of raw materials to reduce the iron content;
- Develop reflector materials with high-temperature stability suitable for secondary reflectors (Fresnel, Central Receivers)**;**
- Development of accelerated ageing testing taking into account specifications of different applications and loads (Primary, secondary, climate variability, abrasion etc.).

KPIs Reflector Materials

Technology / Material parameters	Current performance	Target performance 2020/2030
Reflectance	ρ=0,94 (silver)	ρ=0,95 -0,96
Decrease reflector cost		-25% compared to 2010
Low-iron glass		Recycling, treatment to reduce iron content
Protective front mirror coatings		Reduced soiling rate, high abrasion resistance

1.3. Focus Area 3: Novel materials – Heat transfer fluids

- Applied R&D to develop alternative synthetic fluids with increased operating temperature and long-term stability;
- Applied research on the degradation processes; development of accelerated ageing testing;
- Development of measuring and simulation techniques for physicochemical parameters (density, vapour pressure, viscosity, heat capacity) at high temperatures;
- Develop advanced molten salts mixtures with improved operating temperature range, long-term stability, degradation processes. Provide accelerated ageing tests;
- Research for alternative heat transfer fluids such as liquid metals or gases to allow for higher temperatures, better heat transfer, better chemical stability.

KPIs Heat transfer fluids

Technology / Material parameters	Current performance	Target performance 2020/2030
Synthetic fluids	<400°C	Increased operation temperature >400°C
Molten salts		Reduced freezing temperature (<100°C) and increased temperature limits (700°C)
Innovative HTF such as liquid metals, gases		Allow for higher temperatures and/or improved heat transfer

1.4. Focus Area 4: Novel materials – Structural materials

- Applied research on steels, aluminium, fibre composites or others: improved stiffness and stability for larger collector structures; sustainability (recycling concept and disposal); reduced fabrication time and assembly, cost reduced corrosion protection;
- Heat exchanger structural materials: decrease cost, optimization for different HTF; improved resistance in high-temperature environment with corrosive molten salt and high pressure steam;
- Development of new concepts for fibre composites with lower cost and high precision;
- Applied research on high temperature structural materials: ceramics and alloys at higher temperatures and reduced cost, corrosive-resistant (especially when in contact with heat transfer fluids).

KPIs Structural materials

Technology / Material parameters	Target performance 2020/2030
Collector structure material (steel, aluminium, fibre composits)	Decrease specific cost by 5%*, increase size by 75%, improve performance by 1-2% Upper wind speed limit 17 m/s Decrease assembly cost 5%*
Flexible Joints	Increase temperature to 450°C (oil), 550°C (direct steam) and 600°C (salt)
Fibre reinforced materials	Improve mechanical properties, reduce cost, sustainability
High temperature structural materials (alloys, ceramics)	Allow higher temperatures, reduced cost, corrosive-resistant, higher pressure loads (steam/air)

* KPI for cost w/o considering economy of scale

1.5. Focus Area 5: Novel materials – Storage materials

- Applied R&D on solid ceramic particles, high-temperature phase change materials, solid ceramic particles, graphite, high-temperature concrete: Thermal properties & reduced costs;
- Basic R&D on thermo-chemical energy storage materials: Development of new materials;
- Basic R&D on higher temperature storage materials (at least 600 °C): Development of new materials, thermal properties, any technology.

KPI Storage materials

Technology / Material parameters	Target performance 2020/2030
Heat storage materials	Reduce cost, increase performance, Increase temperatures to 600°C
Materials for thermo-chemical storage	New materials

2. MATERIALS INTEGRATION AND COMPONENT TECHNOLOGIES

2.1. Manufacturing

Pilot 1: Absorber and reflector coatings manufacturing: Application of new advanced absorber and reflector coatings on structural material (metal, glass, ceramics). Verification of optical, thermal properties and durability as well as potential for scale up at lower cost.

KPIs: Develop improved absorber coatings for trough and tower absorbers with absorptivity >0.96, low emissivity <0.1 at temperatures <450°C (synthetic oil troughs), <550°C (salt, DSG, gas troughs), <600°C (salt towers) and <1000°C (air towers). Reflector protective and antisoiling coatings with proven durability of >10 yrs. Preparation for large scale implementation; T0+0

Pilot 2: Profiled multilayer tubes manufacturing: Develop and demonstrate manufacturing of straight and curved tubes and verify chemical stability and durable interconnection between tube layers under realistic stresses. Method should be suitable for large scale production.

KPI: Demonstrate durability >20 yrs in 1 to 4 MWth scale; T0+3

Pilot 3: High temperature synthetic heat transfer fluids: Demonstrate performance of advanced synthetic fluids for high temperatures (>400°C). Investigate decomposition and chemical stability under operation scheme and verify thermal and chemical properties as well as large scale manufacturing capability. Demonstration of cost reduction effect.

KPIs: Target operation temperature of 450°C; Demonstrator in 1 MWth facility. Large scale production capability for >1 GW/yr installed power capacity; T0+0

Pilot 4: Catalyst materials manufacturing: Application of new advanced catalyst materials on substrates. Demonstrate optical, thermodynamic and chemical characteristics and long-term stability. Verify higher conversion rates than today.

KPIs: Durability of coatings >10 yr for temperatures range 800°C to 1200°C. Demo at 100 - 500 kW level: T0+5

Pilot 5: Manufacturing of heat exchangers of ceramics or alloys: Demonstrate improved heat exchangers components for higher temperatures to be used basically for heat storages or recuperation. Verify elevated temperature operation at reduced cost. Heat exchangers should be applicable for oil, steam, salt, air or liquid metals systems.

KPI: Demo of increased temperature by >10-20 K against state of the art at of lifetime >25 yrs. Scale 100 kW to 5 MW; T0+5

2.2. Technology testing

Pilot 1: Testing of materials for storage technologies: Demonstrate improved performance of new storage materials as solid ceramic particles, high-temperature phase change materials, solid ceramic particles, graphite, high-temperature concrete or other new materials. Verify thermal properties and reduced cost.

KPI: Increased specific storage capacity >10%, scale 100kWth to 1 MWth; T0+3

Pilot 2: Testing of new molten salt mixtures: Test and demonstrate new developed molten salt mixtures with lower freezing temperatures, higher upper temperature limits. Investigate and demonstrate the compatibility with tube materials to prevent corrosion. Verify long-term stability.

KPI: increase specific storage capacity >10 %, scale 100 kWth to 4 MWth; T0+ 0

Pilot 3: Testing of porous ceramic or metal structures for central receivers: Demonstrate optical and mechanical performance of new developed ceramic or metal structures for absorbers. If improved with a coating, show the long-term stability of the material combination under normal load conditions (hot spots, cycles, transients).

KPI: Durability of structures >20 yrs, pilot of 400 kWth to 4 MWth. T0+ 0

Pilot 4: Testing of fluidised bed materials: New materials developed for storage or direct illuminated receivers should be tested for its optical and thermal properties and its abrasion resistance and decomposition at high temperatures. A high heat transfer coefficient and general high performance should be verified.

KPI: Temperatures >800 °C; receiver efficiency >80%; scale 200 kWth to 5 MWth; T0+ 5

Pilot 5: Testing materials for piping and tank structures: Components like housings or piping from steel or composites should be tested. Demonstrate long-term resistance to internal corrosion and thermal strains

KPI: Temperatures >400°C; Lifetime of 20 yrs; scale 4 MWh to 20 MWh; T0+ 3

3. RESEARCH INFRASTRUCTURE

Facility 1: Coating technology virtual centre

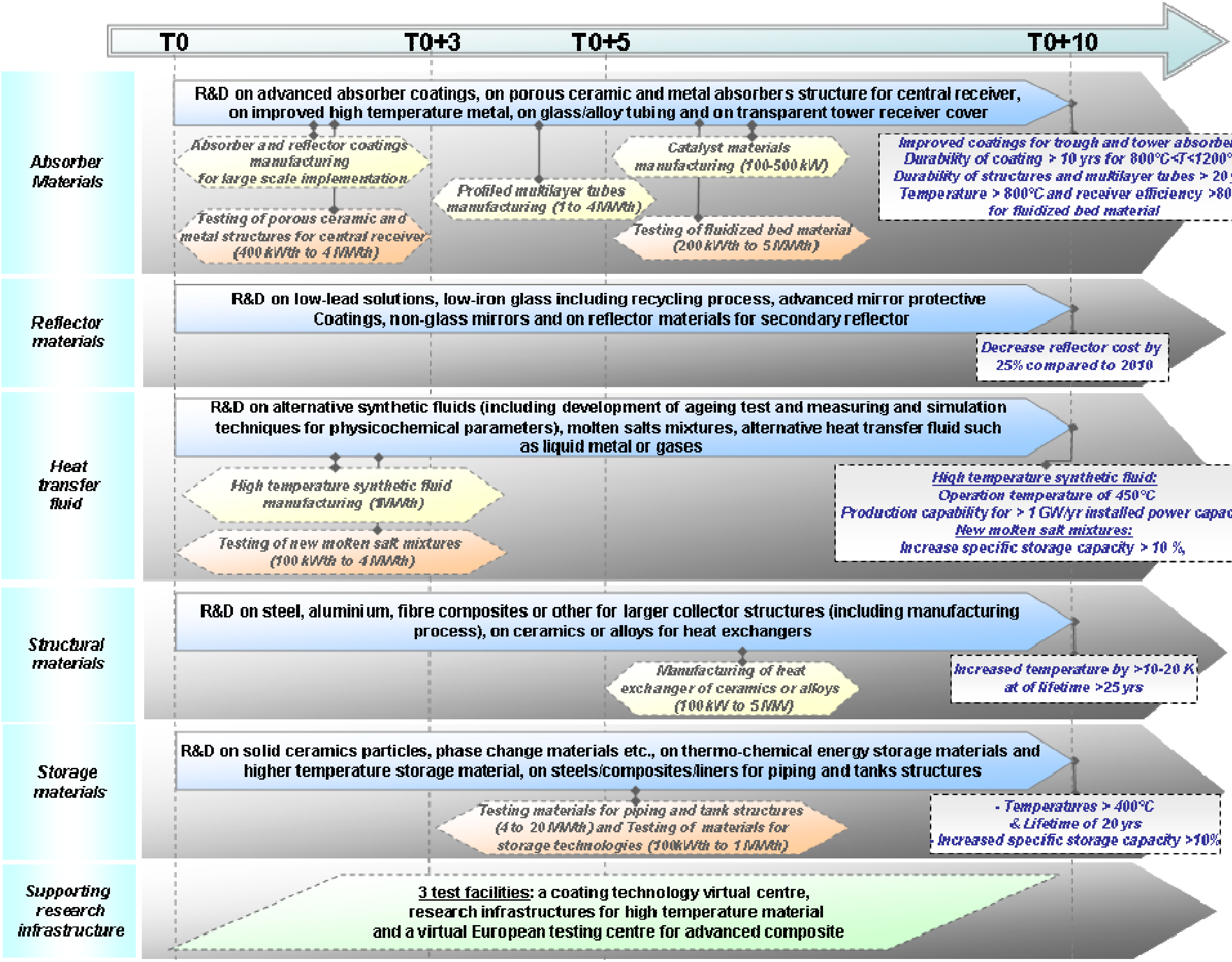
This materials virtual research centre should focus on modelling, physical application and performance testing and durability assessment of advanced coatings for absorber, reflector or catalyst materials. The implementation should start at T0 + 0 years.

Facility 2: High temperature materials research

High temperature materials are required for several applications as tubings, absorbers, heat exchangers, structural materials. To extend today's applications towards higher temperatures, systematic and basic research is required to model, develop and test new alloys and ceramics for CSP and in general for the power plant sector. This should be realised by improved infrastructure at the key materials institutes. Implementation should start at T0 + 3 years.

Facility 3: Advanced Composites

Establish research infrastructure e.g. a European virtual testing centre for advanced composites for light weight, high performance and low cost structures. Implementation should start at T0 + 3 years.


T0
T0+3
T0+5
T0+10
Absorber Materials
R&D on advanced absorber coatings, on porous ceramic and metal absorbers structure for central receiver, on improved high temperature metal, on glass/alloy tubing and on transparent tower receiver cover
Absorber and reflector coatings manufacturing for large scale implementation
Testing of porous ceramic and metal structures for central receiver (400 kWth to 4 MWth)
Profiled multilayer tubes manufacturing (1 to 4MWth)
Catalyst materials manufacturing (100-500 kW)
Testing of fluidized bed material (200 kWth to 5 MWth)
Improved coatings for trough and tower absorbers
Durability of coating > 10 yrs for 800°C<T<1200°C
Durability of structures and multilayer tubes > 20 yrs
Temperature > 800°C and receiver efficiency >80% for fluidized bed material
Reflector materials
R&D on low-lead solutions, low-iron glass including recycling process, advanced mirror protective Coatings, non-glass mirrors and on reflector materials for secondary reflector
Decrease reflector cost by 25% compared to 2010
Heat transfer fluid
R&D on alternative synthetic fluids (including development of ageing test and measuring and simulation techniques for physicochemical parameters), molten salts mixtures, alternative heat transfer fluid such as liquid metal or gases
High temperature synthetic fluid manufacturing (MWth)
Testing of new molten salt mixtures (100 kWth to 4 MWth)
High temperature synthetic fluid:
Operation temperature of 450°C
Production capability for > 1 GW/yr installed power capacity
New molten salt mixtures:
Increase specific storage capacity > 10 %
Structural materials
R&D on steel, aluminium, fibre composites or other for larger collector structures (including manufacturing process), on ceramics or alloys for heat exchangers
Manufacturing of heat exchanger of ceramics or alloys (100 kW to 5 MW)
Increased temperature by >10-20 K at of lifetime >25 yrs
Storage materials
R&D on solid ceramics particles, phase change materials etc., on thermo-chemical energy storage materials and higher temperature storage material, on steels/composites/liners for piping and tanks structures
Testing materials for piping and tank structures (4 to 20 MWth) and Testing of materials for storage technologies (100kWth to 1 MWth)
- Temperatures > 400°C
& Lifetime of 20 yrs
- Increased specific storage capacity >10%
Supporting research infrastructure
3 test facilities: a coating technology virtual centre, research infrastructures for high temperature material and a virtual European testing centre for advanced composite

Materials Roadmap for Geothermal Energy[1]

1. MATERIALS R&D AND RELATED PRODUCT DEVELOPMENT

1.1. Focus Area 1: Materials for accessing geothermal reservoirs

1.1.1 Development and optimization of materials for drill bits with high abrasion resistivity for conventional drilling (2020) and spallation drilling (2030) for hard rocks at large depth and high temperatures (up to 500°C);

1.1.2. Basic and applied research on long-live materials for drilling equipment, including drill bits in highly corrosive environments (H_2S resistant) and on optimising the performance and longevity of well casing alloys for use at high temperature conditions to extend life time and reduce drilling costs;

1.1.3. Development of proppants materials (e.g. resin-coated sand, high-strength ceramics, or sintered bauxite) for high-temperature use;

1.1.4 Borehole Packers: Development of retrievable packers for high pressure operations at high temperature (>150°C for extended operation) Development of elastomer and cement packers for high-temperature applications;

1.1.5 Materials for high temperature (>250°C) down hole monitoring tools: for fibre-optic cables suitable coating materials for the fibres are required to withstand the high temperature and chemically hostile conditions. In addition, mechanically robust and chemically inert materials for downhole cables are required to protect the fibres. To overcome the temperature limit for electronic parts, wider band gap (WBG) materials such as silicon carbide (SiC) and diamond must be developed.

KPIs

Research areas	KPI
1.1.1	Increase in economic depth (>5km) and temperature range (>400°C) for drilling (>5% cost reduction)
1.1.2	Decrease in drilling cost (>5%)
1.1.3	Increase in subsurface heat exchanger performance (>20%)
1.1.4	Demonstrate applicability of materials under service conditions
1.1.5	Increased T range for downhole measurements into reservoirs >300°C

[1] The effective and sustainable use of resources is critical for the further development of energy technologies. Aspects related to recycling, at manufacturing as well as at end-of-life, and design for recycling/cradle-to-cradle approach are an integral part of the proposed developments.

1.2. Focus area 2: Materials for well completion

1.2.1 Development of corrosion resistant materials for pipes to be used for temperatures up to 500°C, pH=1, high salinity and gas content (CO_2, H_2S, CH_4);

1.2.2 Development of low maintenance materials for downhole pumps with extended lifetime and less downtime; development and production of pumps with high resistant materials to withstand harsh conditions, such as high salinity, temperatures > 250 °C, and high gas content; development of new surface coatings such as PVD coatings, nitriding treatments and laser treatments to improve properties in terms of better corrosion and abrasion resistance;

1.2.3 Re-injection: Development of specialised coatings, inhibitors etc for re-injection of separated fluids and gases. Suitable measurement techniques to quantify the precipitation rates with on-line and off-line methods should be developed to fit the site specific conditions;

1.2.4 Development of improved cement for the high temperature conditions in geothermal wells;

1.2.5 Development of pressure seals alternative to conventional elastomer and metal C-rings such as sprayed metal, ceramics or other with long term durability at T >250 °C.

KPIs

Research areas	KPI
1.2.1	Lifetime 30+ years; 70% cost reduction of Ti pipes
1.2.2	Increase lifetime of downhole pumping components to the design lifetime. Improve the performance of downhole pumps, especially Electric Submersible Pumps ESPs, to operate at temperatures of 250°C, mass flow rates of up to 80 kg/s, setting depth 1 km, wellbore diameters of 15 cm to 30 cm, and operating at pressures up to 200 bar. Up to 2025 increase the performance parameters to higher values regarding setting depth, limiting temperature and mass flow rate.
1.2.3	zero-emission geothermal plants
1.2.4	Demonstrate and prove ability of new materials under service conditions (T >250 °C)
1.2.5	Applicability at T >250 °C and harsh environmental conditions (salinity of fluid)

1.3. Focus area 3: Materials for geothermal site operation

1.3.1 Development of corrosion resistant tools and equipment for power plants;

1.3.2 Optimised organic working fluids for binary power plants to increase power plant efficiency including with low temperature resources and for applications such as desalination or cooling;

1.3.3 Heat Exchangers: Development of new materials with high resistance to corrosion under specific conditions of geothermal fluids. The new materials should have less Ni by maintaining high resistance to corrosion. Duplex steels, polymeric materials (coatings), ceramics or sprayed metal could be envisaged as solutions, cladded or multi layered pipe systems may also form a future solution;

1.3.4 Gas separation: development of materials for extended lifetime and increased operational safety, including capability to re-inject separated gases;

1.3.5 Development of more efficient durable environmentally-friendly chemical scaling inhibitors;

1.3.6 Development of high efficient insulation materials at high temperatures (500°C; by 2050).

KPIs

Research areas	KPI
1.3.1	Extension of lifetime (>10%) and reduction of downtime (>5%) of power plant components
1.3.2	Increase in heat exchanger operational temperature range for binary plants (>20%)
1.3.3	Demonstrate applicability of materials under service conditions
1.3.4	Pre-requisite for zero emission plants
1.3.5	Improved lifetime of well (30+ years)
1.3.6	Reduction of transport temperature losses in the geothermal plant (>10%)

2. MATERIALS INTEGRATION AND COMPONENT TECHNOLOGIES

2.1. Manufacturing

Pilot 1: Application and validation of pre-commercial coating systems developed under 1.1.5at high temperature (>250-300°C) operating conditions: T0+4 years.

Pilot 2: Application and validation of pre-commercial coating systems developed under 1.2.3 under high temperature (>500°C) operating conditions including cycling conditions. Protective coatings for pipes and components in power plants should be validated in operating conditions representative of supercritical reservoirs. Bond coating/thermal barrier coatings systems should be validated in representative conditions for hot sections components of gas turbines. Time for implementation: T0+5 years.

Pilot 3: Development of improved organic working fluids for binary power plants to increase power plant efficiency. Time for implementation: T0+5 years.

KPIs:

Pilot	KPI
Pilot 1	Fluids at temperatures at >250-300°C can be measured
Pilot 2	Good performance after 10.000 hours under operating conditions
Pilot 3	Efficiency increase by 20%

2.2. Technology Testing

Pilot 1: Setup large test facility for heat exchangers and working fluids at temperatures up to 500°C, T3+5 years.

Pilot 2: Establishment of research wells, one at supercritical conditions , one in over-pressured reservoirs, one to improve EGS technology and stimulation materials; T0+10.

Pilot 3: Development and experimental validation of integrated models focussed on the material-component performance evolution during long-term service. Experimental validation should be based mainly on field data (operational data, results from materials tested in operating conditions, post-mortem analysis of critical components) to improve the predictive capability of models. Time for implementation: T0+1 year.

