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Energy technology developments beyond 2020 for the transition to a decarbonised European energy system by 2050

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1. INTRODUCTION

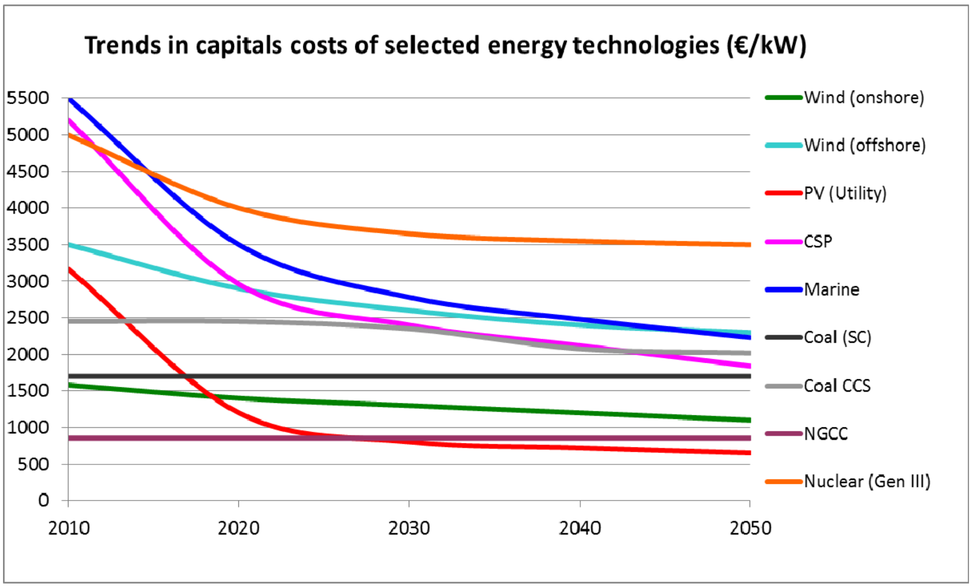
Continuous innovation on energy technologies is a prerequisite for Europe to achieve its long term sustainability goals, such as the decarbonisation of the society and economic growth. This was already recognised in 2006, when the European Commission proposed a European Strategic Energy Technology Plan (SET-Plan), aimed at accelerating the large scale deployment of selected low carbon energy technologies by intensifying research and development (R&D) and demonstration activities, which in turn would advance their commercialisation. The ultimate benefits include reduction of greenhouse gas emissions, improvement of the security of energy supply, development of technology export opportunities and hence economic growth and new highly-skilled jobs.

The SET-Plan in its current form targets the 2020 energy policy goals. The current need to prepare for the 2050 vision creates an impetus to plan energy technology development beyond 2020. This goes hand-in-hand with a long-term vision for the financial and organisational framework for energy technology R&D and demonstration. The need to intensify coordinated activities at European level has become even more important against the backdrop of the financial crisis.

This report presents the potential cost-effectiveness and scale of deployment of a portfolio of energy technologies. It examines their possible roles in the post-2020 European energy system as foreseen in the Energy Roadmap 2050, drawing on data from the European Commission's Strategic Energy technologies Information System (SETIS). Particular attention is given to:

- the longer-term evolution of cost and performance of energy technologies
- technological bottlenecks and other barriers to cost-reduction and commercialisation, and,
- R&D and demonstration priorities for exploiting the full potential for each technology.

This report demonstrates that focused R&D and demonstration can help reducing significantly the cost of low carbon energy technologies, up to 30-80% from current levels by 2050, see Figure 1.1. This in turn will have a large positive impact on the cost of energy in Europe, and hence on the quality of life and industrial competitiveness.



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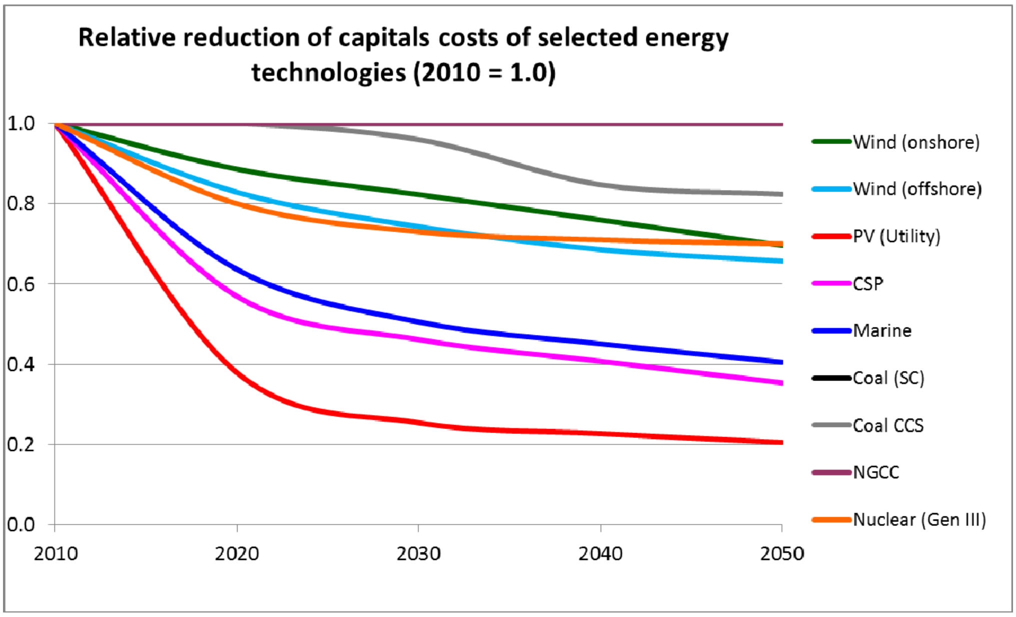