KPIs:

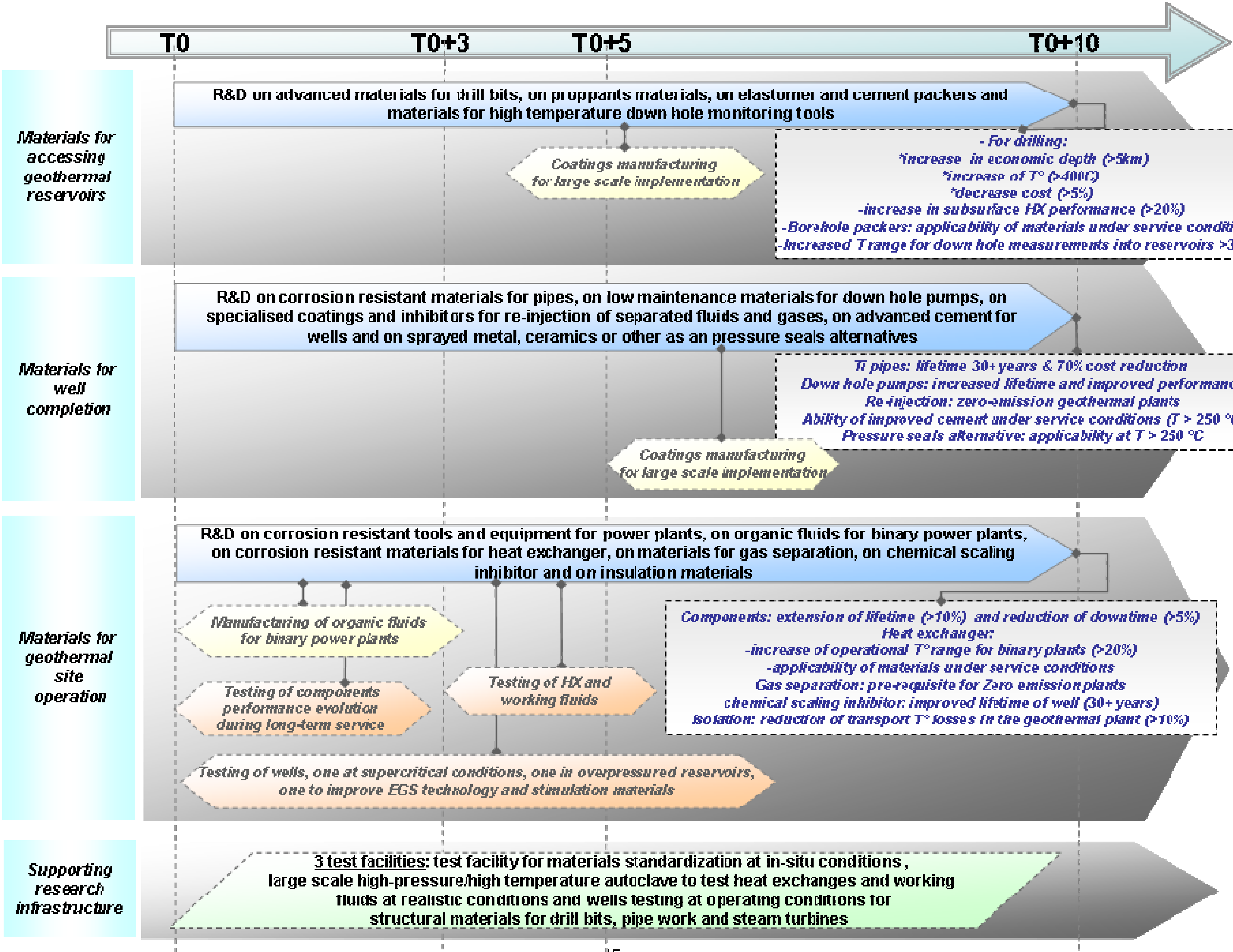
Pilot	KPI
Pilot 1	Materials and tools can be tested at realistic scales and conditions
Pilot 3	Models suitable for prediction of components behaviour in plant. Good agreement between the results from modelling and lab and plant validation data

3. RESEARCH INFRASTRUCTURE

Facility 1: EU laboratory test facility for materials standardisation at in-situ conditions: A network between existing EU test facilities and existing national test facilities within European Countries including selected international partners. Time for implementation: T0+1 year;

Facility 2: Large scale high-pressure/high temperature autoclave to test heat exchanges and working fluids at realistic conditions, T0+4 years;

Facility 3: Research wells to test at operating conditions the structural materials for drill bits, pipe work and steam turbines to minimise the dependence of lab/small scale experimental data. Time for implementation: T0+5 years.



T0
T0+3
T0+5
T0+10
Materials for accessing geothermal reservoirs
R&D on advanced materials for drill bits, on proppants materials, on elastomer and cement packers and materials for high temperature down hole monitoring tools
Coatings manufacturing for large scale implementation
- For drilling:
*increase in economic depth (>5km)
*increase of T° (>400C)
*decrease cost (>5%)
-increase in subsurface HX performance (>20%)
-Borehole packers: applicability of materials under service conditions
-Increased T range for down hole measurements into reservoirs >300°C
Materials for well completion
R&D on corrosion resistant materials for pipes, on low maintenance materials for down hole pumps, on specialised coatings and inhibitors for re-injection of separated fluids and gases, on advanced cement for wells and on sprayed metal, ceramics or other as an pressure seals alternatives
Ti pipes: lifetime 30+ years & 70% cost reduction
Down hole pumps: increased lifetime and improved performance
Re-injection: zero-emission geothermal plants
Ability of improved cement under service conditions (T > 250 °C)
Pressure seals alternative: applicability at T > 250 °C
Coatings manufacturing for large scale implementation
Materials for geothermal site operation
R&D on corrosion resistant tools and equipment for power plants, on organic fluids for binary power plants, on corrosion resistant materials for heat exchanger, on materials for gas separation, on chemical scaling inhibitor and on insulation materials
Manufacturing of organic fluids for binary power plants
Testing of components performance evolution during long-term service
Testing of HX and working fluids
Components: extension of lifetime (>10%) and reduction of downtime (>5%)
Heat exchanger:
-increase of operational T° range for binary plants (>20%)
-applicability of materials under service conditions
Gas separation: pre-requisite for Zero emission plants
chemical scaling inhibitor: improved lifetime of well (30+ years)
isolation: reduction of transport T° losses in the geothermal plant (>10%)
Testing of wells, one at supercritical conditions, one in overpressured reservoirs, one to improve EGS technology and stimulation materials
Supporting research infrastructure
3 test facilities: test facility for materials standardization at in-situ conditions, large scale high-pressure/high temperature autoclave to test heat exchanges and working fluids at realistic conditions and wells testing at operating conditions for structural materials for drill bits, pipe work and steam turbines

Materials Roadmap for Electrical Storage[1]

1. MATERIALS R&D AND RELATED PRODUCT DEVELOPMENT

1.1. Focus Area 1: Energy oriented materials for lower costs, higher life span batteries

1.1.1. Li-Ion system:

- Basic and applied research to develop low cost positive electrode materials, negative electrode materials (substitution of Carbon -based materials) and safe electrolytes (allowing higher charging voltages, wide operating temperature ranges, less fluoride for safety issue, etc.);
- Development of safe and non-flammable electrolytes; solid electrolytes;
- Development of materials and cell architectures, design & integration for high power Li-ion systems with high rate capability, high power sustainability and very long life cycle (in synergy with super capacitors). This includes the development of components for high design performances (Low internal resistance, high thermal dissipation, high life cycle, etc.) as for instance new current collectors and novel positive and negative electrode architectures (3D, etc.), suitable separators to cover such 3D electrodes and process to obtain such architecture;
- Basic and applied research to develop conversion materials to increase specific energy storage compared to insertion materials, including modelling, synthesis, C-rate capabilities investigation etc;
- Development of materials that can supply lithium ions by in situ means (i.e. prelithiated Silicon negative material) and enable use of non pre-lithiated positive materials;
- Development of new processing technologies such as nanotechnologies and functionalised coatings;
- Research and economic assessment of second life applications.

KPIs

Technology/Material	Current performance	Target 2020-2030	Target 2050
Li ion/Energy version	Max. 241Wh/kg – 535Wh/L (Co based); ca. 500 cycles Safe : 130Wh/kg –	ca. 180-350Wh/kg – 350-800Wh/L Safe	>350Wh/kg - > 800Wh/L Safe

[1] The effective and sustainable use of resources is critical for the further development of energy technologies. Aspects related to recycling, at manufacturing as well as at end-of-life, and design for recycling/cradle-to-cradle approach are an integral part of the proposed developments.

	300Wh/L (LFP based); ca. 2000 cycles -20, +60°C ca 500-1000€/kWh (or 25c€/kWh/cycle)	>. 10000 cycles -20, +70°C ca 200€/kWh (or 10c€/kWh/cycle) i.e. phosphates <10€/kg or lamellar oxides <20€/kg; separator <1€/m^2	>10000 cycles -20, +70°C < 200€/kWh
Li ion/Power version	50-90Wh/kg-105-190Wh/L ca. 3kW/kg ca 10000 cycles -10, +60°C > 1000€/kWh	ca. 80-100Wh/kg – 170-220Wh/L >5kW/kg Safe >. 15 years -20, +70°C ca 20€/kW i.e. LTO <10€/kg	>100Wh/kg –220Wh/L ca. 10kW/kg Safe >. 15 years -20, +70°C ca 20€/kW or <

1.1.2. Redox flow systems

- Basic and applied research on new chemistries for faster kinetics, higher voltages and higher energy densities;

- Develop new electrolytes to replace Vanadium. Use of less expensive raw materials for the electrolyte;

- Development of low cost membrane materials with long lifetimes;

- Proof of concept for redox systems without membrane (undivided cells and micro fluidics) particularly showing whether micro fluidic approaches are scalable beyond portable power **(**either use 2 species in solution (undivided) which don't interfere too much (i. e. Pb/Pb or Zn/Ce) or use very low Reynolds number flow (micro fluidics) but large gaps and mixing problems if not single pass like a fuel cell - but need to check if scalable);

- Basic and applied research on novel electrode materials with higher electrochemical activity w/o detrimental effect on durability or with further improvement under battery cycling. Research on nanomaterials and specific surface treatments to increase the electrocatalytic activity;

- Development of innovative designs, electrode, flow systems, modelling, stack design, sealing, taking into account manufacturing issues which especially relates to larger systems, with high cell voltage.

KPIs

Technology/Material	Current performance	Target 2020-2030	Target 2050
Redox Flow Batteries (Vanadium, $ZnBr_2$)	10-20Wh/kg – 15-25Wh/L (Vanadium); 10-20 years (>10000 cycles) 10, +40°C 50-60Wh/kg ($ZnBr_2$based); >2000 cycles Projected service cost (Capex and Opex) 10c€/kWh Energy cost 400€/kWh Power cost 600€/kW	Gen2 Vanadium Bromide 20-40Wh/kg Wider operating T° range (>100°C) Projected service cost (Capex and Opex) 7c€/kWh Energy cost 120€/kWh Power cost 300€/kW	Reduction of total system cost (Capex & Opex) Projected service cost (Capex and Opex) 3c€/kWh Energy cost 70€/kWh Power cost 200€/kW

1.2. Focus Area 2: Power oriented materials for electrochemical capacitors

- Substitution of traditional carbon type materials;
- Development of pseudo-capacitors (redox-based) by use of metal oxides, nitrides or polymer films;
- Development of hybrid capacitors composed of one electrochemical electrode and one battery electrode in aqueous media for low cost and low environmental impact system (c€/F);
- Development of aqueous electrolytes to be used with carbon-carbon systems;
- Development of ionic Liquids for higher voltage ranges with wide operational temperature range and high conductivity. Ionic Liquids-solvent mixtures with high voltage solvents as developed in Li ion batteries (additives/new solvents);
- Proof of concept of asymmetric Li Ion Capacitor (LIC) systems: improve life cycle and improve symmetry of charge-discharge rates to achieve 20-30Wh/kg in synergy with high power Li-ion batteries; proof of concept of ceramic ultra-capacitor with dielectric or insulator with very high permativity;
- Basic and applied research on aqueous hybrid systems for very low cost and low environmental impact using activated carbons;

- Development of surface treatment processes (Functionalised hydrophobic carbon) for carbon-carbon controlling pore sizes (and PSD - Pore Size Distribution) and increased voltage.

KPIs

Technology/Material	Current performance	Target 2020-2030	Target 2050
Supercapacitors (EDLC, pseudo capacitors like oxides, hybrid or asymmetric systems...)	<10Wh/kg (close to 5Wh/kg) 10-20kW/kg (1-5s) ca. 1500-2000m^2g >10000 cycles (>100000cycles depending on systems) Low °C (-40°C)	>10-15Wh/kg ca. c€/F	Electrolyte stability ca. 4.5-5V ca. 3000m^2g active area ca. 600F/g Energy close to power batteries (50Wh/kg)

1.3. Focus Area 3: Materials for non-chemical energy storage

1.3.1. Superconducting Magnetic bearings for Energy Storage (SMES) & Flywheels

- Development of second generation high-temperature superconductors with high critical current density at high magnetic field to allow for SMES devices, Increase of energy density proportional to the magnetic induction;
- Development of lighter polymeric composite wheels to increase rotational speeds;
- Basic and applied research on superconducting magnetic bearings;
- Low cost and high strength composite materials coupled cost engineering of the system (system cost should be considered when selecting the materials in term of cost/performance benefit).

1.3.2. Corrosion resistant materials for Pumped Hydro Storage (PHS) & Compressed Air Energy Storage (CAES)

- Development of advanced materials for mechanical and hydro mechanical equipments to sustain deep and frequent load variations; development of corrosion resistant materials for mechanical and hydro mechanical equipments of sea water pumped storage;
- Development of corrosion resistant and low cost materials for compressed air salt cavern storages (underground bore-hole equipment, the cavern heads, pipes and fittings, etc);

- Applied research on materials improving efficiency, work on high pressure and temperature compressors for Adiabatic CAES. Development of materials for insulation of large heat storage devices for adiabatic CAES, combining high temperature and high pressure cycling, with presence of condensates;

- Development of low price media to store heat in adiabatic CAES, with both mechanical and chemical resistance ensuring 30 years life expectancy with daily cycle.

KPIs for section 1.3

Technology/Material	Current performance	Target 2020-2030	Target 2050
SMES	Highly efficient >95% For short duration storage (electricity stored in magnetic field) Superconducting foil cooled below its critical T°	Reducing critical T° of the superconductors Second HTS generation: >current density at high magnetic field (i.e. >10m; >50A) Enhance performances at high magnetic fields and reduce the cost of YBCO coated conductors	Cost reduction >5-10% ca. 100€/kW (200€/kWh)
Flywheels	High cycle life >100000 cycles ca. 4000$/kWh or ca. 3000€/kWh (1500$/kW or 1000€/kW) Small 5kWh/100kW (with HTS) 5kWh/250kW (with INES -Inertial Energy Storage)	Reduced friction, higher rotation speed for higher energy storage (>10kWh) Large systems demonstration with strong materials like composites to resist the centrifugal forces Rotor manufacturing cost reduction <4000$/kWh or < 3000€/kWh	Cost reduction Projected Capital Cost 200-500€/kWh Higher energy storage >100Wh/kg
Pumped Hydro	GW storage Low cycle cost High capital cost $500/kW to $2000/kW (350 to 1500€/kW) Round trip efficiency 70-80%	Materials radical redesign & research on power electronic components Turbine efficiency improvement, etc.	Efficiency improvement / Cost reduction
CAES	Adiabatic (with heat	Advanced adiabatic	50% cost to meet

	storage; 70% efficiency expected) Diabatic (need extra heat during discharge; 55% efficiency expected) Isothermic (Low capacity & power storages; 70-75% efficiency Liquefied gas (higher cost for similar efficiency but not geographical dependent) CAES $300-350/kWh (200-250€/kWh) or Capital Cost €470/kW-€2170/kW (depends on CAES type and sizing)	materials for high T° thermal storage: stable, resistant, cheap, high heat capacity, good conductivity & low degradation Demonstration of huge thermal energy storage with new media and container to resist pressure (>200-300 bars) and thermal stresses (gradients >600°C) Liquefied gas systems capital cost/demonstration of thermal TES unit cost > $30 to $40/kWh (20 to 30€/kWh) depending on storage capacity	longer-term TES cost goals Costs depend on scale and TES Improving efficiency (>70-75%)

1.4. Focus Area 4 – Novel materials for Post-Li ion, Metal air, Li-S, Na ion

1.4.1. Metal-Air system

Lithium Air

- Development of electrode technologies management to handle precipitated reaction products;
- Basic and applied research on ceramic and glass membrane electrolytes with 10 times higher conductivity, improved mechanical strength;
- Air electrode resistant to poisoning by S, CO, CO_2 or organic polluting agents;
- Development of new generation of air electrode catalysts with limited ageing and no precious metals;
- New liquid electrolytes for anhydrous lithium-air stable both in contact with lithium metal and stable to the air electrode reactions, with high Li_2O_2 solubility;
- Composite lithium electrodes or structured to avoid metallic dendrites and short-circuits;
- Development of membranes for air electrode, packaging; handling air circulation.

Aqueous zinc-air systems

- Development of high area specific capacity zinc electrodes with good cycle lifetime;

- Proof of concept of Reversible air electrodes for alkali electrolyte (currently being done but not perfected);

- Basic and applied research on low cost, high performance bi-functional catalyst for high current density positive electrodes.

Novel metal-air batteries

- Basic and applied research on new (non-Li, non-Zn) metal-air batteries (Al/air, Fe/air, V/air…);

- Development of low cost, low environmental impact, safe ionic liquids to be applied in metal-air batteries;

1.4.2. Solid State Batteries

- Development of new material chemistries for large scale stationary all solid state batteries such as Na-based technologies and all solid state lithium ion batteries (with an interdisciplinary approach to the solid state physics and chemistry, materials science and electrochemistry of battery materials in order to deliver higher energy density of today's lithium-ion batteries at less the cost per kilowatt-hour for a representative stationary application scale);

- Development of electrode/electrolyte interface, charge mechanism and mass transport in solid electrodes and electrolytes, physics and chemistry of negative/positive insertion electrode materials and highly conducting room temperature electrolytes (working on experimental approaches for determining the physical and chemical properties of battery materials);

- Safety concerns by including study of degradation mechanism, developing new electrodes/electrolytes and planar stack designs;

- Proof of concept of all solid state battery systems.

1.4.3. Lithium-sulphur

- Reduce self discharge through polysulphides dissolution decrease;

- Solid electrolytes to prevent polysulphide shuttle;

- Avoid ageing (corrosion, heterogeneous behaviour, etc.);

- Improved safety (solid polymer electrolyte, non volatile, higher boiling temperature electrolytes);

- Suitable structures for electrodes.

*1.4.4. Future alternative battery systems based on inexpensive readily available materials or multi-electron exchange (*Na, Al, Fe, Mg, etc*)*

- Development of suitable negative and positive electrode insertion materials and highly conducting room temperature electrolytes for Na ion systems;
- Development of suitable negative and positive electrode insertion materials and suitbable electrolutes for Mg based batteries;
- Prospective studies for other alternative chemistries.

1.4.5. Low environmental impact, low cost, high power, low energy Aqueous Li ion systems

Development of active electrode materials operating in water stability window, increase in the over potential of water reduction by electrode surface modification with no effect on Lithium ions diffusion, improvement of life cycle in water, these developments should be based on a cross-cutting approach with Li-S, Li-air, etc. to merge knowledge and favour innovation for negative electrode protecting layer.

1.4.6. Liquid metal batteries

Proof of concept using liquid metals for electrodes (i.e. such as pure magnesium and pure antimony for proof of concept) and molten salt as an electrolyte; this includes the development of alloys for optimal performance and cheap manufacture, determination of the smallest size of cell that would not need booster heater.

KPIs for section 1.4

Technology/Material	**Current performance**	**Target 2020-2030**	**Target 2050 and beyond**
Metal air systems	700Wh/kg (Li air Polyplus) Poor Cycles	>500Wh/kg 300-500€/kWh 3000 cycles	500-1000Wh/kg 10000 cycles ca. 100€/kWh
Na-Ion		Expected decrease in battery cost ~40%	
Li-S	350Wh/kg – 350Wh/L (Sion Power) High self-discharge 4-6%/month (sulphur migration), poor life cycle (60-100 cycles) and safety issue -40°C-25°C	500Wh/kg 3000 cycles <350€/kWh	600Wh/kg 10000 cycles ca. 200€/kWh

2. MATERIALS INTEGRATION AND COMPONENT TECHNOLOGIES

2.1. Manufacturing

Pilot 1: Manufacturing platform for Electrical Double Layer Capacitors (EDLC) & Hybrid systems: develop and demonstrate improved high-speed manufacturing methods for capacitor cell fabrication or the development of cheaper electrode materials. Novel fabrication techniques for future generations of materials such as nano materials are also required (T0).

KPIs: Cells production speed-up of 20-50% and reduced production costs on a c€/F basis (<10 €/kW), M-GW scale.

Pilot 2: Industrial pilot for Li ion system: develop and demonstrate manufacturing of low cost, safe, long life cycle, conversion systems, based on research results from pluri electron exchange materials or of new designs materials, cells, or of new processing technologies as developed under heading 1.1.1.

KPIs: System costs of about 200 €/kWh (or 10c€/kWh/cycle) for stationary application; charge-discharge temperature range: -20 degrees C to 70 degrees C; charge cycles: greater than 10 000 times at 70-80 percent design DOD; energy density above 150Wh/kg, compliance to international safety standards.

Pilot 3: CAES: Demonstrate low cost and innovative manufacturing processes for high temperature compressors, thermal storage media and container able to resist to both pressure and thermal stresses; based on materials and processes as developed under heading 1.3.2 (T0+5).

KPIs: Cost of energy storage capacity very low <4-5€/kWh; Size >GWh range.

Pilot 4: Flywheels: Develop and demonstrate manufacturing processes for rotor and motor generator with superior materials as developed under heading 1.3.1 Improving the energy density, building larger systems and reducing the material and manufacturing costs as for SMES (T0+5).

KPIs: Energy density >100Wh/kg and system cost < 2800€/kWh, kW scale units.

2.2. Technology Testing

Pilot 1: A set of electrochemical capacitor demonstrators including power electronics based on the research developments under heading 1.2 for bridging power (seconds) applications (100's kW power range) and for residential peak shaving (few kW power range and long term energy storage (hours) or for multi MW T&D applications (T0). This includes hybrid systems in combination with batteries increasing the voltage level (T0).

KPIs: Energy densities >15Wh/kg; A cost reduction down to maximum of 10 €/kW and a specific power > 30kW/kg.

Pilot 2: A set of demonstrators for large Li ion batteries systems (>1MW) and field testing projects in smaller residential, based on the research developments under heading 1.1 (T0+5).

KPIs: 10-year battery design life and 20-year power and balance-of-system design life; Charge-discharge temperature range: -20 degrees C to 70 degrees C; Charge cycles: greater than 10 000 times at 70-80 percent design DOD; fully installed system (All-in cost to install a step-up transformer) under 200€ per kilowatt-hour.

Pilot 3: Demonstration of MW scale Red-Ox system based on the research developments under heading 1.1.2 and 1.4 with infrastructure (like piping, tanks etc) for safety, operating and life-cycle cost assessment in stationary bulk power storage application (T0+5).

KPI: Reduction of total system cost (Capex & Opex). Service cost ~7c€/kWh; Energy cost ~120€/kWh; Power cost ~300€/kW; Size >MW range.

Pilot 4: Test and demonstrate at GWh scale new thermal energy storage (TES) components based on the research developments under heading 1.3.2, operating at high upper temperature limits; Investigate and demonstrate the compatibility with tube materials to prevent corrosion. Most future research into thermal energy storage may involve high-temperature systems that generate steam and energize air turbine engines. Verify long-term stability, useful service lives and cost-competitive long-term costs (T0+5).

KPIs: Pressure (>200-300 bars -1bar = 0.1MPa) and thermal stresses (stresses resulting from the cyclic temperature and pressure loads: a temperature gradient of over 600°C) (i.e. Commercial steel with allowable stress σ = 234 MPa has σ / ρ @ 30 kJ/k).

Pilot 5: Testing of Flywheels materials based on the research developments under heading 1.3.1: Demonstrate high rotation speed, i.e. high energy density, verify stability (under volume expansion), reduce cost of flywheel rotor & advanced magnetic bearing, develop lightweight vacuum containment vessel, reduce overall system weigh, work on tensile strength. Demonstrate advanced system using radial gap magnetic bearings to levitate thin-walled composite hoops rotated at high speed to store kinetic energy as example with 100,000 discharge cycles under operation for systems discharge time at rated power in the hour range (T0+5).

KPIs: Systems capital costs <200-500€/kWh of storage capacity at scales of 100-300kWh of storage capacity; >10000 cycles (>20 years life); Annual costs, in €/kW-yr, for a 1-hour (200kW); distributed generation application < 200€/kW-y or <500€/kWh. More cost effective as storage duration decreases (20s => < 60€/kW-y or <50€/kW).

Note: Energy storage costs depend on power duration: short (seconds) or long (hours).

3. RESEARCH INFRASTRUCTURE

Facility 1: European Technology Hubs on Storage (T0)

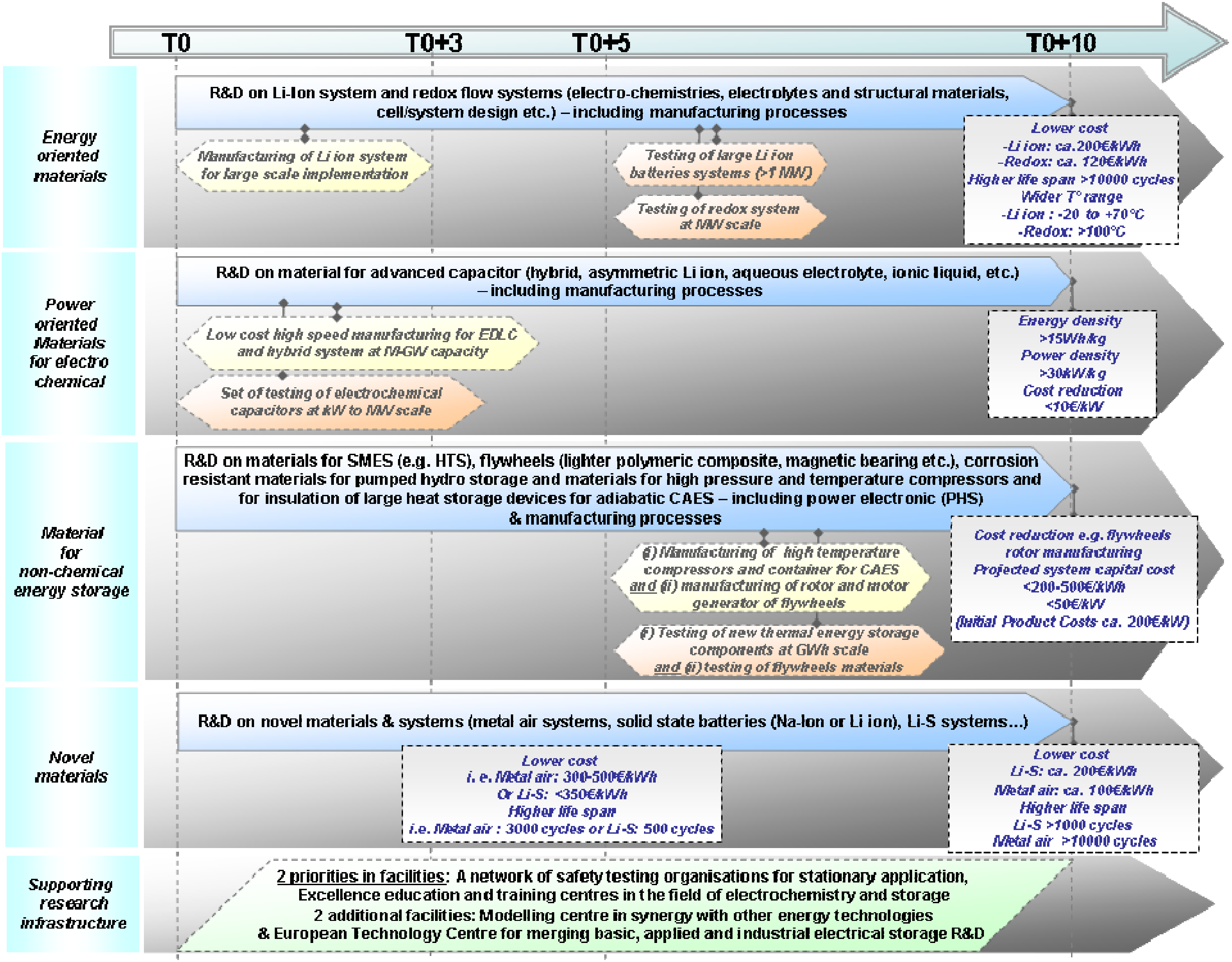
Establishment of trans-European research and innovation networks that cover a wide spectrum of actors from basic and applied research to large industrial firms and inventive start-ups, include a wide range of technologies (batteries, supercapacitors, SMES, etc.). Activities should contain basic and applied research, prototyping, industrial development, and modelling. For the latter, an EU modelling and experimental facility should be considered.

Facility 2: Network of safety testing organisations (T0)

Establishment of an EU organization working in network with MS testing centres to test storage for stationary application, assessing safety performance and certification.

Facility 3: Excellence education and training centres (T0)

Establish education centres and programmes for education and training in the field of electrochemistry and storage.


T0
T0+3
T0+5
T0+10
Energy oriented materials
R&D on Li-Ion system and redox flow systems (electro-chemistries, electrolytes and structural materials, cell/system design etc.) – including manufacturing processes
Manufacturing of Li ion system for large scale implementation
Testing of large Li ion batteries systems (>1 MW)
Testing of redox system at MW scale
Lower cost
-Li ion: ca.200€/kWh
-Redox: ca. 120€/kWh
Higher life span >10000 cycles
Wider T° range
-Li ion : -20 to +70°C
-Redox: >100°C
Power oriented Materials for electro chemical
R&D on material for advanced capacitor (hybrid, asymmetric Li ion, aqueous electrolyte, ionic liquid, etc.) – including manufacturing processes
Low cost high speed manufacturing for EDLC and hybrid system at M-GW capacity
Set of testing of electrochemical capacitors at kW to MW scale
Energy density >15Wh/kg
Power density >30kW/kg
Cost reduction <10€/kW
Material for non-chemical energy storage
R&D on materials for SMES (e.g. HTS), flywheels (lighter polymeric composite, magnetic bearing etc.), corrosion resistant materials for pumped hydro storage and materials for high pressure and temperature compressors and for insulation of large heat storage devices for adiabatic CAES – including power electronic (PHS) & manufacturing processes
(i) Manufacturing of high temperature compressors and container for CAES and (ii) manufacturing of rotor and motor generator of flywheels
(i) Testing of new thermal energy storage components at GWh scale and (ii) testing of flywheels materials
Cost reduction e.g. flywheels rotor manufacturing
Projected system capital cost <200-500€/kWh
<50€/kW
(Initial Product Costs ca. 200€/kW)
Novel materials
R&D on novel materials & systems (metal air systems, solid state batteries (Na-Ion or Li ion), Li-S systems...)
Lower cost
i. e. Metal air: 300-500€/kWh
Or Li-S: <350€/kWh
Higher life span
i.e. Metal air : 3000 cycles or Li-S: 500 cycles
Lower cost
Li-S: ca. 200€/kWh
Metal air: ca. 100€/kWh
Higher life span
Li-S >1000 cycles
Metal air >10000 cycles
Supporting research infrastructure
2 priorities in facilities: A network of safety testing organisations for stationary application, Excellence education and training centres in the field of electrochemistry and storage
2 additional facilities: Modelling centre in synergy with other energy technologies & European Technology Centre for merging basic, applied and industrial electrical storage R&D

Materials Roadmap for Electricity Grids[1]

1. MATERIALS R&D AND RELATED PRODUCT DEVELOPMENT

1.1. Focus Area 1: Materials for advanced Conductors - Current Carrying performance

Further materials development and applied R&D is important for advanced conductors for the next 10 years. Important materials and product development activities will include:

High Temperature Superconductors - HTS

- Basic and applied research on the fundamental material properties for HTS, especially second generation (2G) YBCO to ensure high uniformity of the critical current along the conductor length, enhanced magnetic field performance and reduced AC-losses;

- Development of reliable, high throughput and high yield production technologies for the HTS conductor to enable cost reduction at least by a factor of 10.

KPIs:

Technology/Material parameters	Current performance	Target performance 2020/2030	Target performance 2050
Engineering current (@77K, s.f.)	250 A/mm^2	400-500 A/ mm^2	800 A/ mm^2
Engineering current (@65K, 3T)	50 A/ mm^2	200 A/ mm^2	500 A/ mm^2
AC loss (@77K, 100mT, 50 Hz)	12 mW/m	4 mW/m	<2 mW/m
Standard splice length	200 m	500 -1000 m	2000 m
Production capacity (4mm wire)	1,000 km	50,000 km	1,000,000 km
Performance cost (@77K)	300 €/kA m	30- 40 €/kA m	<15 €/kA m

Advanced Composites

- Development of new carbon fibre and plastic core composite materials with enhanced mechanical, electrical and thermal performance i.e. high capacity, low sag, less joule losses and low electromagnetic field emissions. Increase the current carrying capacity (ampacity) performance of composite materials by at least a factor of 3.

- Develop advanced composites that are resistant to moisture ingress, and have reduced sensitivity to water for overhead lines.

- Development of metal matrix composites, with reduced brittleness for overhead lines

[1] The effective and sustainable use of resources is critical for the further development of energy technologies. Aspects related to recycling, at manufacturing as well as at end-of-life, and design for recycling/cradle-to-cradle approach are an integral part of the proposed developments.

KPIs:

Technology/Material parameters	Target performance
Composite conductors	Price reduction for by half
Composite core porosity	at 0%
Cable	able to withstand peak temperatures of 200ºC
Mechanical properties	Increase of at least a factor of 5

1.2. Focus Area 2: Polymers with Insulating properties at High Voltage

- Development of better performance polymer materials for high voltage cables with increased specific withstand stress (increase of electric field), increased critical temperatures, reduced sensitivity to impurities and to water, and increase mechanical performances (longitudinal to carry stresses during layout and radial to carry stresses in service);

- Development of better materials that reduce the sensitivity of DC cables to trapped charges and enhance their capability to polarity reversal;

- Continuous support to applied R&D for the introduction of nano-particles in insulating materials;

- Study of the long term ageing properties and processability of nano-composites, and also addressing environmental and HSE concerns in connection with the use of nano-particles;

- Enhancement of the ageing performance of line insulators under different environmental conditions, reduction of their sensitivity to pollution deposits, increase of their capability for self cleaning, increase of the allowable mechanical stresses and enhancement of their self healing capabilities;

- Enhancement of ageing performance of station insulators, their mechanical strength and insulation performance without the need of internal glass fiber insulation (longitudinal and radial strength); increase of fire resistance, enhancement of the resistance to chemical aggression; increase of performance in pollution conditions of short and long duration;

- Improvement of extrusion techniques aiming at cost reductions;

- Introduction of on-line quality monitoring and better testing of technology for the finished product.

KPIs:

Technology/Material parameters	Target performance
Insulation	Increase the breakdown strength by a factor of 10
Mawimum service electric field	Larger than 30 kV/mm
Non-metallic water barrier (such as lead)	elimination

In addition the research effort in searching for alternatives to SF_6 as isolation gas should continue to eliminate the current greenhouse and ozone-destroying issues resulting from the use of this material. Further materials research is also necessary for current transformers and insulators.

1.3. Focus Area 3: Wide Bandgap Semiconductors for Power Electronics

- Applied research in the SiC and GaN areas that is comprehensive and vertically integrated by including research effort on the SiC, GaN on Si or GaN on SiC wafer research while it is also addressing epitaxial growth issues;

- Development of high lifetime materials suitable for 20 kV devices for high injection operation to enable single SiC switch devices able of handling 30-50 kV and rated to 1000 A.

KPIs:

	2020		2030		2050
	SiC	GaN on Si	SiC	GaN on Si	
Wafer diameter (mm)	150	200	200	300	
Micropipe density	0		0		
Basal plane dislocation density	Close to 0		Close to 0		
Chip size (cm^2)	1	1 (usable)	2	2	
Operating T (°C)	250	250	250	250	
Projected cost					10 cents/A

1.4. Focus Area 4: Enabling Structural Materials

Materials for Advanced Packaging at High Temperatures

- R&D activities on high temperature packaging materials for power electronic devices to enable them to work reliably, and have an acceptable performance in the specified temperature range. Development and selection of suitable materials to minimize mismatch in coefficients of thermal expansion (CTE) that could lead to die fracture and fatigue; stresses at the die edge can cause horizontal crack propagation and die lifting.

KPIs:

- Minimum mismatch in coefficients of thermal expansion (CTE) between the different materials;
- Minimum diffusion and electromigration at high temperatures between the different materials.

Materials for Low Temperatures

- Understanding the low temperature properties and thermal cycling behavior of most standard materials at cryogenic temperatures especially the mechanisms behind low temperature dielectric breakdown, interface breakdown and mechanical properties of structural materials due to differential thermal contraction.

KPIs:

- Reduce heat transfer from the environment through the cryostat into the low temperature region;
- Cryogenic containers and pipes: identify, develop and test flexible, high strength materials with low thermal conductivity.
- Cryogenic interface materials: identify, develop and test high power current leads with low thermal conductivity

2. MATERIALS INTEGRATION AND COMPONENT TECHNOLOGIES

2.1. Focus Area 1: Advanced Conductors

Technology Testing Pilot 1: HTS

Simulation, qualification and testing of new materials and components and their interaction with the grid to reduce operational risks. Development and deployment of HTS components such as fault current limiters at bus bar level to connect sub-grids, especially at bottlenecks and constrictions, where high power has to be transferred in confined space, e.g. converter stations, tunnels, bridges of HVDC lines, or as urban distribution backbones at medium voltage. Ideally, a set of different pilots needs to be initiated for each of the aforementioned environments.

KPIs:

Application	Operating Conditions Magnetic field (T)	Operating Conditions Temperature (K)	I_c x L (kA-m)
Cables	0.01 – 0.1 (AC)	70 – 77	40.000 to 2,500,000

	0.1 – 1 (DC)		
Generators	1 – 3	30 – 65	2,000 – 60,000
Transformers	0.1 - 1	65 – 77	20,000 – 30,000
Fault Current Limiters	0.1	65 – 77	1000 – 10,000
SMES	2 – 30	4 – 50	20,000 – 30,000
Motors	2 – 5	30 – 65	1000 – 25,000

Manufacturing Pilot 1: HTS – T0+15

Development and testing of new manufacturing processes to significantly improve existing manufacturing technologies such as IBAD, RaBIDS as well as to scale-up novel, non-vacuum deposition methodologies such as Chemical Solution Deposition (CSD).

KPIs:

Target
Capacity = 500 – 1000 km of HTS cable per annum
Cost reduction by a factor of 10
Deposition rates > 0.3 - 0.5 m/min

3. RESEARCH INFRASTRUCTURE

3.1. Focus Area 1: Advanced Conductors

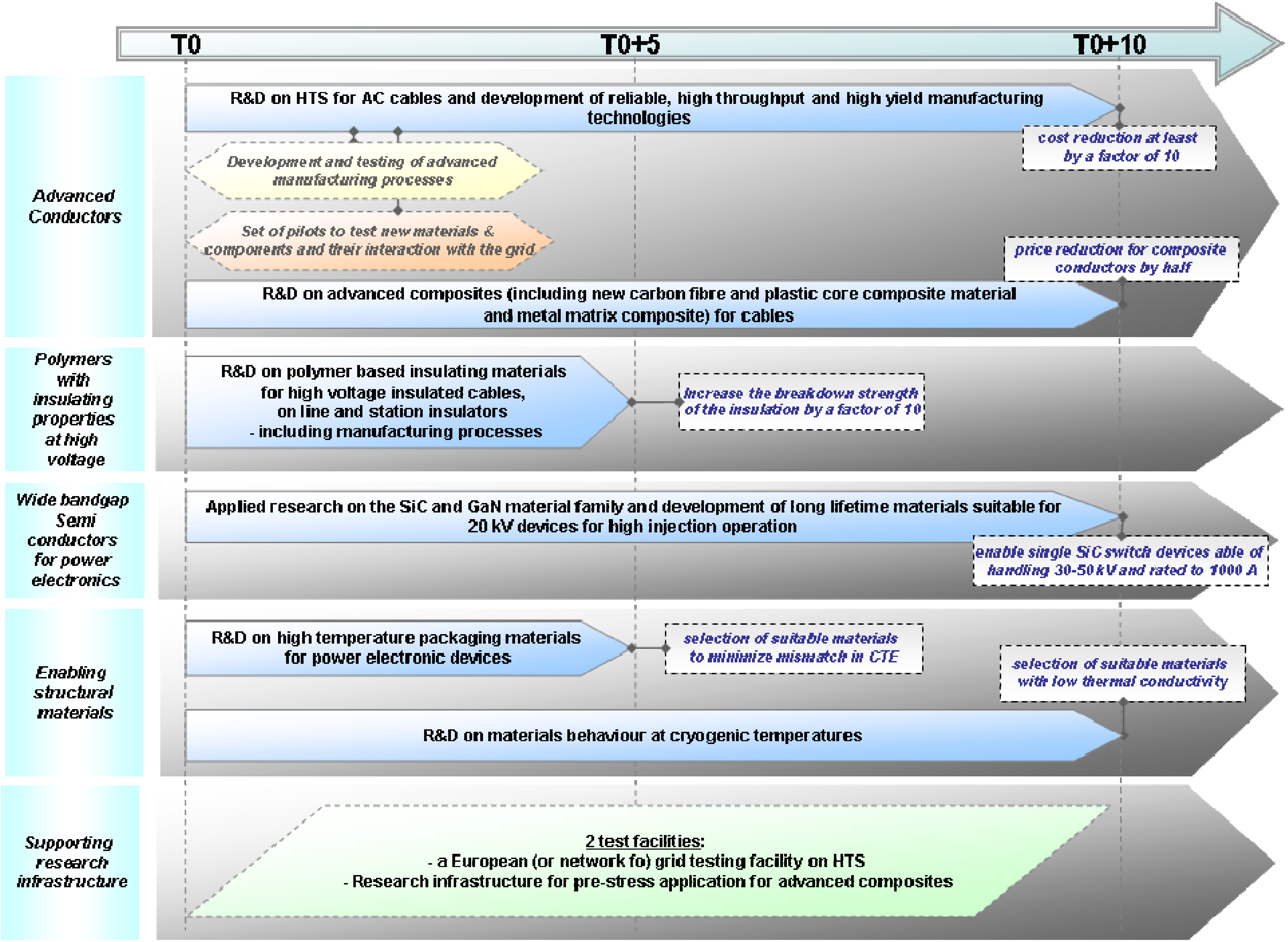
Facility 1: HTS – T0+15

- Establish a European grid test facility where new components can be tested both individually and within a system with complex interactions, and under extreme operation conditions. This can be done by coordinating the existing test centres through a European network based existing centres, and create new facilities either within the existing centres or independently where competence gaps exist.