(b)

Figure 1.1. Capital cost reductions for selected energy technologies: (a) in absolute values, (b) relative reductions from 2010 cost levels. Source: JRC-SETIS analysis

2. SETTING THE SCENE: ENERGY TECHNOLOGIES BEYOND 2020

2.1. Evolution of Europe's energy system

The EU objective of reducing domestic greenhouse gas emissions by 80-95% by 2050 requires a major transformation of the European energy system. The power sector in particular needs structural change: according to the decarbonisation scenarios of the Energy Roadmap 2050, it needs to achieve significant reductions in greenhouse gas emissions already in 2030 (57-65%) and to reach near-complete decarbonisation by 2050 (96-99%). The projected structure of the energy system for two of the scenarios is shown in Figure 2.1.

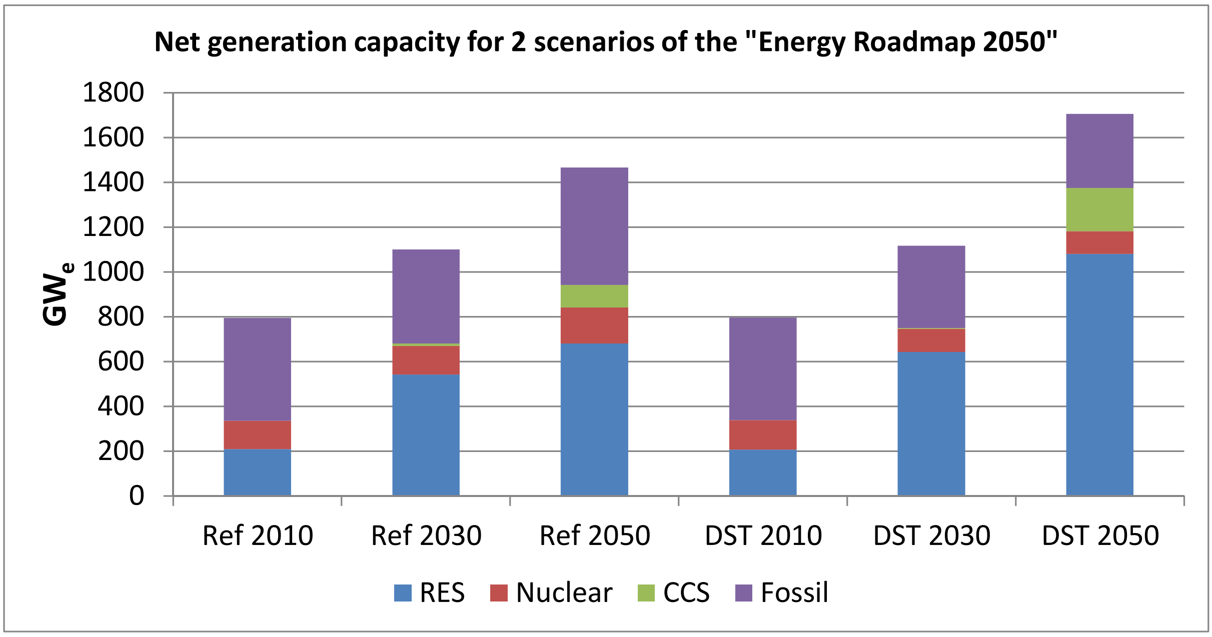


Figure 2.1. Evolution of net electricity capacity in the EU between 2010 and 2050 according to two scenarios from the Energy Roadmap 2050: the Reference (Ref) and the 'Diversified Supply Technologies' (DST) scenarios

In both the 'Reference' and the 'Diversified Supply Technologies' (DST) scenarios[1], electrification of the energy system is a major trend, resulting in much larger electricity generation capacities by 2030 and 2050 compared to today. Fossil-fuel capacity without carbon capture is slowly phased out and growth at the 2030 horizon is concentrated in solar, biomass/waste and wind and some other renewable energy sources (RES). By 2050 there is also a substantial role for carbon capture and storage (CCS).