- Equip existing test centres with the latest hardware simulation and test infrastructure to qualify new components.

Facility 2: Advanced Composites – T0+10

Develop pre-stress application experience for carbon fibre and plastic core composites to enable field application of these materials. Enable this with the establishments of a European test facility that is accessible to all.


T0
T0+5
T0+10
Advanced Conductors
R&D on HTS for AC cables and development of reliable, high throughput and high yield manufacturing technologies
Development and testing of advanced manufacturing processes
Set of pilots to test new materials & components and their interaction with the grid
cost reduction at least by a factor of 10
price reduction for composite conductors by half
R&D on advanced composites (including new carbon fibre and plastic core composite material and metal matrix composite) for cables
Polymers with insulating properties at high voltage
R&D on polymer based insulating materials for high voltage insulated cables, on line and station insulators - including manufacturing processes
increase the breakdown strength of the insulation by a factor of 10
Wide bandgap Semi conductors for power electronics
Applied research on the SiC and GaN material family and development of long lifetime materials suitable for 20 kV devices for high injection operation
enable single SiC switch devices able of handling 30-50 kV and rated to 1000 A
Enabling structural materials
R&D on high temperature packaging materials for power electronic devices
selection of suitable materials to minimize mismatch in CTE
selection of suitable materials with low thermal conductivity
R&D on materials behaviour at cryogenic temperatures
Supporting research infrastructure
2 test facilities:
- a European (or network fo) grid testing facility on HTS
- Research infrastructure for pre-stress application for advanced composites

Materials Roadmap for Bioenergy[1]

1. MATERIALS R&D AND RELATED PRODUCT DEVELOPMENT

1.1. Focus Area 1: Structural materials to reduce time to market & life cycle costs

- High strength, wear and corrosion resistant steels, alloys and protective coatings with improved component life at high temperature - for heat exchangers, gas coolers, gas cleaning, tar/water condensers, superheaters, combustion engines, gas turbines, furnace or container walls, feedstock treatment and handling;

- Development of polymer, ceramic and other materials (alternative to those in the above paragraph) with improved durability;

- Generation of design-relevant materials data, advanced design concepts and definition of operating limits of materials with respect to feedstock;

- Recycling strategies for high-value material recovery;

- Improved monitoring and life assessment/life prediction methods.

1.2. Focus Area 2: Catalysts

- Higher selectivity and yield, improved stability and functionality such as bi-/multi-functional catalytic systems, with focus on micro-porous carrier materials (micro-structured catalytic reactors) with modified active metal centres, application technology (coating), recoverable/recyclable and environmentally acceptable in:

  - Bio-oil and syngas upgrading and stabilization such as oxygen removal (decarboxylation), de-NOx, cracking, hydro-treating, conversion to platform-chemicals and fuels;

  - Conversion of primary products to platform-chemicals and fuels;

  - Direct conversion of biomass to sugars or chemicals;

1.3. Focus Area 3: Membranes

Advanced ceramic, polymeric or metallic membranes for:

- Gas separation e.g. for O_2, H_2, CO_2, CH_4;

- Separation of (inhibitory or intermediary) products from biomass pretreatment, separation/recycling of enzymes, immobilization of cells, downstream processing in (continuous) separation of fermentation products.

[1] The effective and sustainable use of resources is critical for the further development of energy technologies. Aspects related to recycling, at manufacturing as well as at end-of-life, and design for recycling/cradle-to-cradle approach are an integral part of the proposed developments.

1.4. Focus Area 4: Hydrolytic enzymes and novel microorganisms

- New enzymes from metagenomic libraries of natural sources with high throughput screening methods; enzymes with new functionalities and improved process-related properties;

- New hydrolytic enzymes/enzyme complexes through evolutionary design and protein engineering with 2 times higher efficiency and yield (esp. on recalcitrant biomass);

- Novel expression hosts, genetic systems and vectors for a broader range of genes from metagenomic libraries (especially thermophilic);

- Improved production organisms, vectors and genetic systems for production of industrial enzymes;

- Microorganisms/microbial systems for simultaneous microbial conversion of polysaccharides to biofuels (consolidated bioprocessing) and of microorganisms utilizing C5-sugars, CO_2 or syngas.

1.5. Focus Area 5: Photosynthesis

- Highly transparent materials for photosynthetic processes (photobioreactors): transparent to solar radiation, ultra-violet filtering, low cost, anti-fouling, durable and recyclable;

- Identification and development of better suitable strains from microalgae or bacteria: non-bleaching, with better process relevant parameters;

- Photon receptors and catalysts for artificial photosynthesis.

2. MATERIALS INTEGRATION AND COMPONENT TECHNOLOGIES

2.1. Manufacturing

Pilot 1 (Focus Area 1): Development of Corrosion Resistant Steels, Alloys and Coatings (T0+5 to +15)

Development of manufacturing and fabrication processes for use of special steels and alloys as well as processes for the application of existing and novel surface coatings to structural components, also processes for welding dissimilar high-alloy and coated components, for use in different equipment designs including combustion turbines with bio-oil, syngas and biogas, with suitable feedstock mixture in varying composition; use for acidic or alkaline feedstock pretreatment equipment (cookers), and for storage containers and transportation equipment, considering economy and reducing service time; development, design and performance tests for presses, grinding machines, heat exchangers for pre-treatment.

KPI Corrosion Resistant Steel

Technology/ Material	Current performance	Target performance 2020/2030	Target performance 2050

Corrosion resistant steels and weldments	Problems of fouling, corrosion and wear depending on biomass and biomass/coal fuel mixtures	Successful demonstration for bioenergy technologies	Advanced technologies operating with novel materials and design at very high conversion efficiencies
Diffusion, spray and weld coatings with high strength, and wear and erosion resistance	Able to deal with fossil fuels at moderate conversion efficiency. Problems with technology application and composition	Coatings for biomass/bio-energy systems working at high conversion efficiencies & new innovative long-life coatings	Coatings working at very high (e.g. ultra-super-critical) conversion efficiency

Pilot 2 (Focus Area 1): Active Coating Application Techniques (T0+3 to +25)

Development of processes for the application of active coatings with incorporated catalysts on micro-structured carriers (Microchannel Reactor Technology).

KPI Coating Technologies Resistance

Technology/ Material	Current performance	Target performance 2020/2030	Target performance 2050
Coating technology for MRT	coating technology not sufficient	See table 1 at the end of the roadmap	See table 1

Pilot 3 (Focus Area 5): Photosynthetic Process Materials with Proper Design (T0+5 to +20)

Pilot for developing optimal transparent materials in optimal design: transparent material with proper design in combination with optimal photosynthetic strains and for artificial photosynthesis. Performance tests of different transparent tubing materials for illumination of cultures in photosynthesis and for artificial photosynthesis.

KPI Material Photosynthesis

Technology / Material	Current performance	Target performance 2020/2030	Target performance 2050
Transparent material in combination with design	Fowling through cell adsorption; high price	Pilot of price competitive material with optimised design for high efficiency	Fully implemented plant with optimal light-exposure systems
Optimised organisms	MOs sensitive for bleaching; low performance	Micro-algae and bacteria with bleaching tolerance and optimised product formation	High performance micro-algae and bacteria for desired products with high yield

Catalyst systems for artificial photosynthesis	Early research state	Suitable/affordable photon receptors and electron transfer catalysts in lab scale	Demonstration plant with optimal lighting design and optimal catalytic material

2.2. Technology Testing

Pilot 1 (Focus Area 1): Fluidised Bed Material (T0+5 to +25)

Testing and developing novel multifunctional bed materials for gasification reactors; technical performance testing of different bed materials in CCS and H_2-production plants.

KPI Functional fluidised bed material

Technology/ Material	Current performance	Target performance 2020/2030	Target performance 2050
Dedicated bed material design for optimum performance	Early stages of functional bed design and use	Established functional beds with catalytic capability for multiple processes in one step	New functionalities with lower costs

Pilot 2 (Focus Area 2): Novel Catalysts, Poisoning Resistance and Long Life (T0+5 to +25)

Testing of multifunctional catalysts for various processes, including activity in advanced liquids (ILs) or at lower temperature e.g. in catalytic systems for micro-structured catalytic reactors, and catalyst reutilization and recycling.

KPI Catalysts

Technology/ Material	Current performance	Target performance 2020/2030	Target performance 2050
Novel catalysts	Insufficient performance, poisoning and poor recycling	Long-life catalysts for new conversions, 100% recycling	Lower costs
Direct conversion of biomass	Not available	Depolymerization and hydrogenation of biomass polymers to chemicals	Poison resistant; new functionalities
Nano-structured carrier material	Test phase	Application developed by 2015, pilot by 2020	New functionality, lower costs

Pilot 3 (Focus Area 3): Novel Polymeric, Ceramic or Metallic Membranes and Filters (T0+3 to +20)

For gas separation and purification, and separation of non-fermentable components from pre-treated pulps and process intermediates for an effective biochemical conversion to biofuels. Testing the technical performance in the different biomass-to-energy pathways

KPI Novel Membranes and Filters (see table 2 at the end of the roadmap)

Technology/ Material	Current performance	Target performance 2020/2030
Novel separation processes & materials for use in different phases of bioenergy production aimed at developing effective production processes	Lack of sufficient separation limits the performance of biofuel production processes and the performance of biochemical conversion routes	At least three novel separation processes developed; one each for gas, inhibitor and product separation; effective lignin separation schemes developed

Pilot 4 (Focus Area 4): Strains and Vectors for Screening and Industrial Production of Recombinant Enzymes (T0+3 to +35)

Large scale production of recombinant proteins in industrial scale needs new strains and genetic systems and a testing pilot for optimal expression, upscaling, monitoring and downstream handling in fermentation procedures especially with new production strains and products (up to the m^3 range with all up- and down-stream as well as analytical equipment)

KPI Novel Recombinant Enzymes

Technology/ Material	Current performance	Target performance 2020/2030	Target performance 2050
Large scale production of recombinant proteins for industrial use	Production only possible for selected bacterial and fungal proteins in few hosts and after trial and error development, often cell-internal production	Three more eukaryotic (plant and fungal) and bacterial production hosts each with product secretion; rational development of 100% higher yield	Routine expression of proteins in high yield with the host of choice, allowing correct glycosylation and protein modification; Predictable design for production and up-scaling
New hosts and genetic systems for enzyme screening	Mainly E. coli	At least two thermophilic bacterial hosts, one Gram-positive and archaeal host, + genetic systems; one in vitro-system	Two more eukaryotic and archaeal, Gram-negativ and –positive bacterial hosts each; in vitro gene expression systems suitable for high-throughput screening
New strains for SSF	Not available	Two new strains simultaneously fermenting cellulose to biofuels; C5 + C6 sugar fermenting	New products and economic yield from biomass
Novel enzymes and enzyme complexes with gene	Slow and inefficient with recalcitrant biomass	>90% hydrolysis of polysaccharides in <18 hrs; reduced	>98% hydrolysis in <10 hrs with <3 kg/to enzyme at >60°C and pH <4,5

engineering/evolutionary design		enzyme need, specific activity +100%	

3. RESEARCH INFRASTRUCTURE

Facility1: Research centres of excellence and scientific networks

To bring biologists, (bio)chemists, chemical engineers and engineers together for intensified research in:

- *Pre-treatment technologies*: materials for mechanical, physical and chemical technologies, enzymes and solvents for fibre deconstruction and sugar yield, for separation of polysaccharides from lignin, leaving lignin in a physical and chemical native structure;

  - Improved process design for reducing materials requirements and facilitating material recycling;

  - Online monitoring technology and equipment for process control and analysis;

  - Data generation for understanding of process environments, process modelling and life cycle analysis in all processes;

  - In fermentation: larger scale, plug-flow or continuous scheme, solid-state fermentation, and higher cell density (e.g. cell immobilization);

  - Integration of bioenergy production in platform chemical production (biorefinery).

- *Catalysis*: investigation of new reaction pathways (functionality especially for carbohydrates); application to surfaces (microporous material); catalysts with longer lifetime and resistance to poisoning; catalyst cleaning, reutilization, recycling and safe disposal.

- *Biochemistry of sugar compounds* - biomass to platform chemicals.

- *Enzymes*: new enzymes from microbes; their activity enhancement (e.g. by genetic engineering and direct evolution); expression and production of industrial amounts of recombinant proteins; enzyme mechanisms on insoluble substrates; development of enzyme theory for solid substrates.

- *Biomass fermentation*: intensified research for:

  - Fermentation strains and metabolic engineering: screening & development of new microorganisms for new products (biofuels and platform chemicals), simultaneous saccharification and fermentation (SSF), higher yield and selectivity, at higher temperature, simultaneous utilization of C6 and C5 sugars, metabolic engineering including gene regulation systems in microorganisms;

- Continuous and plug-flow fermentation schemes (including strain development);

- *In situ* separation of valuable by-products and fermentation products from culture and their (re)utilization (e.g. membranes, pervaporation, vacuum);

- Use of alternative feedstock (new varieties and mixes); substrate flexibility and mixture; removal of toxic by-products from substrate pre-treatment (filters, membranes, sorbents);

- Development of growth and production stimulating additives (nitrogen source etc.);

- Methane fermentation (biogas): understanding microbial communities and their interaction; optimised inoculants; process parameters, additives for optimised microbiota;

- Downstream processing: purification of fermentation products from dilute aqueous solutions (sorbents, extraction, membranes, pervaporation, vacuum).

- *Process monitoring equipment and software*: developing monitoring systems/equipment in combustion, gasification, catalysis, or fermentation processes (such as for biogas or alcohols).

- *Impact of biomass utilization:* full Life Cycle Analysis for biomass utilization from plant growing to by- and end-product reutilization; Territorial Impact Analysis for impact of biomass growing on soil, land and water use; studies on ecological, economical or social structures impact, technical needs, plant breeding and selection, planning, legislation, standardisation, and politics (reduces material needs).

- *Use of CO_2 as carbon source in fermentation and photosynthesis*: development of production strains and fermentation processes needs a concerted action of a wide range of science fields.

- *Residue utilization:* utilization of ashes from combustion and fermentation; impact of disposal (deactivation); leaching of trace elements (e.g. phosphorous); use as fertilizer.

Table 1:

KPIs: Coating Technologies to Provide Active Catalytic Coatings

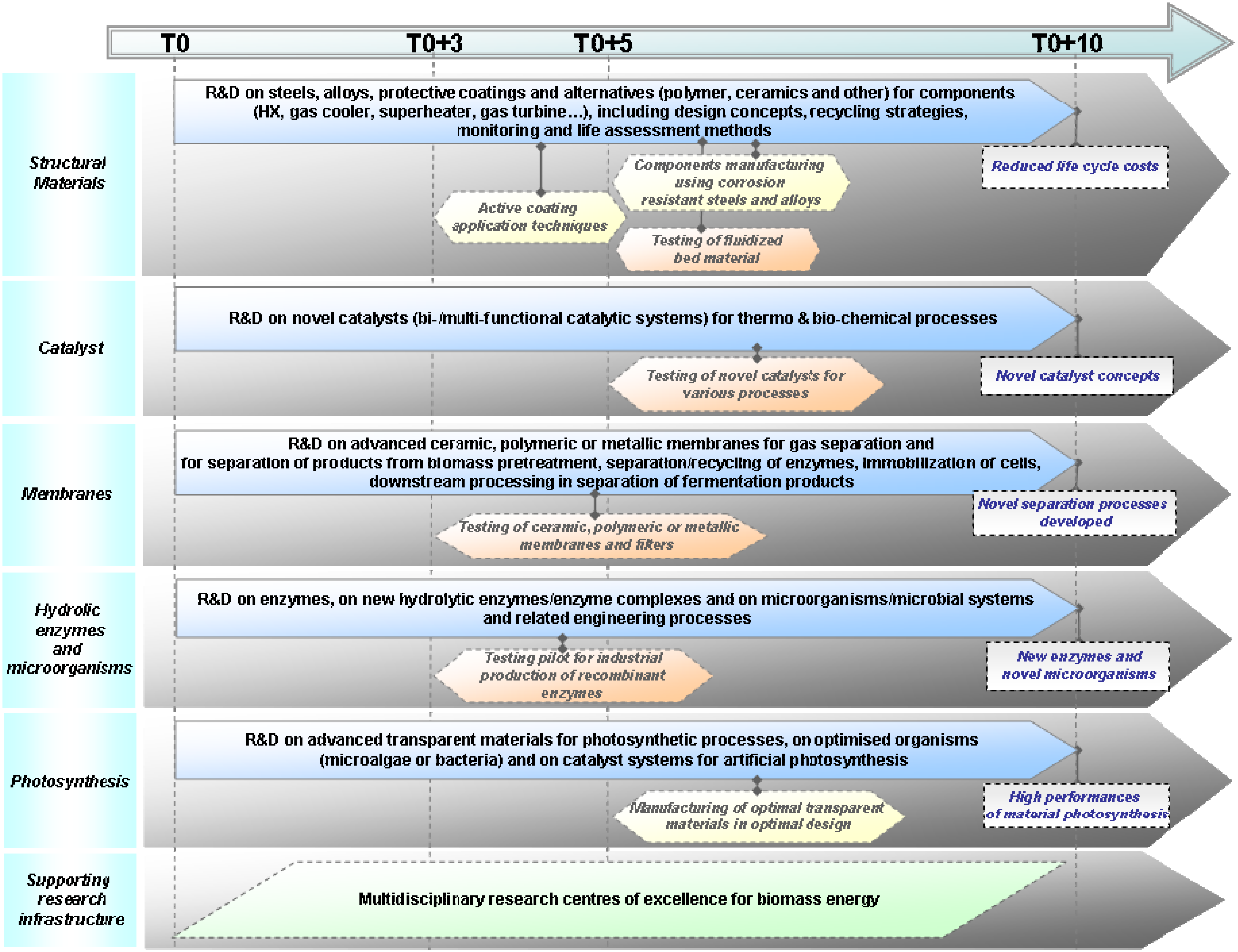
Technology/ Material	Current performance	Target performance 2020/2030	Target performance 2050
Microchannel Technology/ Development of small modular reactors (SMRs) made of special metallic alloys for liquid biofuels production by Fischer-Tropsch synthesis applied to technologies based on Biomass-to-liquid (BtL) or Waste-to-Liquid (WtL)	Not yet commercially available Metallic alloys used in the manufacturing of reaction units able to endure extreme process conditions. Carburization-resistant alloys and metal dusting phenomena High costs of special metallic alloys, assembly and micromachining technology Insufficient technology of filling catalyst particles to the microchannel. New methodology uses catalyst coating techniques with: *Coating layer thickness:* > 50 μm *Loading:* > 3 mg/cm^2 *Adherence level (%):* < 90% *Low reproducibility of obtained results* Demonstration tests in two pilot BtL plants (1 barrel per day (bbl/d)) in Güssing-Austria and USA.	Demonstration projects or flagship plants based on structured technologies (microchannel technology) Commercial scale BtL plant with FT microchannel reactor (production capacity ≤ 50 bbl/d) Deposition methods with reduced costs and simplified preparation stages for homogeneous, dense, thin and well adherent coating layer of catalyst materials: *Coating layer thickness:* 10-20 μm *Loading:* ≈1 mg/cm^2 *Adherence level (%):* 100 *Improved reproducibility*	Large scale industrial deployment of BtL and WtL plants based on microchannel technology and with production capacities > 50 bbl/d.