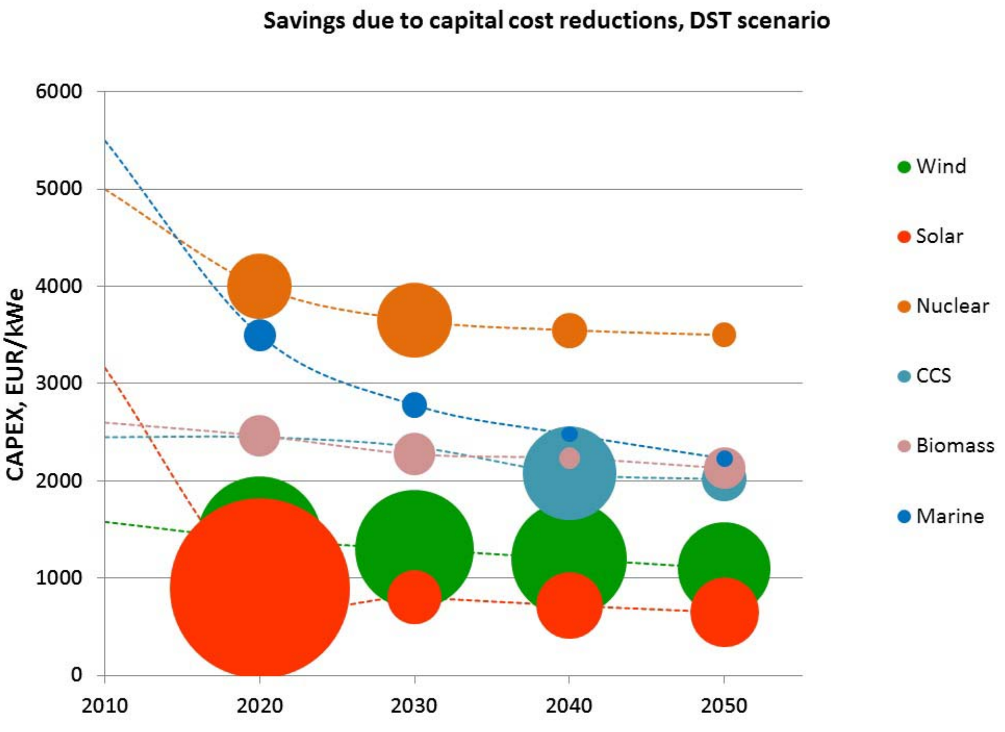
[1] The analysis herein builds upon two of the scenarios of the 2050 Energy Roadmap: the Reference scenario, which reflects a business-as-usual trajectory for the energy system and the DST scenario, which is the most technology-neutral amongst the decarbonisation scenarios considered in the Roadmap,

2.2. The need for innovation in energy technologies

The large-scale deployment of low-carbon energy technologies beyond 2020, as needed for meeting the vision for decarbonisation by 2050 requires that the costs of these technologies decrease substantially compared to the current levels. This requires large-scale innovation in low-carbon technologies as well as removal of non-technological barriers.

Of all the technologies addressed by the SET-Plan only wind and solar power in favourable locations can currently compete in the market without some form of economic incentive for power generation or grid access. This implies that substantial innovation and therefore investment to trigger and sustain it will be needed to reduce costs and realise the economics of scale associated with large scale deployment. The challenges however differ from technology to technology: the need for innovation is more critical when large-scale deployment of that technology is foreseen (and/or targeted). In addition, the need for innovation is also higher if the potential for future cost reductions of that technology is large.

This is illustrated herein using the results from the DST scenario of the Energy Roadmap and in particular the needs for investment in new capacities per technology, although similar conclusions can be drawn if other decarbonisation scenarios were considered. Preliminary calculations show that the total undiscounted cost savings could reach 350 billion euro during the period 2010 – 2050, once the capital cost reductions estimated in this report are realised, as a result of research & innovation and market measures. More than half of these savings will be realised after 2020. Most of these savings will come from initiatives in the wind and solar energies, followed by nuclear energy, CCS, bioenergy and marine energy. It is noted that no significant cost savings are expected from the conventional fossil fuel sector, although research & innovation are required to continuously improve environmental and operational performance. These results are summarised in Figure 2.2.



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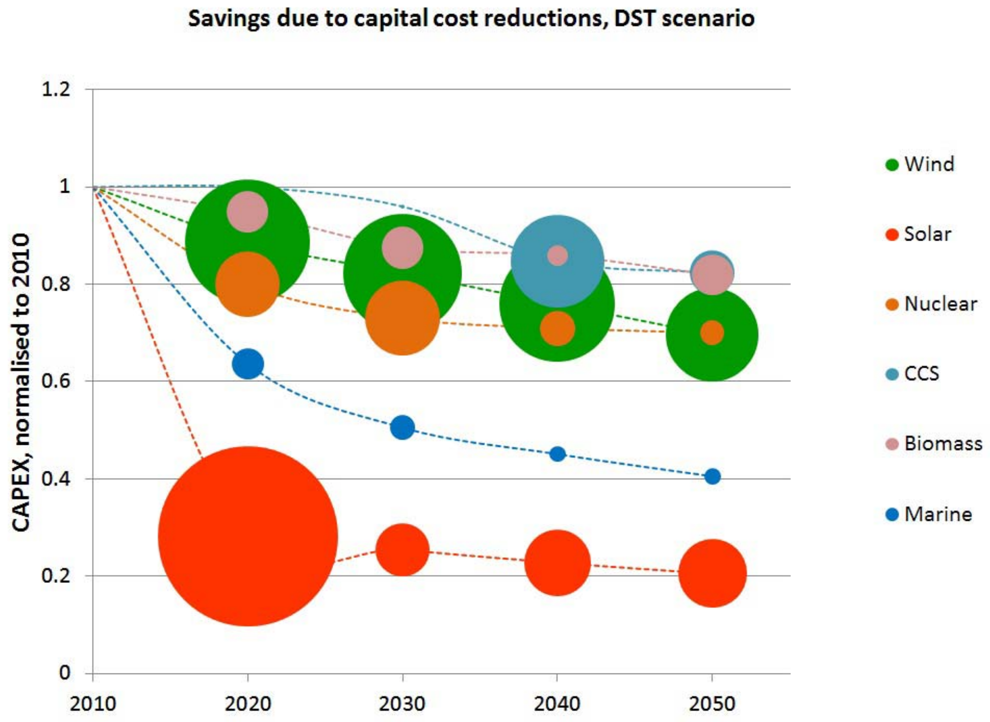

(b)

Figure 2.2. Reduction of capital costs of power generation technologies in absolute (a) and relative (b) terms. The size of 'bubbles' indicate the savings achieved by the reduction of capital costs of each technology per decade, demonstrating the impact of research, development and innovation in energy on the capital investments for the development of a decarbonised energy system.

Energy technology policy in the EU should therefore address a broad portfolio of technologies:

- **Solar**, which is deployed at very large scale and has the potential for a large cost decrease;
- **Wind**, which is also deployed at very large scale, and requires a continuation of ongoing innovation, especially offshore;
- **Biomass / waste**, which requires innovation in order to sustain deployment throughout the 2010-2050 period;
- **CCS**, which will be deployed mostly after 2030, but requires innovation also before 2030 in order to make the technology ready for the market;
- **Nuclear**, which continues to play a role due to large replacement investments both before and after 2030;
- **Advanced fossil fuel technologies**, due to their bridging role up to the 2050 horizon;
- **Marine energy**, which will be deployed at smaller scale than wind or solar, but require large cost reductions to improve competitiveness in order to harvest the enormous marine energy potential.

- **Energy efficiency technologies** for both the domestic/tertiary and industrial sectors, which are crucial for reducing the European needs for energy
- **System enabling technologies**, such as electricity networks and electricity storage technologies, which will facilitate the large scale deployment of RES technologies

The following chapters discuss these technologies in detail, in particular with regard to the research, development and demonstration/deployment (RD&D) actions that need to be taken to shape the post-2020 European energy system in line with the 2050 vision for a decarbonised economy.

3. PHOTOVOLTAIC SOLAR ELECTRICITY

3.1. Market evolution

Photovoltaic (PV) power generation capacity has grown rapidly over the last ten years and at the end of 2012 the cumulative installed PV capacity worldwide exceeded 100 GW. The EU has played a key role in this development with a cumulative installed capacity of 69 GW. As shown in Fig. 3.1, this growth considerably exceeds the trend foreseen in the national renewable action plans (NREAPa) and in the scenarios used for the Energy Roadmap 2050. The industry's baseline scenario now forecasts 333 GW by 2030[2], well above that predicted in the 2050 Energy Roadmap "high RES" scenario. It is clear that there are huge opportunities for photovoltaics in the future, accompanied by substantial evolution of the product, the power distribution system itself and the market. PV technology and its deployment is a now global business with both high innovation and market turnover. Since 2009, China (including Taiwan) is leading production, now providing about 70% of PV modules for the world-wide market, closely followed by Europe. Japan and USA are catching up. At the same time R&D in all parts of the world is increasing, focussing on reducing costs, increasing conversion efficiency and improving large-scale manufacturing processes.

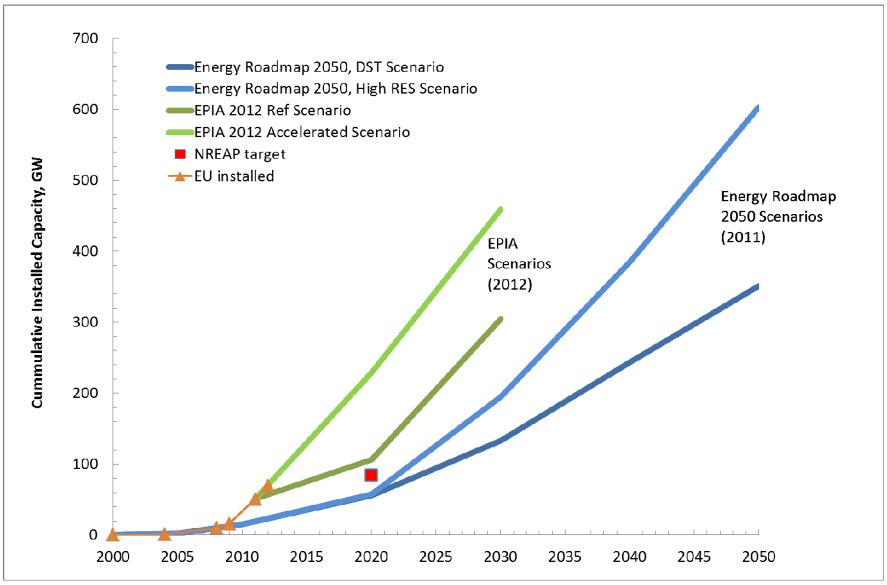

Fig 3.1 Scenarios for the future growth of PV generation capacity in the EU

3.2. Technology needs

To improve the cost structure and cost competitiveness of the European PV industry, research along the whole value chain from raw material processing, cell and module manufacturing to power electronics and system integration including local storage options is required. Besides the improvements of solar cells and modules, innovation in the "upstream industry" (e.g. materials, polysilicon production, equipment manufacturing), as well as the downstream industry (e.g. inverters, BOS components, system development, installations and integration into the existing or

[2] EPIA, Connecting the Sun, 2012.

future electricity infrastructure) in required to enable PV technology to contribute as a major electricity source in the future.