Table 2:

KPIs for Pilot 3: Novel Membranes and Filters

Technology/ Material	Current performance	Target performance 2020/2030	Target performance 2050
Membrane Technology / Metallic dense membranes based on Pd and/or Pd alloys for H_2 separation from gaseous mixtures and applications of Catalytic Membrane Reactors (CMRs). Hydrogen separation modules for decentralised applications	Not yet commercially available **<u>Present Specification:</u>** ΔP *Capability*: < 27 bar *Flux:* 67 $Nm^3/(m^2.h)$@ 2 bar *Stability*: 1-2 years *Selectivity*: 99.99 % (H_2/N_2) depending on the initial composition. *Sulphur tolerance*: <250 ppm Low CO tolerance *Cost of membrane* (€/m^2): ≈ between 1.500 and 2.000 for the membrane and 5.000 for the module *Thickness* 3 - 9 μm	ΔP *Capability*: 35-40 bar *Flux:* ≤100 $Nm^3/(m^2.h)$@ 6.9 bar. *Stability:* ≤ 5 years. *Selectivity*: 99.99 % Sulphur tolerance: ≤ 1000 ppm Increased CO tolerance *Reduced cost*: ≤ 750 €/m^2 • new metallic porous supports • Alternatives to Pd with optimum diffusivity, flux; reducing stresses resulting from H_2 dilatation. • metallic membranes <3 μm for improving flux and reducing cost • new materials for the manufacturing of metal interdiffusion barrier layers • compact and modular CMRs with capacities in terms of H_2 flow ≤50 Nm^3/h - development of commercial plants at small scale	• Commercial availability • Metallic membranes with improved performance, durability and cost effectiveness, safer, and more environmental friendly, for H_2 separation and several chemical and biochemical processes ΔP *Capability*: > 40 bar. *Flux:* >100 $Nm^3/(m^2.h)$@ 6.9 bar. *Stability:* > 5 years. *Selectivity:* 99.99 % Sulphur tolerance: > 1000 ppm 20 % reduced cost of support

Membrane Technology / Ceramic membranes based on mixed ion electron conductive membranes (MIEC) for oxygen or H_2 production	Not yet commercially available Lack of durable membranes in harsh chemical and mechanical conditions Low oxygen permeability (reduced flux and yield) ΔP *Capability*: ≈ 1 bar *Flux:* < 5 $Nm^3/(m^2.h)$ @ 850 ºC air/inert gas *Stability*: 3 years *Selectivity*: 99.99 % *Sulphur tolerance*: < 10 ppm *Cost of membrane* ≈ 5000 €/m^2 about for mono channel tubes	ΔP *Capability*: about 1 bar. *Flux:* > 5 $Nm^3/(m^2.h)$@ 850 ºC by use of hollow fibres *Stability*: > 5 years. *Selectivity*: > 99.99 % *Sulphur tolerance*: > 10 ppm *Cost of membrane* < 5000 €/m^2 for mono channel tubes; < 1000 €/m^2 for hollow fibres	Commercial availability Expected ≈ 20 % reduced cost of support



T0
T0+3
T0+5
T0+10
Structural Materials
R&D on steels, alloys, protective coatings and alternatives (polymer, ceramics and other) for components (HX, gas cooler, superheater, gas turbine…), including design concepts, recycling strategies, monitoring and life assessment methods
Active coating application techniques
Components manufacturing using corrosion resistant steels and alloys
Testing of fluidized bed material
Reduced life cycle costs
Catalyst
R&D on novel catalysts (bi-/multi-functional catalytic systems) for thermo & bio-chemical processes
Testing of novel catalysts for various processes
Novel catalyst concepts
Membranes
R&D on advanced ceramic, polymeric or metallic membranes for gas separation and for separation of products from biomass pretreatment, separation/recycling of enzymes, immobilization of cells, downstream processing in separation of fermentation products
Testing of ceramic, polymeric or metallic membranes and filters
Novel separation processes developed
Hydrolic enzymes and microorganisms
R&D on enzymes, on new hydrolytic enzymes/enzyme complexes and on microorganisms/microbial systems and related engineering processes
Testing pilot for industrial production of recombinant enzymes
New enzymes and novel microorganisms
Photosynthesis
R&D on advanced transparent materials for photosynthetic processes, on optimised organisms (microalgae or bacteria) and on catalyst systems for artificial photosynthesis
Manufacturing of optimal transparent materials in optimal design
High performances of material photosynthesis
Supporting research infrastructure
Multidisciplinary research centres of excellence for biomass energy

Materials Roadmap for Novel materials for the fossil energies sector, including carbon capture and storage[1]

1. MATERIALS R&D AND RELATED PRODUCT DEVELOPMENT

1.1. Focus Area 1: Novel materials –Absorber Materials

1.1.1 Optimization of liquid absorbents and development of non-conventional absorbents for CO2-over N2 separation;

1.1.2. Optimization of solid looping materials for high temperature CO2 capture solid adsorbents and development of others non-conventional adsorbents for CO2-over N2 separation;

1.1.3. Optimization of polymeric and inorganic membranes for lifetime longer than 30.000 hours. Development and structuration of non-conventional polymeric and inorganic CO2 over N2 separation membranes and inters of the absorption tower.

KPIs:

Research areas	KPI
1.1.1	Service life such that the make up flow cost is lower than 2-3 euros/t CO2 captured
1.1.2	CO2 capacity higher than 5mol/kg; power plant efficiency drop <6%
1.1.3	Permeation rates(flux) from 1 to over 100 Barrers for micro porous membranes (molecular sieve carbon and polymers)

1.2. Focus area 2: Functional materials for oxyfuel and pre combustion technologies

1.2.1 Development of oxygen carrier for Chemical Looping technologies with the aim to reach up scalability and improved/optimal Chemical Looping performance. Concentration on kinetic limits;

1.2.2 Development of sorbents for CO2/H2S separation from syngas and sorption enhanced water gas shift and sorption enhanced reforming or gasification;

1.2.3 Development of oxygen separating membrane materials resistant to steam and SO2 at working conditions;

1.2.4 Development of hydrogen separating membranes suitable for integration in practical operating conditions.

[1] The effective and sustainable use of resources is critical for the further development of energy technologies. Aspects related to recycling, at manufacturing as well as at end-of-life, and design for recycling/cradle-to-cradle approach are an integral part of the proposed developments.

KPIs:

Research areas	KPI
1.2.1	Service life such that the make up flow cost is lower than 2-3 euros/t CO2 captured
1.2.2	Service life such that the make up flow cost is lower than 2-3 euros/t CO2 captured
1.2.3	Flux higher than 20Nml/min.cm^2 (for oxygen separating MIEC-membranes) at temperatures > 750ºC. Thermo-mechanical stability to allow lifetime longer than 10.000 hours
1.2.4	Flux higher than 20Nml/min.cm^2 (for hydrogen separating MIEC-membranes) at temperatures > 750ºC. Thermo-mechanical stability to allow lifetime longer than 10.000 hours

1.3. Focus area 3: High temperature strength materials

1.3.1 Optimization of F/M steels to be used at temperatures up to 650ºC and higher Cr materials to be used up to 670ºC;

1.3.2 Development and qualification of advanced iron-nickel alloys (Ni<40%) to be resistant to fireside corrosion;

1.3.3 Optimization of γ' strengthened nickel base alloys (composition, heat treatment, etc.) to improve the microstructure stability as well as the mechanical properties, creep strength and fatigue characteristic;

1.3.4 Development of nickel base alloys to be used up to 800ºC;

1.3.5 Proof of concept of new fabrication routes for ODS to be cost competitive with the Ni base alloys.

KPIs:

Research areas	KPI
1.3.1	Creep strength of 100MPa after 100.000 hours at the operating temperature
1.3.2	Creep strength of 100MPa after 100.000 hours at the operating temperature
1.3.3	Creep strength of 100MPa after 100.000 hours at the operating temperature
1.3.4	Creep strength of 100MPa after 100.000 hours and stability of microstructure under cyclic loads at temperature up to 800ºC
1.3.5	Lower cost than nickel base alloys - Cost reduction by a factor of about two

1.4. Focus area 4: Environmental effects on advance materials

1.4.1 Influence of steam in creep, fatigue, creep assisted fatigue crack growth in solid solution and particle strengthened nickel alloys;

1.4.2 Oxidation and corrosion of nickel base alloys in the hot gas path due to altered working fluids for IGCC;

1.4.3 Development of protective coating and thermal barriers coating systems for steam and gas turbines as well as overlay welding, suitable to withstand cyclic operation conditions;

1.4.4 Development of models based on field and lab data for life time prediction and assessment of critical components: Models for fireside corrosion for nickel alloys under new operating conditions, kinetic and thermodynamic models for fouling/slagging/corrosion/erosion in co-combustion, etc.

KPIs:

Research areas	KPI
1.4.1	Creep strength of 100MPa after 100.000 hours at the operating temperature
1.4.2	Integrity of oxide layers after test time longer than 10.000 hours
1.4.3	Integrity of coating systems after a number of cycles representative for each type of plants
1.4.4	Good predictive capacity of experimental observation from field

1.5. Focus area 5: Novel materials

1.5.1 Computational and experimental validation of refractory metal based alloys to be used up to 1800ºC;

1.5.2 Development of oxide fibre/oxide ceramic (CMC) and fibre reinforced materials for gas turbine application;

1.5.3 Development of improved intermetallic materials to be used for gas turbines;

1.5.4 Development of gradient materials for steam turbines application with special attention to questions concerning manufacturing of components and repairing.

KPIs:

Research areas	KPI
1.5.1	Required mechanical properties for the foreseen use at temperatures up to 1800ºC
1.5.2	Required mechanical properties for their use in some components of gas turbines

1.5.3	Required mechanical properties for their use in some components of gas turbines
1.5.4	Required mechanical properties for their use in some components of steam turbines

1.6. Focus area 6: Materials for storage technologies

1.6.1. Research into standard completions materials (cement, steel, elastomer);

1.6.2. Research into new well materials (including composites);

1.6.3. Research into materials for leakage repair;

1.6.4. Materials for favouring dissolution of CO2 and catalysts for in situ mineralization.

KPIs:

Research areas	KPI
1.6.1	Adequate long-time behaviour when exposed to CO_2
1.6.2	Better long-term resistance to CO_2, impurities and saline brine attacks
1.6.3	Required mechanical and chemical properties for better repair of leakages
1.6.4	Required mechanical and chemical properties for favouring dissolution of CO2 and catalysts for in situ mineralisation

2. MATERIALS INTEGRATION AND COMPONENT TECHNOLOGIES

2.1. Manufacturing

Pilot 1: Validation of processing and manufacturing (welding, bent, heat treatment, repair) of advanced nickel base alloys developed under heading 1- focus area 3 for steam turbine and boiler technologies: long term creep rupture test for more than 10.000 hours, cold-strain effects on creep properties, weldment strength reduction factor determination. Time for implementation for existing alloys: T0+0; and for new developed alloys: T0+4 years.

Pilot 2: Fabrication and validation of mock-up of large components of nickel base alloys (welded rotor, casting for USC) and dissimilar welded joints (nickel alloys/ferritic alloys) under operating conditions. The mock-up should reproduce the more critical dimensions/ characteristics of the components to be validated. Time for implementation: T0+0 years.

Pilot 3: Application and validation of pre-commercial coating systems developed under heading 1- focus area 4 under new operating conditions including cycling conditions. Protective coatings for pipes and boiler components in USC power plants should be validated in operating conditions representative of co-combustion mode and oxy-combustion mode. Bond coating/thermal barrier coatings systems should be validated in representative conditions for hot sections components of gas turbines. Time for implementation: T0+4 years.

Pilot 4: ODS steels are considered an attractive material for the fabrication of components of fossil power plants operating at high temperature. But fabrication and welding of these alloys are critical issues to be resolved:

a) Optimization of non fusion joining techniques for ODS. To scale the more promising up with the final objective of using them for weldment of actual components. Time for implementation: T0+0 years;

b) Implementation of industrially feasible fabrication route for ODS, such as mechanical alloying with especial attention to the homogeneity and reproducibility of commercial heats. Time for implementation: T0+0 years;

c) Qualification of commercial ODS alloys in simulated industrial/operating environment. Time for implementation: T0+4 years.

KPIs:

Pilot	KPI
Pilot 1	Retention of creep strength at operating temperature after more than 10.000 hours Establishment of cold forming strain for nickel base alloys (20% seems to be possible) Establishment of the weld strength reduction factor and improved if possible
Pilot 2	Stability of microstructure and acceptable oxidation rate for base and weld metals after 10.000 hours under operating conditions (steam at 700ºC)
Pilot 3	Good performance(integrity, no spalling, adherence, etc.) after 10.000 hours under operating conditions
Pilot 4	a) No modification of the microstructure, lack of joining defects, acceptable behaviour in the qualification tests (bending, tensile, etc.) b)Production of commercial heats of ODS steels according to specification c)Mechanical properties data and oxidation rates at room and high temperature

2.2. Technology Testing

Pilot 1: Testing proven absorbents and post-combustion membranes (either existing or novel materials, proven at lab scale) in industrial/operational setting on pilot scale (MW scale).Time for implementation: T0+0 years.

Pilot 2: Scale up and integration of available oxygen carriers in CLC-plant, (MW scale) Time for implementation: T0+0 years.

Pilot 3: MWs range pilot for sorption-enhanced water gas shift or sorption enhanced reforming or gasification. Time for implementation T0+ 3 years.

Pilot 4: Integration of hydrogen separating membranes and oxygen separating membranes developed under heading 1- focus area 2in small-scale oxyfuel and precombustion power plant concept. Time for implementation: T0+ 5 years.

Pilot 5: Development and experimental validation of integrated models focussed on the material-component performance evolution during long-term service. Experimental validation should be based mainly on field data (operational data, results from materials tested in operating conditions, post-mortem analysis of critical components) to improve the predictive capability of models). Time for implementation: T0+0 years.

Pilot 6: A set of pilots to validate the materials for storage technologies (developed under heading 1 – focus area 6) in real-life conditions and to enable further upscaling.

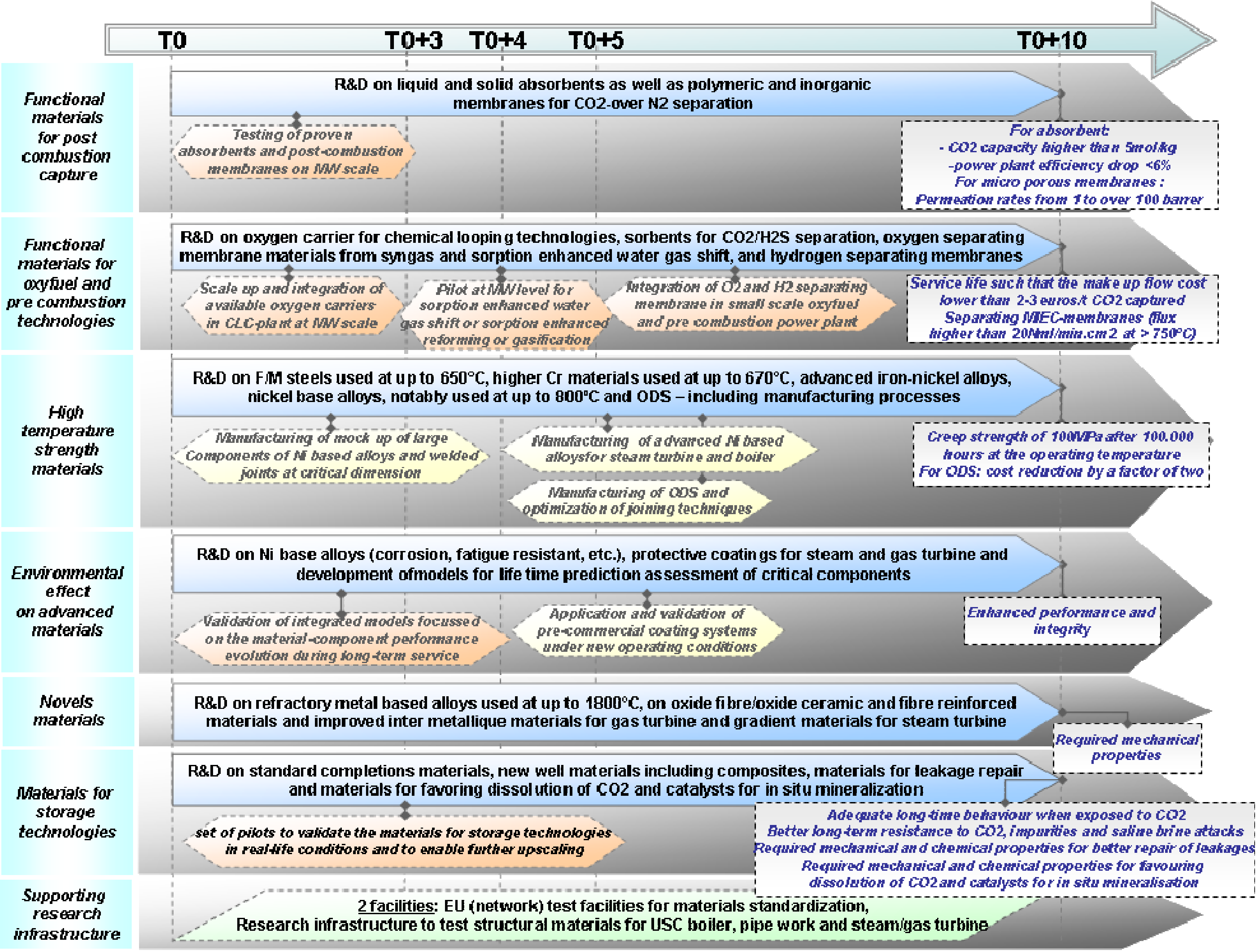
KPIs

Pilot	KPI
Pilot 1	Power plant efficiency drop <6%. Thermo-mechanical stability for a lifetime > 10.000 hours
Pilot 2	Service life longer than 10.000 hours
Pilot 3	Efficiency of 50%
Pilot 4	Service life longer than 10.000 hours
Pilot 5	Models suitable for prediction of components behaviour in plant. Good agreement between the results from modelling and lab and plant validation data
Pilot 6	Validation of materials for storage technologies in real-life conditions

3. RESEARCH INFRASTRUCTURE

Facility 1: EU test facility for materials standardization: A network between existing EU test facilities and existing national test facilities within European Countries including selected international partners. Time for implementation, T0+1 years.

Facility 2: Research infrastructure to test at "realistic" scale and operating conditions the structural materials for USC boiler, pipe work and steam turbines and for gas turbine and minimize the dependence of lab/small scale experimental data. Time for implementation, T0+0 years.



T0
T0+3
T0+4
T0+5
T0+10
Functional materials for post combustion capture
R&D on liquid and solid absorbents as well as polymeric and inorganic membranes for CO2-over N2 separation
Testing of proven absorbents and post-combustion membranes on MW scale
For absorbent: - CO2 capacity higher than 5mol/kg -power plant efficiency drop <6% For micro porous membranes : Permeation rates from 1 to over 100 barrer
Functional materials for oxyfuel and pre combustion technologies
R&D on oxygen carrier for chemical looping technologies, sorbents for CO2/H2S separation, oxygen separating membrane materials from syngas and sorption enhanced water gas shift, and hydrogen separating membranes
Scale up and integration of available oxygen carriers in CLC-plant at MW scale
Pilot at MW level for sorption enhanced water gas shift or sorption enhanced reforming or gasification
Integration of O2 and H2 separating membrane in small scale oxyfuel and pre combustion power plant
Service life such that the make up flow cost lower than 2-3 euros/t CO2 captured Separating MIEC-membranes (flux higher than 20Nml/min.cm2 at > 750°C)
High temperature strength materials
R&D on F/M steels used at up to 650°C, higher Cr materials used at up to 670°C, advanced iron-nickel alloys, nickel base alloys, notably used at up to 800°C and ODS – including manufacturing processes
Manufacturing of mock up of large Components of Ni based alloys and welded joints at critical dimension
Manufacturing of advanced Ni based alloys for steam turbine and boiler
Manufacturing of ODS and optimization of joining techniques
Creep strength of 100MPa after 100.000 hours at the operating temperature For ODS: cost reduction by a factor of two
Environmental effect on advanced materials
R&D on Ni base alloys (corrosion, fatigue resistant, etc.), protective coatings for steam and gas turbine and development of models for life time prediction assessment of critical components
Validation of integrated models focussed on the material-component performance evolution during long-term service
Application and validation of pre-commercial coating systems under new operating conditions
Enhanced performance and integrity
Novels materials
R&D on refractory metal based alloys used at up to 1800°C, on oxide fibre/oxide ceramic and fibre reinforced materials and improved inter metallique materials for gas turbine and gradient materials for steam turbine
Required mechanical properties
Materials for storage technologies
R&D on standard completions materials, new well materials including composites, materials for leakage repair and materials for favoring dissolution of CO2 and catalysts for in situ mineralization
set of pilots to validate the materials for storage technologies in real-life conditions and to enable further upscaling
Adequate long-time behaviour when exposed to CO2 Better long-term resistance to CO2, impurities and saline brine attacks Required mechanical and chemical properties for better repair of leakages Required mechanical and chemical properties for favouring dissolution of CO2 and catalysts for in situ mineralisation
Supporting research infrastructure
2 facilities: EU (network) test facilities for materials standardization, Research infrastructure to test structural materials for USC boiler, pipe work and steam/gas turbine

Materials Roadmap for hydrogen & Fuel Cells[1]

1. MATERIALS R&D AND RELATED PRODUCT DEVELOPMENT

1.1. Focus Area 1: ionic and electronic conductors for H2&FC technologies

Ionic conductors (electrolytes)

- Develop high proton-conductivity polymers operating at low water contents (< 20% relative humidity) over an extended temperature range up to 100-150°C; develop thin membrane (thickness <30 micron), mechanically and chemically robust;

- With reduced cost compared to present state-of-the-art;

- Develop hydroxyl-ion conducting polymers of adequate chemical and thermal stability;

- Develop polymer-based electrolyte with low gas permeability for water electrolysis operation at elevated pressure (>100 bar);

- Develop proton-conducting electrolytes for operation at 250-600°;

- Design stable oxide-ion conducting electrolytes which can sustain thermal cycling and load cycles; development of oxide-ion conducting materials operating at lower temperature (600-700°C);

- All these material developments need to consider their processability and address Health, Safety and the Environment (HSE) concerns in connection with their use (recycling), as well as their long-term ageing performances under different environmental conditions.