Research in photovoltaic devices over the last few years has seen major advances in efficiency, reliability and reproducibility, but it is clear that there is the potential for further progress, both in terms of existing device structures and in relation to new device topologies. Key to those advances is an understanding of material properties and fabrication processes. Research is required for specific aspects of device design and fabrication, together with consideration of the new production equipment necessary to transfer these results into the fabrication processes. In parallel, advances in the system architecture and operation will allow the increases in cell efficiency to be reflected in the energy output of the system. Innovative manufacturing technologies for PV electricity fall under the headings of:

1) *Printed Solar Cells:* Further cost reduction in solar cell manufacturing needs new and innovative technologies, which offer the possibility to lower capital costs of new manufacturing plants, increase throughput and yield and provide flexible design options to create new products for the building industry in Europe. Such production technologies also offer substantial reductions in energy payback time, reinforcing the industry's credentials as an environmentally sustainable electricity source. The leading role of Europe in PV technology development, nanotechnology and manufacturing systems engineering offers a unique opportunity to lead innovation in the PV industry and to regain European leadership in high value, customer adapted PV component manufacturing.
2) *PV modules as building materials:* Building markets are dominated by local regulations and building codes, but the building material market can develop to a world-wide market with huge opportunities for the European industry. The development of PV modules as a standard building material for roof or wall elements needs a multidisciplinary research and development programme involving the PV manufacturing, the building materials industry as well as certification bodies.
3) *Buildings as smart grid elements:* The combination of localised PV electricity, storage and local supply and demand management makes buildings the smallest independent unit which need a smart grid. Once the necessary technology and control mechanisms are developed, the step of linking multiple smart buildings could lead to a widespread deployment of the smart grid technology. If Europe were to develop such an innovative concept, it could take the industrial leadership for driving the development and industrialisation of this technology.

Besides fostering such innovation in the longer term, European PV research should help the existing industry to stay at the cutting edge of a wide range of technologies in commercial production and in the laboratory. No clear technological “winners” can yet be identified, as reflected by the investments being made worldwide in production capacity for many different technologies, and in the numerous concepts with large commercial potential being developed in laboratories. Therefore, it is important to support the development of a broad portfolio of options rather than a limited set. Common topics for all this research needs can be summarised as:

1) *Efficiency, energy yield, stability and lifetime:* Since research is primarily aimed at reducing the cost of PV electricity it is important not to focus solely on initial capital investments (€/W_p), but on the energy yield (kWh/W_p) over the economic or technical lifetime.
2) *High productivity manufacturing, including in-process monitoring & control:* Throughput and yield are important parameters in low-cost manufacturing and essential to achieve the cost targets.

3) *Environmental sustainability:* The energy and materials requirements in manufacturing as well as the possibilities for recycling are important for the overall environmental quality of the product.

4) *Applicability:* Moving towards the standardisation and harmonisation in the physical, mechanical and electrical characteristics of PV modules can contribute to reducing the costs of installation. Ease of installation and the aesthetic quality of modules (and systems) are important if they are to be used on a large scale in the built environment.

3.3. Cost reductions

Over the last two decades PV system prices have decreased all over the world, significantly driven by technology and market developments (Fig. 3.2). The change of the market from supply restricted to demand-driven, and the resulting overcapacity for solar modules has resulted in a dramatic price reduction of PV systems of more than 50% over the last four years. In the fourth quarter of 2012, the average system price for systems smaller 10 kWp was in the range of 1.75 €/Wp in Germany and 2.10 €/Wp in Italy. Quotes for large systems are already much lower, with turnkey system prices of 1€/Wp reported for projects to be finished in 2013[3]. These developments suggest that the PV Technology Platform's strategic research agenda's target for 2030 of 1 €/kW for turnkey 100 kW system (in 2011 euro, excluding VAT) may well be a reality already by 2020. Long term potential for substantial further reductions remains, as indicated by Fig. 3.2, showing capital cost trends. In this respect, it should be borne in mind that future PV systems are likely to be highly sophisticated and multi-functional, integrating storage capabilities with a sophisticated interface to the grid. Electrical batteries are becoming increasingly interesting, especially for small-scale storage solutions in the low-voltage distribution grid. Net electricity system prices should fall to 0.046 €/kWh in 2020. With levelised costs of electricity (LCOE) from PV systems moving below 0.10 €/kWh in the near future, the additional storage cost already makes sense in markets with high peak costs in the evening, where only a shift of a few hours is required.