Electronic conductors (catalyst carriers, bipolar plates, Gas Diffusion Layers)

- Develop more efficient and cheaper bipolar plates, cell spacers, current collectors for the different fuel cell and water electrolysis technologies;

- Improve corrosion and mechanical stability of gas distribution layers;

- Develop stable and conductive catalyst-carriers with large surface areas.

[1] The effective and sustainable use of resources is critical for the further development of energy technologies. Aspects related to recycling, at manufacturing as well as at end-of-life, and design for recycling/cradle-to-cradle approach are an integral part of the proposed developments.

KPIs – ionic and electronic conductors for H_2&FC technologies

	s.o.a. 2010	2015	2020	Ultimate
Polymer electrolytes				
Peak stack temperature (°C)	90	105	120	150
H^+ conductivity (S/cm) at peak T, 20%RH	0.1	0.1	0.1	0.1
Hydrogen crossover (mA/cm^2, 1 bar)	> 2	0.5 – 1.0	< 0.5	< 0.1
Operating pressure for electrolysis (bar)	50	130	350	700
Durability under i and T cycling (hours)	5,000	10,000	15,000	50,000
Solid-oxide electrolytes (O2-)				
Operating temperature (°C)	800-950	700 - 800	600 - 700	600 – 700
Durability, stationary conditions (hours)	15,000	30,000	50,000	75,000
Durability (cycle number)	few 10s	few 100s	1,000	3,000
Bipolar plates, GDLs				
H_2 permeation flux ($Ncm^3/s/cm^2$)	1 - $2x10^{-6}$	10^{-7} - 10^{-6}	< $1x10^{-7}$	< $1x10^{-7}$
Durability under i and T cycling (hours)	Align with electrolyte performances for each technology			
Cost	Reduce cost of GDL by more than 50%			

1.2. Focus Area 2: catalysts for H2&FC technologies

Catalysts for Low Temperature application

- Develop supported platinum-group-metal catalysts with reduced mass loadings for application in acidic media (fuel cells and water electrolysis);
- Overcome carbon corrosion and Pt dissolution in PEM fuel cells;
- Develop enhanced catalysts for application in alkaline media.

Catalysts for High Temperature application

- Improve catalysts durability and tolerance to fuel and steam impurities.

Catalysts for steam methane reforming

- Develop new catalysts with improved efficiency and durability or improve existing ones.

KPIs - catalysts for H_2&FC technologies

	s.o.a. 2010	2015	2020	ultimate
PEM FC & WE				
PGM total content (mg/cm^2)	0.4	< 0.2	< 0.1	< 0.05
Durability under i cycling (hours)	5,000	10,000	15,000	50,000
Solid Oxide FC & WE				
Sulphur tolerance (ppm)	< 10	< 100	< 1000	few %
Durability under i and T cycling (hours)	15,000	40,000	50,000	75,000

1.3. Focus Area 3: other functional materials for H2&FC technologies

Hydrogen purification materials

- Develop gas-adsorption materials with improved sorption kinetics and selectivity;
- Develop new materials for H_2 purification by permeation: proton-conducting dense ceramic membranes, palladium alloys materials, organic membranes; develop ultra-thin films and support materials; optimize microstructure.

Hydrogen storage materials

- Metal hydrides & physio-sorption: enhance gravimetric capacities at temperatures as close to ambient as possible; develop novel, energy efficient, compact and cost effective hydrogen storage materials operating at low pressures; investigate and understand weak chemisorption effects (doping); upscale novel nano-structured materials; design new structures with the aid of modeling approaches;
- Chemical hydrides: develop cost efficient off-board regeneration methods; investigate the applicability of liquid organic carriers with emphasis on refuelling and infrastructure aspects (addressing regeneration energy and cost issues);
- Complex hydrides: develop novel materials with improved reversibility, thermodynamics, and kinetics features; destabilization of high temperature hydrides by thermodynamic tailoring and/or nano-structuring; develop appropriate catalysts;
- Develop materials for innovative concepts like solid-pressurised H_2 storage.

Materials for thermochemical cycles

- Improve kinetics of metal/oxide systems for application in thermochemical cycles.

KPIs - other functional materials for H_2&FC technologies

	s.o.a. 2010	2015	2020	ultimate
H_2 purification materials				
Membrane thickness (μm)	> 5	1	< 0.5	0.1
Durability (hours) T cycles, corrosion resistance	1,000	5,000	10,000	10,000
H_2 storage materials				
Gravimetric capacity (wt.%)	< 4	6	9	> 10
Volumetric capacity at system level (g/l)	< 30	30	40	> 70
Cost (€/kg H_2 stored)*	> 5000*	1500	850	< 500

*cost estimate based on prototype status or small scale series production, to be revised in 2015

1.4. Focus Area 4: structural materials for H2&FC technologies

Materials for the storage of pressurised H_2

- Develop new and innovative materials with improved mechanical properties; reduce costs (investigate use of low cost carbon fibers); develop vessel concepts and manufacturing processes including safety aspects.

Materials for the storage of cryogenic H_2

- Develop innovative materials to tackle boil-off and permeation effects; improve long-term reliability and stability of the distribution system to reach performance levels of pressurised tanks.

Materials for the storage of cryo-compressed H_2

- Develop materials to increase storage capacity while reducing cost (factor 10).

Materials for large scale storage of pressurised H_2 (large tanks, geological storage)

- Investigate material corrosion issues due to the specific environment and ageing of buried tanks (with either compressed or liquid H_2);

- Investigate the formation of H_2S by sulfato-reducing bacterial activity or reaction of H_2 with Pyrite (FeS_2) in natural cavities.

Materials for the transport of H_2

- Investigate corrosion and H_2 embrittlement to improve durability (through adjusted material composition and surface coating).

Materials for coal gasification

- Improve corrosion resistance of metallic components in contact with hot syngas that are exposed to sulphur environment, chloride-assisted stress-corrosion cracking or erosion due to particles.

Materials for thermochemical cycles

- Improve corrosion-resistance of materials to thermal cycling.

Sealant materials

- Develop vitro ceramics, glass, mica based materials able to maintain hydrogen tightness and to withstand thermal cycles, with recovery stages.

KPIs – structural materials for H_2&FC technologies

	s.o.a. 2010	2015	2020	ultimate
Pressurised H_2 storage				
Durability under P cycles (cycles)	1,000	1,500	1,500	1,500*
Projected cost (€/kg H_2 stored)	600**	300**	100**	tbd
Cryo-compressed H_2 storage				
Durability under P cycles (cycles)	100	1,000	1,500	1,500*
Projected cost (€/kg H_2 stored)	600**	300**	100**	tbd
Thermochemical cycles				
Durability under T cycles (hours)	few 100s	few 1,000s	5,000	10,000
H_2 sealant materials				
Durability continuous operation (hours),	15,000	30,000	50,000	75,000
Durability (cycle number)	few 10s	few 100s	1,000	3000

* To be revised in 2015.

** Cost estimates based on a production of 500,000 units.

1.5. Focus Area 5: novel materials for H2&FC technologies

Advanced electrolytes (ionic conductors)

- Perform basic research on innovative concepts: ultra-thin membranes and ultra-high conductivity; enhanced membrane chemical, photo-chemical and thermal stability.

Advanced Catalysts

- Develop non-PGM catalysts for low temperature acidic applications; target catalytic activity as close as possible to those of PGM catalysts.

Advanced photo-materials

- Develop advanced materials for photo-electrochemical applications: semi-conductors, inorganic dyes, electrolytes.

Advanced materials for H_2 storage

- Develop innovative hydrogenated materials with enhanced capacity and reversibility;

- Develop high tensile strength (>1000 MPa) materials for light weight pressure vessels.

KPIs - novel materials for H_2&FC technologies

Technology	KPI	ref. material	>2020	ultimate
Adv. Electrolytes	Proton conductivity (S/cm) at ref. T	H^+ conductors	factor 2	max achiev.
Adv. Photomat	Resistance to photo-corrosion (hrs)	Electrochemical	50% ref.	idem ref. mat.
Adv. Catalysts	Efficiency at 1 A/cm^2	PGM catalysts	80% ref.	idem ref. mat.
Adv. H_2 storage	Gravimetric capacity (wt.%)	Hydrides (4 wt. %)	> 10 wt. %	max achiev.
Adv. H2 storage	Volumetric capacity (kg H_2 / m^3)	40	60	max achiev.
Adv. H2 storage	Cycling stability (cycles)	> 700	> 1,500	> 5,000

2. MATERIALS INTEGRATION AND COMPONENT TECHNOLOGIES

2.1. Manufacturing

Pilot 1: PEM membrane electrode assemblies for fuel cell and water electrolysis (implementation at T0+4-6)

Develop automated and continuous roll-to-roll MEA manufacturing processes targeting cost reduction, high quality components (no crack, homogeneity of composition, constant thickness) with competitive performances, and operation at higher temperature, higher current density and higher pressure (electrolysis).

KPIs: for fuel cells: -20°C < T < 120°C; relative humidity < 20%; durability up to 15,000 hours. KPI for electrolysis: 60 < T < 150°C; 1 < P < 350 b; I = several A/cm².

Pilot 2: Solid oxide MEAs for water electrolysis applications (implementation at T0+3)

Develop automated manufacturing processes of novel (operation at reduced operating temperature and constant performance levels; with increased surface area) and robust solid oxide MEAs to greatly reduce manufacturing cycle time by 50%.

KPIs: T (600-700°C); durability (several thousand thermal cycles).

Pilot 3: Photo-electrochemical cells for H_2 production (implementation at T0+5)

Develop and demonstrate the manufacturing of efficient and durable photo-electrochemical water splitting reactors for hydrogen production.

KPIs: current density (toward several tens mA/cm^2); durability (several thousand hours).

Pilot 4: Hydrogen storage tanks for automotive applications (implementation: T0+4)

Develop and demonstrate the manufacturing of low cost hydrogen storage tanks of large volumetric and gravimetric densities and high loading/unloading kinetics.

KPIs: gravimetric capacity >7.5 wt.%; volumetric capacity at system level >40 g/l; refuelling within a few minutes (<4 min); cycling (more than 1500 cycles).

2.2. Technology Testing

Pilot 1: High pressure water electrolyzers for H_2 refueling stations (implementation at T0+3)

Testing of large scale high pressure water electrolyzers based on the research development under heading 1.1. Demonstrate similar efficiency and durability compared to low pressure electrolyzers. Demonstrate operation with intermittent power sources. Implementation in H_2 refueling stations.

KPIs: delivery rate: >100 m^3/hour; operating pressure >100 bars.

Pilot 2: Demonstration of large scale solid oxide water electrolysis and coupling to high temperature heat sources (implementation at T0+5)

Testing of large solid oxide water electrolyzers. Address performance and durability issues. Demonstrate the possibility to use high temperature heat sources from either nuclear or concentrated solar power. Provide an economic assessment. Pilot size: 50-100 kW.

KPIs: efficiency: 80%HV at several A/cm^2; durability: toward 50,000 hours.

Pilot 3: Large scale hydrogen storage (implementation at T0+5)

Testing of large scale hydrogen storage infrastructure for hydrogen refueling stations.

KPIs: capacity >40 g/l; durability; high safety of installation.

3. RESEARCH INFRASTRUCTURE

Facility 1: European facility on fuel cell technologies for automotive applications(implementation at T0+5)

Establish an accredited European facility to test the entire fuel cell stack and H_2 tanks to benchmark the current technology level (cross check performance of commercial/prototype products, including homologation and safety evaluation, in situ characterisation using large scale scientific instruments), to identify future directions for research, and to develop harmonised test protocols based on real condition operations.

Facility 2: Virtual technology centre on large scale hydrogen production by water electrolysis (implementation at T0+5)

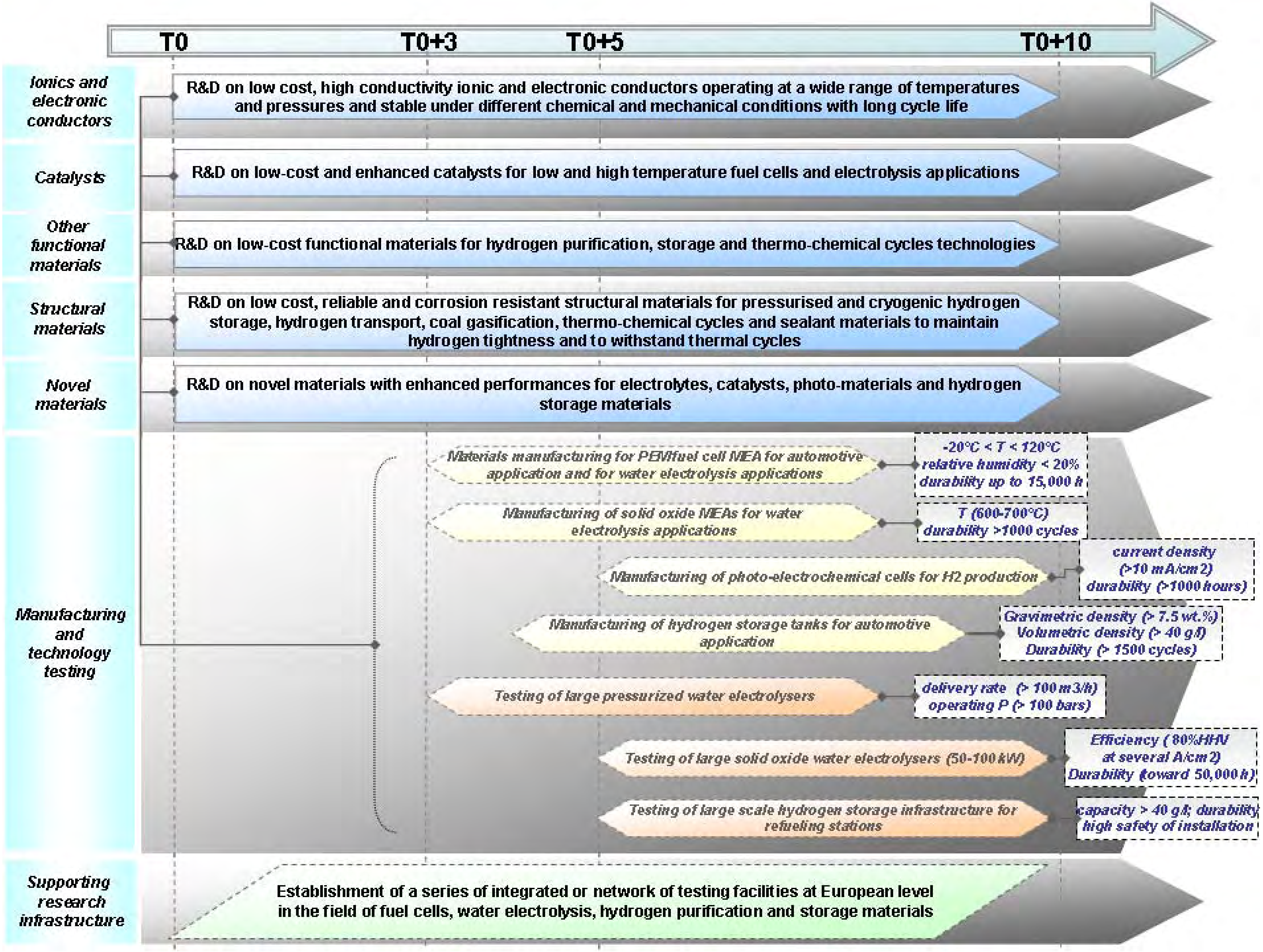
This material research centre should focus on modelling, development and performance testing of advanced water electrolysis processes for energy storage and grid management applications. Synergies should be developed with test facilities proposed by other energy technologies (PV, wind, etc.).

Facility 3: EU virtual facility on hydrogen purification and storage materials for H_2&FC technologies (implementation at T0+5)

Establish a virtual integrated European H_2 storage materials test facility, i.e. coordinate networking actions between existing test facilities for the testing of materials and technologies. Promote instrumentation and in-situ testing taking advantage of large scientific instruments. Develop harmonised test protocols, including for example pollutants influence. Test facility/networking actions should gather academic and industry partners.

Test Facility 4: Structural materials for H_2&FC technologies (implementation at T0+5)

Cross cutting issues with some other energy technologies and safety organisation (Hysafe). Common testing of materials sharing similar structural properties (such as mechanical and corrosion resistance) using similar methodologies.


T0
T0+3
T0+5
T0+10
Ionics and electronic conductors
R&D on low cost, high conductivity ionic and electronic conductors operating at a wide range of temperatures and pressures and stable under different chemical and mechanical conditions with long cycle life
Catalysts
R&D on low-cost and enhanced catalysts for low and high temperature fuel cells and electrolysis applications
Other functional materials
R&D on low-cost functional materials for hydrogen purification, storage and thermo-chemical cycles technologies
Structural materials
R&D on low cost, reliable and corrosion resistant structural materials for pressurised and cryogenic hydrogen storage, hydrogen transport, coal gasification, thermo-chemical cycles and sealant materials to maintain hydrogen tightness and to withstand thermal cycles
Novel materials
R&D on novel materials with enhanced performances for electrolytes, catalysts, photo-materials and hydrogen storage materials
Manufacturing and technology testing
Materials manufacturing for PEM fuel cell MEA for automotive application and for water electrolysis applications
-20°C < T < 120°C relative humidity < 20% durability up to 15,000 h
Manufacturing of solid oxide MEAs for water electrolysis applications
T (600-700°C) durability >1000 cycles
Manufacturing of photo-electrochemical cells for H2 production
current density (>10 mA/cm2) durability (>1000 hours)
Manufacturing of hydrogen storage tanks for automotive application
Gravimetric density (> 7.5 wt.%) Volumetric density (> 40 g/l) Durability (> 1500 cycles)
Testing of large pressurized water electrolysers
delivery rate (> 100 m3/h) operating P (> 100 bars)
Testing of large solid oxide water electrolysers (50-100 kW)
Efficiency (80%HHV at several A/cm2) Durability (toward 50,000 h)
Testing of large scale hydrogen storage infrastructure for refueling stations
capacity > 40 g/l; durability high safety of installation
Supporting research infrastructure
Establishment of a series of integrated or network of testing facilities at European level in the field of fuel cells, water electrolysis, hydrogen purification and storage materials

Materials Roadmap for Nuclear fission[1]

1. MATERIALS R&D AND RELATED PRODUCT DEVELOPMENT

1.1. Focus Area 1: Commercially available materials R&D for innovative reactor concepts[2].

- Component and system specific characterisation and validation of already available materials;
- Development of testing procedures to account for environmental effects and high temperature on mechanical properties;
- Development of joining and welding procedures (including mixed welding, welding of thick components etc.);
- Creation of materials database including coolant (primary and secondary), thermal, mechanical and irradiation effects (single and combined effect);
- Integrity assessment of components lasting for long-time operation.

KPIs:

- Standardisation of test procedures and post-test investigation strategies;
- Quantification of performance in environment (temperature, irradiation and coolant compatibility);
- Down selection of reference materials and availability of relevant design database.

1.2. Focus Area 2: ODS for cladding application (LMFR)

The general requirement of claddings is to contain the fuel and the fission gas while keeping dimensional stability for high fuel burn-up under all predictable conditions.

- Selection of alloy composition appropriate for specific applications via screening;
- Manufacturing routes assessment and optimisation via screening;
- Up-scaling studiesof heats from laboratory to industrial quality production (cladding tubes) at affordable costs;
- Procedures for welding/joining with high integrity;

[1] The effective and sustainable use of resources is critical for the further development of energy technologies. Aspects related to recycling, at manufacturing as well as at end-of-life, and design for recycling/cradle-to-cradle approach are an integral part of the proposed developments.

[2] Even if several classes of materials have been identified for the various components of the four ESNII systems and high temperature reactors, it turned out that three classes of materials, namely the austenitic steels AISI 316L and Ti stabilised 15Cr-15Ni, the modified ferritic/martensitic 9Cr steel and Ni alloys have been considered for use in more than one ESNII system.

- Development of procedures and characterisation of reference ODS (e.g. softening, low temperature embrittlement, sudden fracture behaviour, tensile properties, creep and fatigue resistance, anisotropy (if it occurs), stability of ODS particles under long term ageing and under irradiation, corrosion resistance at high temperatures (in liquid metals), fuel cladding interaction, reprocessing, etc.).