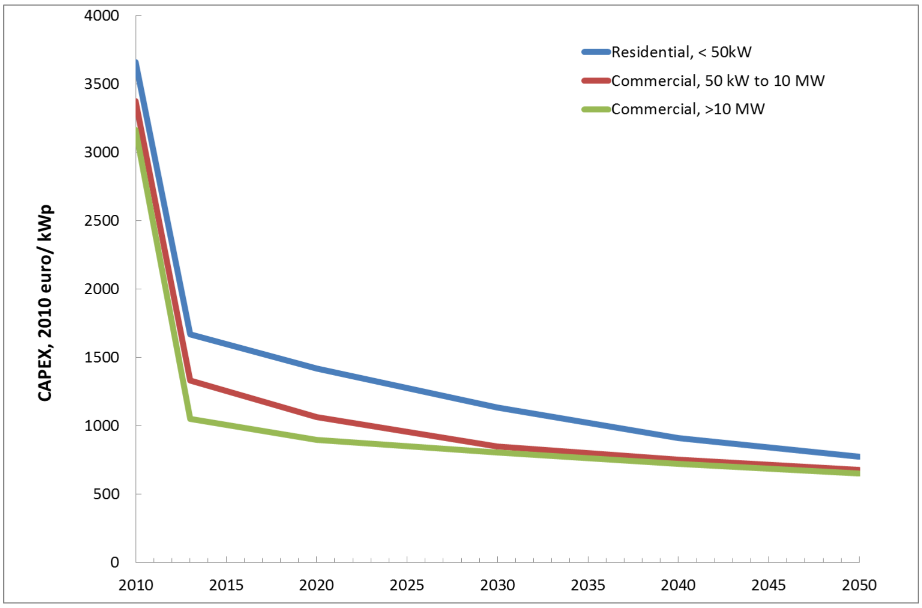

Fig. 3.2 Capital cost trends for PV systems.

[3] Bloomberg New Energy Finance, PV Market Outlook Q3 2012, 7 August 2012

3.4. Soft measures influencing deployment

After the massive cost reductions for the technical components of PV systems like modules, inverters BOS, etc., the next challenge is to lower the soft costs of PV system installations, like the permitting or financing costs. Despite the fact that PV system components are world-wide commodity products, the actual price for installed PV systems differs significantly (Fig. 3.3). The reason for these differences are manifold and vary from different legal requirements for permitting, licensing and connection to the grid to the different levels of maturity of the local PV market with impacts on competition between system developers and installers. A convergence of PV system prices in Europe is happening fast and it can be expected that this will open new opportunities for PV generated electricity to increase its share in European electricity generation.

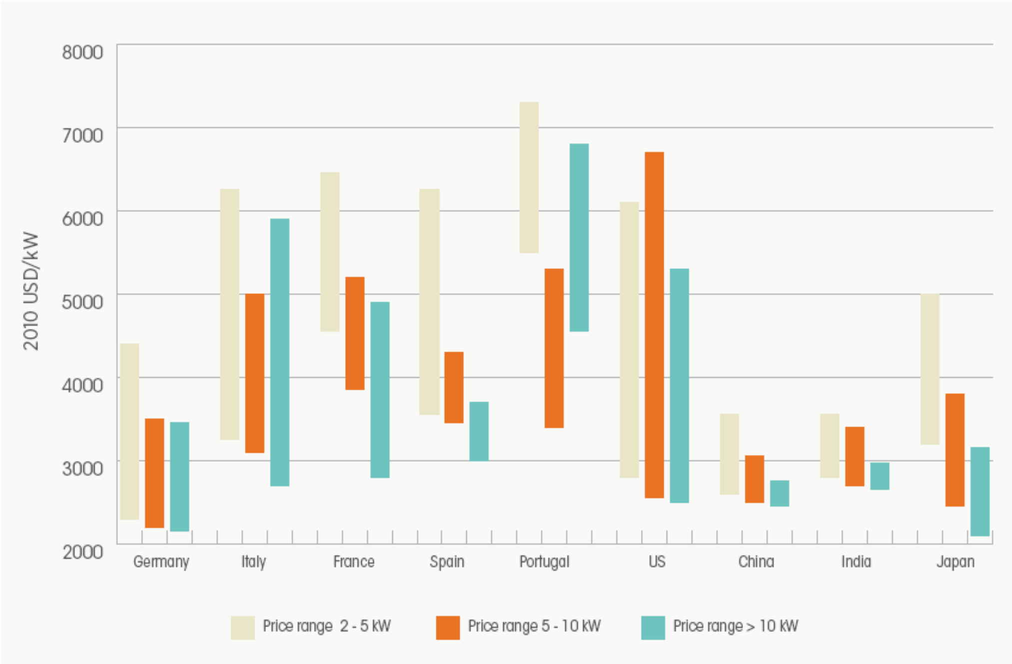

Fig.3.3: Variation of PV system prices in 2011 (source IRENA)[4]

[4] IRENA, 2012, RENEWABLE ENERGY TECHNOLOGIES: COST ANALYSIS SERIES, Volume 1, Power Sector, Vol4/5, Solar Photovoltaics.

4. CONCENTRATED SOLAR POWER GENERATION

4.1. Market evolution

Between 1985 and 1991, the Solar Energy Generating Systems (SEGS) I through IX (parabolic trough), with a total capacity of 354 MW[5], were built in the Mohave Desert, USA. After more than 15 years, the first new major capacities of concentrated solar power (CSP) Plants came online with Nevada One (64 MW, USA) and the PS 10 plants (11 MW, Spain) in the first half of 2007.

At the end of January 2013, CSP plants with a cumulative capacity of about 1.9 GW were in commercial operation in Spain, which corresponds to about 69% of the worldwide capacity of 2.74 GW. Together with those plants under construction and those already registered for the feed-in tariff this should bring Spain's CSP capacity to about 2.5 GW by the end of 2013. This capacity is equal to 60 plants which are eligible for the feed-in tariff. In total, projects with a total capacity of 15 GW have applied for interconnection. This is in line with the European solar industry initiative, which aims at a cumulative installed CSP capacity of 30 GW in Europe, out of which 19 GW would be in Spain.