KPIs:

- ODS with optimised composition capable to operate at:
    - temperatures of 400-650°C;
    - irradiation doses higher than 150 dpa;
    - creep life exceeding 80 000 hours for 100 MPa;
    - Coolant compatibility and fuel/cladding mechanical and chemical interaction;
    - Suitability for reprocessing.

1.3. Focus Area 3: SiC_fSiC for cladding application (GFR and LFR)

- Structural composite manufacturing development and strategies to up-scale from laboratory to industrial scale at affordable costs;
- Establishing new standard test methods;
- Design of needed testing infrastructures;
- Characterisation program oriented to the development of data for design and also for modelling activities and investigation of environmental effects.(data should confirm: leak-tightness, dimensional stability, thermal conductivity, strength and ductility, chemical compatibility, compatibility with fuel and reprocessing strategies).

KPIs:

- SiC_fSiC cladding (optimised) capable to operate at:
    - nominal operational temperature of 900-1100 °C;
    - irradiation dose > 60-80 dpa (in SiC);
    - mechanical stresses from coolant and internal stresses due to fuel swelling, fission gas release and thermal through-thickness temperature gradients; and be:
    - compatible with coolant (He, Pb) and with carbide fuel;
    - suitable for reprocessing.

1.4. Focus Area 4: Coatings (corrosion and erosion/wear protection in LMFR)

The requirements on the coatings for fuel cladding are quite stringent since the cladding is a safety barrier. Therefore high quality production process and product quality assurance are relevant items.

- Screening tests for selection of composition and production procedures for twofold purposes: 1. stellite replacement (wear resistance) and 2. corrosion protection where FeCrAlY based coatings are considered as reference;
- Standardisation of quality assurance protocols (adapted for the different applications);
- Definition of characterisation procedures for the specific application (cladding, stellite replacement);
- Up-scale of coating procedure from laboratory to component scale strategies at affordable cost;
- Qualification and validation tests in realistic conditions for the specific application.

KPIs:

- High quality coating (adherence, coherence, stability) and qualified coating procedure;
- Coating capable to operate undercladding conditions (see ODS or SiC_fSiC conditions above);
- Erosion and wear resistant (relevant for stellite replacement);
- The coating should possibly show self-healing properties.

1.5. Focus Area 5: Novel materials (Ti-based alloys)

- Assessment of Ti-alloys as e.g. Ti_3SiC_2, Titanium Aluminides for what concerns properties and manufacturing processes for nuclear applications;
- Preliminary characterisation and composition adjustment;
- Assessment based on selected criteria of these materials and definition of a long-term R&D program for further development.

KPIs:

- Applicability of Ti-Alloys as pump impeller in LFR;
- Mechanical Performance of Ti-Alloys comparable of the of Ferritic/Martensitic and ODS steels;
- Availability of data on these materials to perform future judgment on component development.

2. MATERIALS INTEGRATION AND COMPONENT TECHNOLOGIES

2.1. Manufacturing

Pilot 1: Manufacturing of 9Cr steel heat exchanger

The selection of 9Cr steel as heat exchanger material for the innovative system is driven by the better thermal conductivity of this material with respect to austenitic steel and the lower thermal expansion. Indeed, for the liquid metal systems this class of steel is indicated as a one option to be considered for the building of the heat exchanger (with primary and secondary coolant). Materials data generated in the Focus Area 1 will allow the full characterisation of this material and will drive the design of the heat exchanger where also welding and joining are essential items to be tested.

KPIs:
Manufacturing of heat exchanger under design relevant conditions and nuclear standards, T0+5;
Implementation of industrialised welding procedure and non-destructive test methods, T0+5;
Demonstration cost reduction, T0+10.

Pilot 2: Manufacturing of ODS for fuel cladding

Manufacturing of cladding tubes with representative dimension (with selected composition and production route as from focus area 2). Appropriate joining technologies should be available to close the tubes with their end-caps. Moreover, reactor core spacers (wire or grids) should be applicable to the cladding for the different reactor concepts. The entire pin as well as pin bundles should be made available for full scale testing.

KPIs:
Manufacturing of pin and bundle under design relevant conditions and nuclear standards, T0+7;
Implementation of industrialised welding procedure and non-destructive test methods, T0+7;
Demonstration of industrialisation of method at affordable cost, T0+15.

Pilot 3: SiC_fSiC for fuel cladding

Cladding tubes for the gas cooled system (and possibly also for Pb cooled system) with appropriate and qualified production route as established in focus area 3 should be made available. The tubes should have representative dimensions and end-caps should be welded/joined with qualified technologies. Single pin and pin bundles should be made available for a full scale testing of this concept.

KPIs:
Manufacturing of pin and bundle under design relevant conditions and nuclear standards, T0+8;
Implementation of industrialised joining procedure and non-destructive test methods, T0+8;
Demonstration of industrialisation of method at affordable cost, T0+15.

Pilot 4: Coatings

Coating pilot plant(s) to treat relevant components for LMFR (stellite replacement, corrosion protection.

KPIs: Pilot Plant(s) availability at affordable cost for coating application on large scale components, T0+7.

2.2. Technology Testing

Pilot 1: Testing of heat exchanger out of pile

Heat exchanger testing should be performed in appropriate facilities to demonstrate the feasibility of the concepts with the selected material and manufacturing / welding procedures. The tests should be performed with the relevant heat transfer media and in relevant thermal and mechanical conditions. The test parameters should account for normal operational conditions as well as identified transients.

KPIs: Endurance and performance of HEX within a relevant parameter range being this between 300°C and 600°C in relevant environment, T0+7; Confirmation of component performance under transient conditions Confirmation of heat transfer capability, T0+8.

Pilot 2: Testing of ODS cladding tubes out of pile and possibly in pile

The tests should be aimed at demonstrating the concept, which should include also properties related to the entire fuel cycle. The test matrix of the single pin and the fuel bundle should include normal operational conditions and predicted transients. The ODS cladding should be also tested in the relevant environments, being this Na or Pb.

KPIs: Performance of pin and bundle within a relevant parameter range being this between 300°C and 600°C in relevant environment, T0+8; Pin and bundle performance under transient conditions (parameters are predicted by design), T0+8; Confirmation of chemical compatibilities and reprocessing possibility. T0+12 In-pile assessment, T0+15.

Pilot 3: Testing of SiC_fSiC cladding tubes out of pile and possibly in pile

The tests should demonstrate the concept. The testing approach should include single pin and pin bundle tests. The testing parameters should account for normal operational conditions and identified transients. The cladding SiC_fSiC should be tested in the relevant environments being this He and Pb out of pile and when ESNII system available also in-pile.

KPIs:
Performance of pin and bundle within a relevant parameter range being this from ~ 300°C up to 1000°C in relevant environment, T0+8;
Pin and bundle performance under transient conditions (parameter are predicted by design), T0+10;
Confirmation of chemical compatibilities and reprocessing possibility. T0+12
In-pile assessment, T0+17.

Pilot 4: Confirmation of wear resistance and corrosion resistance of large scale coated components

The tests should demonstrate the concept and should be performed on coated large scale components. The testing parameters should account for normal operational conditions and identified transients.

KPIs:
Demonstration of wear resistance of large scale components in Na environment at relevant conditions, T0+5;
Demonstration of corrosion resistance of pin and bundle in Pb and Pb-Bi in a temperature range of 300 – 550°C, T0+7;
For both concept in-pile assessment, T0+12.

3. RESEARCH INFRASTRUCTURE

A mapping of needed infrastructures to develop the ESNII reactors has been performed in the project ADRIANA. To this end some infrastructures exists but need often refurbishment. Some additional infrastructures need to be built.

Facility 1: Irradiation facilities

Irradiation facilities are needed for the development of nuclear materials. The ESNII facilities would be very much appropriate to serve also for this objective.

Facility 2: Hot laboratories

A number of hot-laboratories equipped with advanced measurement and testing techniques are mandatory for the development of materials.

Facility 3: High Temperature testing systems

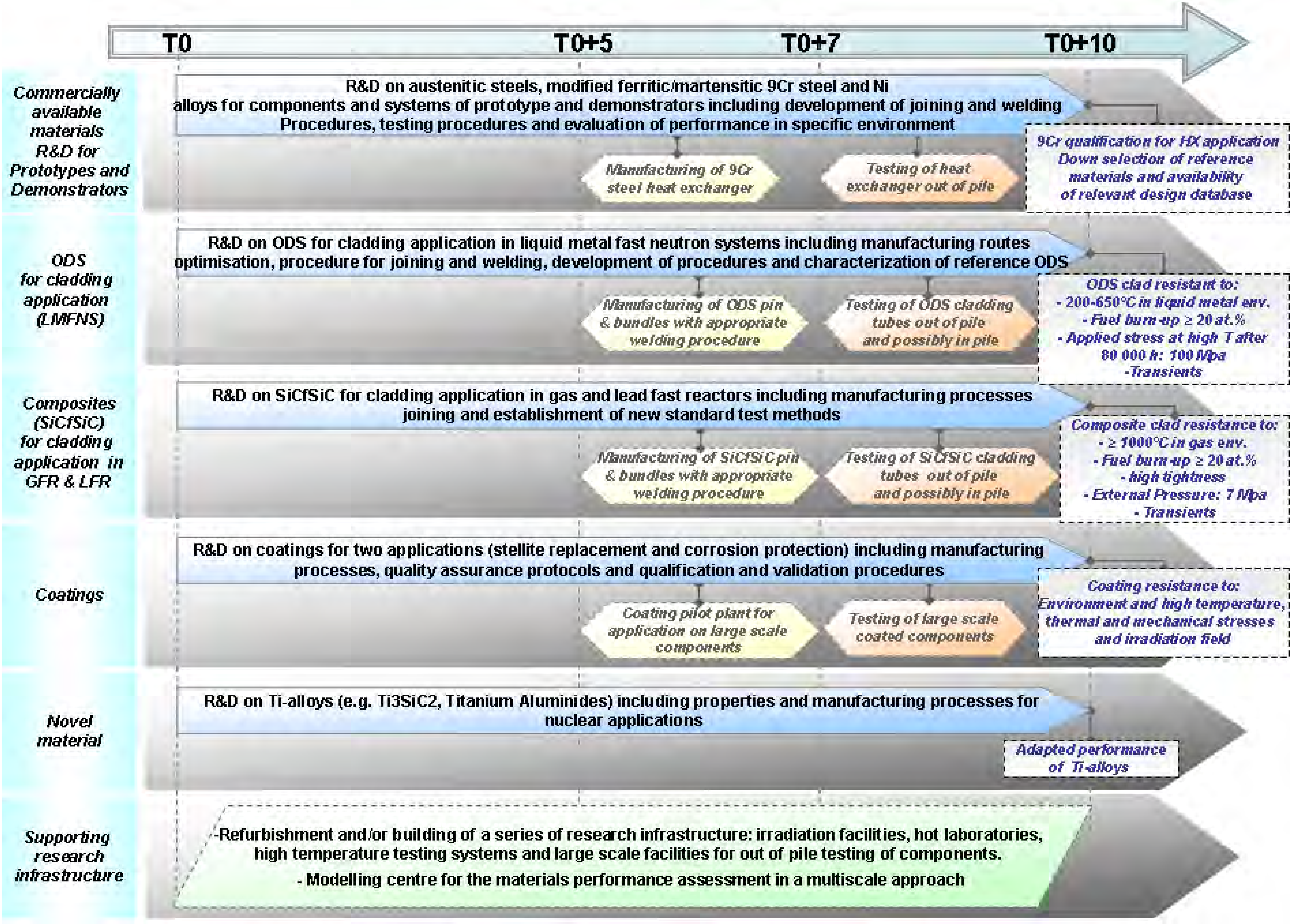
High temperature testing systems to assess mechanical properties (tensile, creep, fatigue, etc.) in relevant environments are mandatory for the screening and characterisation of materials.

Facility 4: Large scale facilities for out of pile testing of components

Out-of-pile testing of developed components can be performed in large scale facilities that operate in representative conditions.

Facility 5: Modelling centre

A modelling centre would be of high relevance for the materials performance assessment in a multiscale approach. The objective would be through fundamental understanding to improve predictive capabilities as well as long-term operation assessment. Moreover, also materials development can be supported by physical model development.



T0
T0+5
T0+7
T0+10
Commercially available materials R&D for Prototypes and Demonstrators
R&D on austenitic steels, modified ferritic/martensitic 9Cr steel and Ni alloys for components and systems of prototype and demonstrators including development of joining and welding Procedures, testing procedures and evaluation of performance in specific environment
Manufacturing of 9Cr steel heat exchanger
Testing of heat exchanger out of pile
9Cr qualification for HX application Down selection of reference materials and availability of relevant design database
ODS for cladding application (LMFNS)
R&D on ODS for cladding application in liquid metal fast neutron systems including manufacturing routes optimisation, procedure for joining and welding, development of procedures and characterization of reference ODS
Manufacturing of ODS pin & bundles with appropriate welding procedure
Testing of ODS cladding tubes out of pile and possibly in pile
ODS clad resistant to:
- 200-650°C in liquid metal env.
- Fuel burn-up ≥ 20 at.%
- Applied stress at high T after 80 000 h: 100 Mpa
-Transients
Composites (SiCfSiC) for cladding application in GFR & LFR
R&D on SiCfSiC for cladding application in gas and lead fast reactors including manufacturing processes joining and establishment of new standard test methods
Manufacturing of SiCfSiC pin & bundles with appropriate welding procedure
Testing of SiCfSiC cladding tubes out of pile and possibly in pile
Composite clad resistance to:
- ≥ 1000°C in gas env.
- Fuel burn-up ≥ 20 at.%
- high tightness
- External Pressure: 7 Mpa
- Transients
Coatings
R&D on coatings for two applications (stellite replacement and corrosion protection) including manufacturing processes, quality assurance protocols and qualification and validation procedures
Coating pilot plant for application on large scale components
Testing of large scale coated components
Coating resistance to: Environment and high temperature, thermal and mechanical stresses and irradiation field
Novel material
R&D on Ti-alloys (e.g. Ti3SiC2, Titanium Aluminides) including properties and manufacturing processes for nuclear applications
Adapted performance of Ti-alloys
Supporting research infrastructure
-Refurbishment and/or building of a series of research infrastructure: irradiation facilities, hot laboratories, high temperature testing systems and large scale facilities for out of pile testing of components.
- Modelling centre for the materials performance assessment in a multiscale approach

Materials Roadmap for energy efficient materials for buildings[1]

1. MATERIALS R&D AND RELATED PRODUCT DEVELOPMENT

1.1. Focus Area 1: Structural elements

1.1.1. Develop advanced cement/concrete production processes to reduce embodied Energy/Carbon

- Use of alternative blends and their influence on concrete specifications and usability. Radically increase the recycled aggregate and/or waste fraction while maintaining/increasing technical properties;

- Technologies to increase the use of waste streams from other sectors to fuel cement kilns (Pozzolanic Fly Ash - PFA, Ground Granulated Blast Furnace Slab - GGBFS);

- Further development of low or negative carbon cements, starting from current developments, e.g. based on non-carbonate raw material as magnesium silicate, belite cements and geopolymers. CO_2 neutral concrete (e.g. incorporating yeast);

- Research & Development on materials for fluidised bed process;

- Research & Development on materials for CO_2 capturing and storing (CCS), including oxyfueling and gas cleaning, in synergy with the materials roadmap for Novel Materials for the Fossil Energies Sector, including Carbon Capturing and Storage.

1.1.2. Develop advanced and high-performance concrete and composite products to reduce building Operational Energy/Carbon

- Improved use of nanotechnologies to increase insulation and thermal inertia properties of concrete or composite structures, including thermal concrete (e.g. distributed Styrofoam, Foam concrete), thermally insulated products, thermal inertia (capacitance) of concrete;

- Light weight concrete with expanded clays as aggregates, geopolymer precast concrete, autoclaved aerated concrete, cellular concrete, concrete with stabilised Phase Change Materials (PCM);

- Development of new products based on self-healing concrete, aerogels plus concrete, nanoporous concrete.

1.1.3. Develop advanced and high-performance steel-based products to reduce building Embodied Energy/Carbon

- Further development of light weight steel products based on high strength steels and perforated structural beams;

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[1] The effective and sustainable use of resources is critical for the further development of energy technologies. Aspects related to recycling, at manufacturing as well as at end-of-life, and design for recycling/cradle-to-cradle approach are an integral part of the proposed developments.

- Improvement of existing technologies and development of markets for the reuse of structural steel elements and for reducing the embodied carbon of structural elements.

1.1.4. Develop new advanced methods for evaluation of material durability

- Generate fundamental understanding of mechanisms that influence the durability of the different properties of construction materials, products and components, including improved Life Cycle Analysis (LCA) tools and reliable, fast and robust ageing models;

- Definition and application of common metrics and the development of processes to generate improved durability, including reliable test methods and inspection procedures.

KPIs:

Research areas	Target
1.1.1	Long-term target zero-emission cement; thermal energy consumption per ton of clinker from 3.8 GJ in average to 3.5 GJ; share of alternative fuel and biomass in cement production; Clinker to cement ratio to 0.73 by 2020; waste content in cement or concrete
1.1.2	Insulation and thermal properties increased by 20-25 % with respect to current best-performer concrete products (e.g. thermal conductivity values < 0.1 W $m^{-1}K^{-1}$ for lightweight concrete); cost-effective materials: performance improvement is achieved with zero cost increase
1.1.3	Embodied carbon reduced in steel structural elements by 20-30%; performance improvement is achieved with zero cost increase
1.1.4	Knowledge is available to estimate durability for main construction materials and for main traditional and new properties; Construction materials can be 100 % inspected and maintained in-situ with no impact on the building functionality

1.2. Focus Area 2: Finishes and envelope

1.2.1. Develop advanced production processes for ceramic products (tiles, bricks) to reduce Embodied Energy/Carbon

- Improvement of energy efficiency (radically-new dryers, kilns, burners for kilns, dry-milling processes, not-firing production, alternative/waste/cleaner fuels) and performances (higher flexibility, new control systems) of production cycles for tiles and bricks. Increased recycled fraction in bricks, use of paper fibres for lightweight bricks;

- Investigate innovative material formulations allowing reduced embodied energy by lower temperature cycles and by recycling. Bricks without mortar (click brick) easier to reclaim in case of demolition of a building. Bricks incorporating biotic renewables (e.g. hempcrete). Unfired bricks;

- Preliminary lab-scale prototypes of production machineries embedding results from basic research.

1.2.2. Develop advanced and high-performance ceramic products (tiles, bricks) to reduce building Operational Energy/Carbon

- Development of composite ceramic tiles with layers of insulating materials and higher thermal inertia. Ultra thin or elastic ceramic slabs for low-energy transport and/or prefabrication. Surface properties (e.g. infrared reflectivity for outdoor, humidity-buffering surfaces for indoor control, surface active materials, self-cleaning or with microbiological action, etc.) must be further developed to become cost-effective for industrial implementation. Low-cost bricks with advanced heat-storage or insulating materials;

- New ceramic materials for advanced facades with renewable energy storage integrated (e.g. ceramic PV tiles, etc.);

- Materials with embedded sensor for life-long advanced monitoring and control;

- New adhesives for cost-effective installations;

- Study of cost-effective industrial upscale of ceramic materials with new functionalities.

1.2.3. Develop advanced and high-performance materials and products for internal finishes (plasterboards, PCMs, coatings)

- Development of basic materials and materials combination for internal finishes, mainly focusing on plasterboards, Phase Change Materials (PCMs), coatings and on products based on their possible combination. Nanotechnologies can help to improve performances in terms of both surface and bulk functionalities. Internal liner products and coatings that promote internal day lighting entrance within buildings;

- Reduction of embodied energy in production and during the life cycle. Research and innovation towards prolonged product service life and minimum maintenance needs offers significant opportunities. Use of nanotechnologies for new materials and surface properties to improve durability and reduce maintenance needs.

1.2.4. Develop advanced and hig-performance steel-based products to reduce building Operational Energy/Carbon

- Development of advanced coatings and technologies for new envelope products such as advanced steel products with integrated solar technologies (e.g. transparent solar collectors and roof integrated PV); further development of high/low solar reflectivity/absorbance finishes and coatings of steel envelope products; steel joints for highly glazed façades;

- Further development of better thermally isolated steel products;

- Improved use of thermally broken details in steel structures (improved thermal breaks at penetrations and further development of thermal studs.) and developement of integrated heating/cooling systems and PCMs within lightweight, structural steel;

- Development of new cladding products., e.g. vacuum insulated panels, panels insulated with other (waste) streams, e.g. cellulose.