In the USA more than 4.5 GW of CSP are currently under power purchase agreement contracts, which specify when the projects have to start delivering electricity between 2010 and 2014. More than 100 projects are currently in the planning phase mainly in Spain, North Africa, India and the USA. In December 2009, the World Bank's Clean Technology Fund (CTF) Trust Fund Committee endorsed a CTD resource envelope for projects and programmes in five countries in the Middle East and North Africa to install more than 1.1 GW of CSP by 2020.

4.2. Technology needs

Increased R&D efforts and strategic alignment of national and EU programmes are necessary to realise all the potential embedded in technology innovation. Demonstrating next generation CSP technologies is critical to address medium- to long-term competitiveness. The implementation plan of the Solar Europe Industry Initiative (SEII) describes the strategic RD&D components to boost innovation and reach competitive levels in the energy market.

Despite entering a commercial ramp-up phase, CSP technology is still in a development stage, displaying high potential for technical improvements. The industry is already focused on the R&D of the next stage of technology improvements, which shall have great impact on costs and efficiency of CSP plants. These improvements, which can be either technology specific or horizontal to most technologies, are centred on three main areas:

- Increase power generation efficiency, mainly through the rise of the operating temperature leading to higher turbine efficiency, but also through improvements in reflecting facets[6] and receivers
- Reduce solar field costs by minimizing costs and through design optimization that can lead to more cost effective solar fields deployment
- Reduce internal resource consumption through reduction of needed water and auxiliary parasitic consumption[7]

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[5] The capacity figures given are MW_{el} (electric) not MW_{th} (thermal)
[6] Mirror's capacity to reflect sun radiation
[7] Plant operations require consumption of electricity (e.g. to pump fluids). This type of consumption is called parasitic consumption

Key components to reduce the solar field cost are support structures, including foundations, mirrors and receivers. These costs will tend to decline over time as the overall volume increases. For the support structures, developers are looking at reducing the amount of material and labour necessary to provide accurate optical performance[8] and to meet the designed "survival wind speed". Given that the support structure and foundation can cost twice as much as the mirrors themselves, improvements here are very important.

For mirrors, cost reductions may be accomplished by moving from heavy silver-backed glass mirror reflectors to lightweight front-surface advanced reflectors (e.g. flexible aluminium sheets with a silver covering and silvered polymer thin film)[9]. The advantages of thin-film reflectors are that they are potentially less expensive, will be lighter in weight and have a higher reflectance. They can also be used as part of the support structure. However, their long-term performance needs to be proven. Ensuring that the surface is resistant to repeated washing will require attention. In addition to these new reflectors, there is also work underway to produce thinner, lighter glass mirrors.

Currently operating parabolic trough plants use a synthetic aromatic fluid (SAF) as heat transfer fluid. This fluid is organic (benzene) based and as such cannot reach temperatures above 400ºC with acceptable performance due to its decomposition at higher temperatures. This limited temperature range is capping overall steam cycle efficiency. To overcome this obstacle, developers are focusing on the development of alternative fluid technology, namely: molten salt, direct steam generation, nanotechnology improved fluids and alternative inorganic fluids.

Today's state-of-the-art thermal energy storage solution for CSP plants is a two-tank molten salt thermal energy storage system. The salt itself is the most expensive component and typically accounts for around half of the storage system cost, while the two tanks account for around a quarter of the cost. Improving the performance of the thermal energy system, its durability and increasing the storage temperature hot/cold differential will bring down costs. For solar towers, increasing the hot temperature of the molten salt storage system should be possible (up to 650°C from around 560°C), but will require improvements in design and materials used. The development of heat transfer fluids that could support even higher temperatures would reduce storage costs even further and allow even higher efficiency, but it remains to be seen if this can be achieved at reasonable cost. If direct steam towers are developed, current storage solutions will need to be adapted, if the capacity factor is to be increased and some schedulable generation made available.

4.3. Cost reduction

The current CSP market is dominated by the parabolic trough technology. More than 80% of the CSP power plants in operation or under construction are based on this technology. As a consequence, most of the available cost information refers to parabolic trough systems. The cost data for parabolic trough systems are also the most reliable, although uncertainties still remain, because it is the most mature CSP technology.

[8] Flexing of the support structures in windy conditions can have a negative impact on the concentration of sunlight on the receivers.
[9] Silver-backed glass mirrors are highly specular, that is to say they concentrate the sun's rays into a narrow cone to intersect the receiver. Any new reflector solutions need to also be highly specula.

The current investment cost for parabolic trough and solar tower plants without storage are between 3500 €/kW and 5500 €/kW[10]. Fig. 4.1 illustrates the development of the capital cost experience curve to date, while Fig. 4.2 shows the future trend. CSP plants with thermal energy storage tend to be significantly more expensive, but allow higher capacity factors, the shifting of generation to when the sun does not shine and/or the ability to maximise generation at peak demand times.