KPIs:

Research areas	Target
1.2.1	20 % specific reduction in embodied energy and CO_2 emission; production time and costs reduced by 50 % through innovative, efficient and predictable manufacturing processes; industrialised production which at the same time allows for individual design and flexibility
1.2.2	Insulation (thermal, acoustic, electro-magnetic) and storage capabilities increased by 20-30 % with respect to current best-performer ceramic products (e.g. lightweight ceramic materials with bulk density reduced to < 300-400 kg m^{-3} and thermal conductivity values < 0.1-0.2 W $m^{-1}K^{-1}$). Energy consumption for transport reduced by 30 %. Ceramic-based products are 100 % optimised for industrialised prefabrication and high usability. Long term: ceramic products capable to adapt 100 % indoor environmental conditions depending on changing use requirements
1.2.3	Insulation and storage capabilities increased by at least 30 % with respect to current best-performer products for internal finishes (e.g. thermal conductivity values < 0.1 W $m^{-1}K^{-1}$ for plasterboards with zero cost increase). 25 % specific reduction in embodied energy assessed of the whole life cycle. High usability for energy efficient building retrofitting with cost reduction of about 20-30% with respect to state of the art
1.2.4	Insulation and thermal properties increased by 30-40 % with respect to current best-performer steel products; cost-effective materials: performance improvement is achieved with zero cost increase; improvement of heat island effect

1.3. Focus Area 3: Glased component – light directing elements

1.3.1. Develop advanced production processes for glass production to reduce embodied Energy/Carbon

- Use of alternative fuels (e.g. non-food biomass in the form of agricultural waste) instead of fossil fuels, increase of recycled raw materials, use of new burner technologies (e.g. submerged);

- Realisation of different end-products with fewer new efficient and flexible technology

1.3.2. Develop advanced and high-performance windows (glass, frames) to reduce building Operational Energy/Carbon

- Low-emissivity, reflection surfaces, vacuum glazing optimization of solar energy and daylight transmittance, insulated frames, passive frames, light directing elements, sun pipes, prismatic rooflights or holographic-optical elements. Intelligent windows (integration to indoor and outdoor temperatures monitoring). Glass with controlled light transfer, switchable properties of coatings (extension of life-cycle) using nanotechnologies, ETFE-film very light translucent building components, energy-harvesting glasses; aerogel glazing;

- Applied research: cost-efficient renovation processes and products based on the advanced glass products developed in basic research;

- Development of innovative steel products/joints for highly glazed and double skin façades.

KPIs:

Research areas	Target
1.3.1	Decrease in total manufacturing energy demand > 25%; up to 100% reduction in CO_2 emissions; >50% reduction in NO_x emissions; increase in demand for renewable, local energy sources by approximately 10 GWh/year; significant increase of recycling content and alternative fuel use
1.3.2	Overall U-value improved depending on the climatic region close to a wall (or down to 0.1-0.2 W/m^2K) with zero cost increase. 30 % better with the same light transfer is probably possible. Windows weight reduction in the order of 50 %

1.4. Focus Area 4: Insulation

1.4.1. Develop advanced production processes for traditional (fossil fuel and mineral based) insulation materials production to reduce embodied Energy/Carbon

- LCA-based measures to reduce environmental impact in production of fossil fuel or mineral based insulation materials: increase recycling content (e.g. paper fibres), manufacturing efficiency and renewables in production. Use of CO_2 as a raw material substituting petroleum in e.g. polyurethane insulation;

- Substitution towards/incorporation of renewable and/or biodegradable biobased materials. Bio-based PUR. Bio-based binders e.g. Ecose glasswool with incorporation of starch-based resins;

- Lab-scale prototypes of production processes embedding results from basic research.

1.4.2. Develop bio-based insulation materials (biotic renewables, bio-based polymers and plastics) to reduce Embodied Energy/Carbon

- Biotic renewables (sheep's wool, woodfibre insulation, hemp insulation, etc.). Nanotechnology-based biofibres, regenerated fibers (e.g. from waste paper). Development of sustainable growth solutions in different fields (e.g. timber based);

- Development of bio-based polymers and plastics leading on the long-term to replace even energy-intensive construction materials like steel and concrete.. Chemistry and manufacture of nanotechnology-based biopolymers and fibres from various sources; bio-based binders e.g. soy based biopolymer foam insulation; natural fibre insulation (with wood residue, hemp and flax fibre) with thermal bonding technology using bio-based PLA. Replace even energy-intensive construction materials like steel and concrete on the long term;

- Evaluation of potential gains in terms of embodied energy compared to conventional materials by LCA of bio-based materials;

- Lab-scale prototypes of production processes embedding results from basic research.

1.4.3. Develop advanced and high-performance nanotechnology-based insulation materials and coatings (including LCA studies specifically related to nanotechnologies) to reduce building Operational Energy/Carbon

- Basic research on nanotechnological treatment and optimization for traditional fossil fuel and mineral based insulation materials. Nano-porous insulation double efficient in terms of thermal resistance. Nano-porosity chemistry. Modelling short term and long-term mechanics and physics of new materials. Development of nanofoams (aerogels, for EPS silica or carbonmatrix);

- Nanotechnologies for advanced aerogel, hybrid aerogels, new nano-materials and nano-cellular foams for Vacuum Insulation Panel (VIP) cores, etc;

- Nanotechnology coatings with variable surface optical properties (low emissive and/or high IR reflective nanocoating for building envelope components, ITO, ATO nanoparticles);

- Nano-porous insulation occupational health; LCA studies specifically related to nanotechnologies in insulation materials.

1.4.4. Develop new materials combining structural properties and/or thermal resistance/inertia and/or lightweight

- Foamglass, nano-foams, foam insulation with addition of storage capacity: basic research for material optimization and applied research to investigate material integration in new constructive solutions (e.g. breaking cold bridges, combination between reinforcement and insulating material, constructive strength for heavy and pulling loads). Improvement of thermal inertia in lightweight materials with the use of additives. Form-stables PCM with thermal conductivity improvement. Production of form-stable PCM additives. Incorporation in a huge range of new and ordinary construction materials (pilot scale of the additives and plant scale of the incorporation process);

- Increase recycling content, manufacturing efficiency and renewables in production of foamglass.

1.4.5. Develop new insulation products for easy and cost-effective installation and refurbishment (this receive inputs from 1.4.2, 1.4.3 and 1.4.4)

New products based on basic materials from 1.4.2, 1.4.3 and 1.4.4 have to be developed specifically for cost-effective installation, low intrusive renovation works and low labour-intensive finishing or mounting processes. Materials and design for new generation VIPs. Applied research e.g. on VIP for building practice, long term durability evaluation (e.g. in case of damages), joining technologies. Advanced adhesives, sealants and polymer barrier layers.

KPIs:

Research areas	Target
1.4.1	20 % specific reduction in embodied energy and CO_2 emission; increasing recycled content up to 90 %
1.4.2	For biotic renewable such as hemp, miscanthus, bamboo a carbon-neutral cycle has to be achieved; High efficiency manufacturing (lower costs, higher speed, reduced energy and process resource consumption). Biobased-polymers can technically replace up to 90% of petroleum-based polymers at a longer run. Improvement of thermal conductivity (down to 0.02-0.03 W $m^{-1}K^{-1}$) of bio-based insulation materials by nanotechnologies with a cost reduction in the order of 20 %
1.4.3	Nanotechnology based insulation materials (aerogels, nanocellular foams, etc.) must guarantee a high thermal performance (more then 10 times higher than conventional materials). Improvement of thermal conductivity (< 0.003 W $m^{-1}K^{-1}$). Reduction of commercial production cost (currently niche market because of high costs, e.g. silica aerogel products are about 4000 US$/$m^3$ to be reduced of at least 30-40 % to increase market share)
1.4.4	Advanced materials allow effective solutions for breaking cold bridges. Thermal properties (mainly resistance and inertia) of structural/lightweight materials increased of 30 % with respect to current best performers. 20 % specific reduction of embodied energy in production
1.4.5	New insulation products and panels are cost-effective and easy applicable for retrofitting in existing buildings. Typical U-values decreased of 20-30 % for a given thickness, with a cost reduction of at least 25-30 %, considering also installation costs

1.5. Focus Area 5: Novel materials – bringing selected materials to super-high performances

1.5.1. Develop radically new manufacturing concepts for large volume Energy/Carbon intensive building materials

Long-term research activities focused on production of Energy/Carbon intensive materials, as cement, ceramic, glass, etc. Parallel, but in connection, to Ref. 1.1.1, 1.2.1, 1.3.1 and 1.4.1-2, radically new manufacturing concepts have to be investigated with potential industrial scale-up after 2030. New paradigms for building material production and actions for their up-take.

1.5.2. Develop super insulation properties of cost-effective materials to minimize building Operational Energy/Carbon

Long-term research activities focused on development of super insulation (thermal, acoustic, electro-magnetic) and storage capabilities of the different envelope materials (mainly exploiting future nanotechnology-based solutions or new materials concepts).

KPIs:

Research areas	Target
1.5.1	Minimization of embodied Energy/Carbon in total building material production by at least 30 % by 2050 with no production cost increase and 100% re-use and recyclability
1.5.2	Maximization of insulation/storage properties by at least 60 % with respect to current best-performer building materials (e.g. thermal conductivity < 0.001 W $m^{-1}K^{-1}$) with 50 % cost reduction (including installation and maintenance cost) by 2050

2. MATERIALS INTEGRATION AND COMPONENT TECHNOLOGIES

2.1. Manufacturing

Pilot 1 (T0 + 3) - Pilot manufacturing plant for cement/concrete production with reduced embodied energy/carbon (ref. 1.1.1)

Industrial implementation of production pilot including all most promising developments from previous R&D steps (ref. 1.1.1, mainly focused on use of alternative blends, increased recycling and waste streams, low carbon or neutral cement production, fluidised bed process, CCS). Pre-competitive research to support international standardization on blended cements and concretes that uses a high recycling content.

KPIs: Indicators established for 1.1.1 at the lab level should be here achieved at the industrial pilot level with no significant cost increase. Wide implementation should allow: direct emissions reduced by 5 % in EU by 2020, even with a growing production trend; CO_2 captured in cement production up to 3-6 % by 2020, with potential means to reach 40-45 % reduction by 2050;

Pilot 2 (T0 + 3) - Pilot manufacturing plant for ceramic materials production with reduced embodied energy/carbon (ref. 1.2.1)

Development of pilot production line with high efficiency and flexibility implementing innovations based on previous basic/applied research results from 1.2.1 (e.g. new burners, new methods and material formulations for low temperature production, advanced dedicated control systems, etc.). New reference test facilities (at least one large production pilot where different solutions can be tested) are needed.

KPIs: Indicators established for 1.2.1 at the lab level should be here achieved at the industrial pilot level with zero cost increase. Improvement of production quality to almost 100 % of 1st choice products with high flexibility and reduced production batches tailor-made to the markets demands.

Pilot 3 (T0 + 3) - Pilot manufacturing plant for glass production with reduced embodied energy/carbon (ref. 1.2.1)

Development of pilot production line implementing innovations based on previous basic/applied research results from 1.3.1 (e.g. new burners, use of alternative fuels, increased recycling content, etc.). For new production processes, at least one real scale pilot is needed to validate achievements.

KPIs: Indicators established for 1.3.1 at the lab level should be here achieved at the industrial pilot level with no significant cost increase.

Pilot 4 (T0 + 5) - Pilot manufacturing plant for traditional insulation materials (fossil fuel and mineral based) production with reduced embodied energy/carbon (ref. 1.4.1, with some inputs from ref. 1.4.3)

Development of pilot production line implementing innovations based on previous basic/applied research results from 1.4.1 (e.g. increased recycling content, etc.). Cost-effective industrial upscale. For new production processes, at least one real scale pilot is needed to validate achievements.

KPIs: Indicators established for 1.4.1 at the lab level should be here achieved at the industrial pilot level with zero cost increase.

Pilot 5 (T0 + 3) - Pilot manufacturing of advanced bio-based insulation materials (ref. 1.4.2)

Development of pilot production lines implementing innovations based on previous basic/applied research results from 1.4.2 (e.g. production for insulation nanotreated biotic renewables, for advanced bio-plastics, etc.). Cost-effective industrial upscale. To be considered: diffusion of bio-based materials is dependent upon establishment of strategically important bio-refinery pilot plants, gasification plants for new process and demonstrators in the EU. For new production processes, at least one real scale pilot is needed to validate achievements.

KPIs: Indicators established for 1.4.2 at the lab level should be here achieved at the industrial pilot level with zero cost increase. Evaluation to be performed by transparent and dedicated LCA methodologies.

2.2. Technology Testing (including performance based Technology Updating, i.e. after performances are evaluated, a feedback for improvement has to be implemented)

Pilot 1 (T0 + 4) Pilot technology testing for durability evaluation methods, mainly applied to energy efficient structural materials (ref. 1.1.4, focus on testing also products from ref. 1.1.2 and 1.1.3)

The methods based on research performed in 1.1.4 must be implemented in pilot testing facilities, in order to verify potentials and provide European references and database on materials and properties, and refined according to achieved results. Also new materials from 1.1.2 and 1.1.3 should be tested. Prenormative research on durability evaluation procedures for new and advanced functionalities.

KPIs: Knowledge, standards and procedures are available for durability evaluation of building materials. Uncertainty in durability evaluation is statistically defined and used.

Pilot 2 (T0 + 4) System pilot technology testing for building operational energy/carbon performances (including durability and usability) of the new materials and products for envelope, finishes, windows and insulation (focus on testing products from ref. 1.2.2, 1.2.3, 1.2.4, 1.3.2, 1.4.2, 1.4.3, 1.4.4 and 1.4.5)

A coordinated network of facilities has to be developed to test new materials and products for envelopes, finishes, windows and insulation in use conditions of reference buildings. One reference test facility should be available for each of major climate EU areas identified by geoclusters. Each facility should allow easy comparative evaluation of different solutions for constructive schemes and life-cycles typical of the area. Feedback to material development should be provided based on achieved performances, as well as to pre-normative research.

KPIs: Indicators established for 1.2.2, 1.2.3, 1.2.4, 1.3.2, 1.4.2, 1.4.3, 1.4.4 and 1.4.5 at the lab level should be here assessed and finally achieved at the industrial pilot level. Cost-effective usability for retrofitting should be assessed in reference demo cases.

3. RESEARCH INFRASTRUCTURE

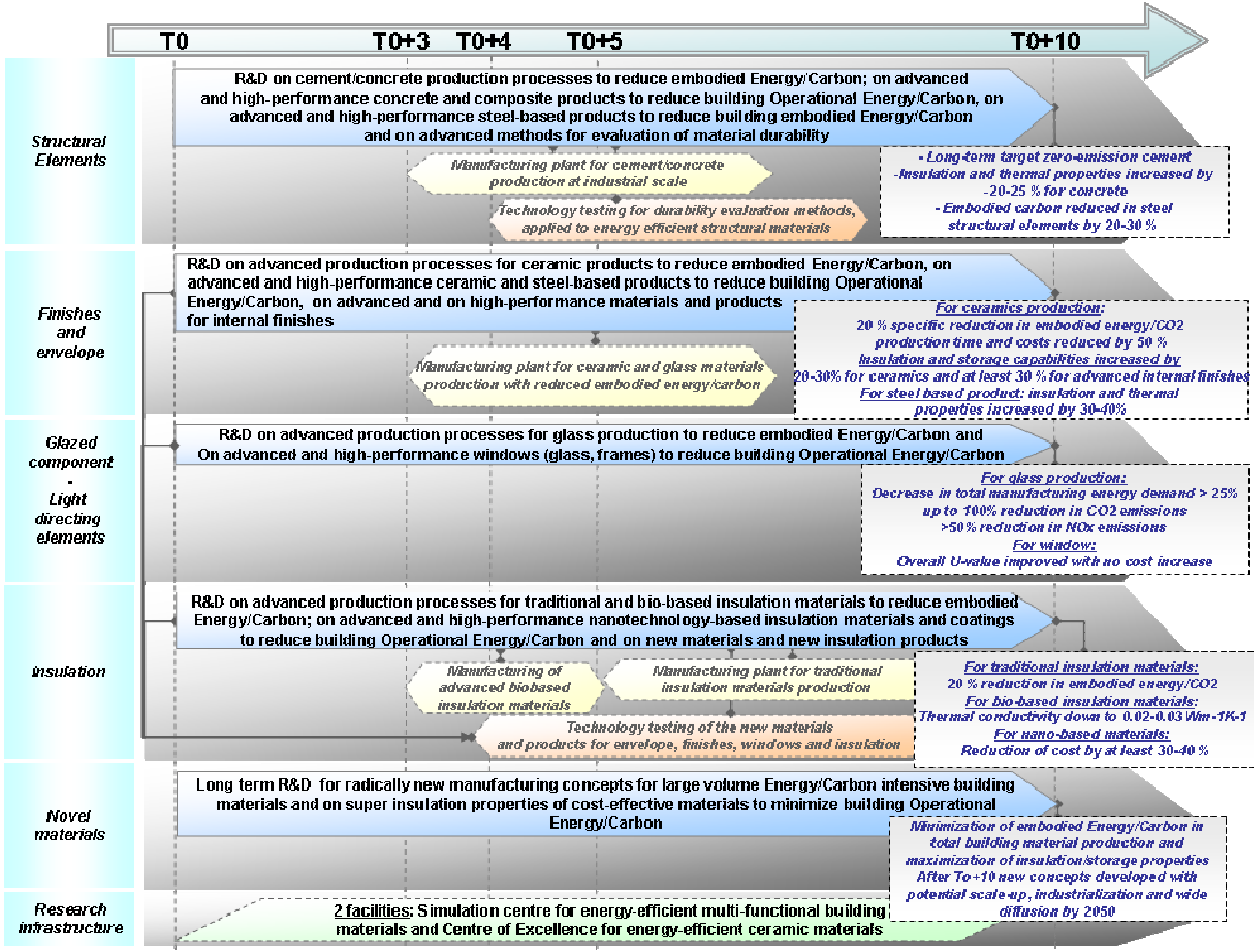
Facility 1 – Simulation centre for energy-efficient multi-functional building materials (Start at T0)

Development of a dedicated research unit focused on:

- Studying (e.g. from other industrial sectors, from other nano-technology development field, etc.) new specific material solutions for buildings;
- Developing simulation models of the whole material life cycle, including production, installation, use, end-of-life, recycling;
- It should encourage cross-fertilization among different materials, as many basic technologies (e.g. nano) or steps in the life-cycle could be common.

Facility 2 – Centre of Excellence for energy-efficient ceramic materials (Start at T0)

European coordination to create a knowledge “hub” and facilitate R&D for the several high-tech companies and research centres specialised on energy-efficient ceramic materials and related processes. This Network of Excellence will avoid fragmentation and will develop and support high-quality European products to survive to (often not correct) competition from Far East producers.


T0
T0+3
T0+4
T0+5
T0+10
Structural Elements
R&D on cement/concrete production processes to reduce embodied Energy/Carbon; on advanced and high-performance concrete and composite products to reduce building Operational Energy/Carbon, on advanced and high-performance steel-based products to reduce building embodied Energy/Carbon and on advanced methods for evaluation of material durability
Manufacturing plant for cement/concrete production at industrial scale
Technology testing for durability evaluation methods, applied to energy efficient structural materials
• Long-term target zero-emission cement
-Insulation and thermal properties increased by -20-25 % for concrete
- Embodied carbon reduced in steel structural elements by 20-30 %
Finishes and envelope
R&D on advanced production processes for ceramic products to reduce embodied Energy/Carbon, on advanced and high-performance ceramic and steel-based products to reduce building Operational Energy/Carbon, on advanced and on high-performance materials and products for internal finishes
Manufacturing plant for ceramic and glass materials production with reduced embodied energy/carbon
For ceramics production:
20 % specific reduction in embodied energy/CO2
production time and costs reduced by 50 %
Insulation and storage capabilities increased by 20-30% for ceramics and at least 30 % for advanced internal finishes
For steel based product: insulation and thermal properties increased by 30-40%
Glazed component - Light directing elements
R&D on advanced production processes for glass production to reduce embodied Energy/Carbon and On advanced and high-performance windows (glass, frames) to reduce building Operational Energy/Carbon
For glass production:
Decrease in total manufacturing energy demand > 25%
up to 100% reduction in CO2 emissions
>50 % reduction in NOx emissions
For window:
Overall U-value improved with no cost increase
Insulation
R&D on advanced production processes for traditional and bio-based insulation materials to reduce embodied Energy/Carbon; on advanced and high-performance nanotechnology-based insulation materials and coatings to reduce building Operational Energy/Carbon and on new materials and new insulation products
Manufacturing of advanced biobased insulation materials
Manufacturing plant for traditional insulation materials production
Technology testing of the new materials and products for envelope, finishes, windows and insulation
For traditional insulation materials:
20 % reduction in embodied energy/CO2
For bio-based insulation materials:
Thermal conductivity down to 0.02-0.03 Wm-1K-1
For nano-based materials:
Reduction of cost by at least 30-40 %
Novel materials
Long term R&D for radically new manufacturing concepts for large volume Energy/Carbon intensive building materials and on super insulation properties of cost-effective materials to minimize building Operational Energy/Carbon
Minimization of embodied Energy/Carbon in total building material production and maximization of insulation/storage properties
After To+10 new concepts developed with potential scale-up, industrialization and wide diffusion by 2050
Research infrastructure
2 facilities: Simulation centre for energy-efficient multi-functional building materials and Centre of Excellence for energy-efficient ceramic materials