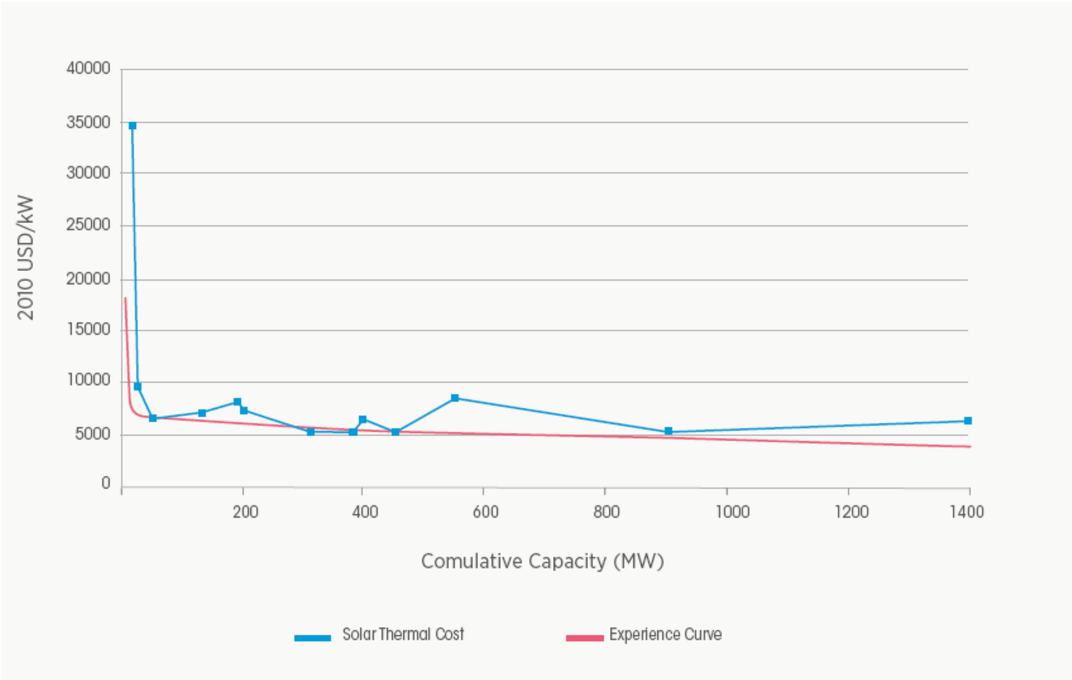

Fig. 1: CSP historical cost data, cumulative capacity growth and experience curve (Source IRENA)

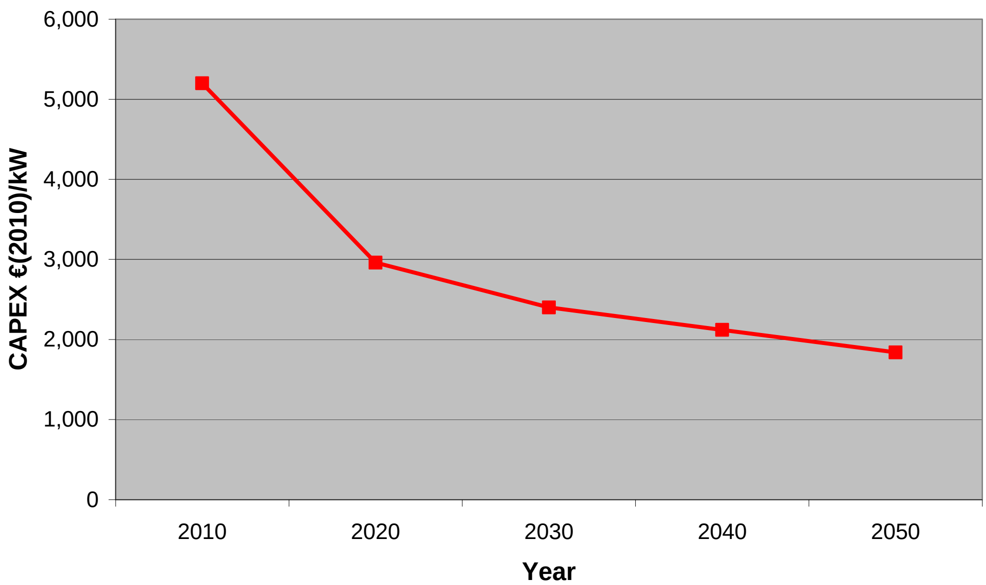

Fig 2: Capital cost estimates to 2050 for concentrated solar power plants.

[10] Source: IRENA, 2012, RENEWABLE ENERGY TECHNOLOGIES: COST ANALYSIS SERIES, Volume 1, Power Sector, Vol4/5, CSP

4.4. Soft measures influencing deployment

The cost-competitiveness of CSP plants is a key barrier. There is a strong need for developing long term policy frameworks to foster and secure CSP technology developments and investments worldwide. On the technology front, component improvements and scaling-up of first generation technologies are necessary for cost reduction. The demonstration of new technologies at system level and relevant scale is also crucial for CSP cost-competitiveness on the long term. However, these R&D and innovation activities are not covered by industrial and private funds. As a result, there is a current shortage of equity capacity. This situation is also relevant for today's technology. The necessary work on critical elements for first generation technologies such as adjustment of steam turbine to CSP specification is not performed today. Reaching a critical mass among players is an essential ingredient. Yet, a structuring of the CSP industry as well as an expertise broadening is on-going, but it is still in its infancy. Finally, the development of specific enabling technologies, for example, grid infrastructure for importing CSP energy from neighbouring countries, is an important focus for the sector developments. Hydrogen production is a potential industrial field for synergies with CSP technologies. Although these concepts are at an R&D phase, current developments on the heliostat or other heat transfer components will certainly benefit this field. In the short term, shared developments can be envisaged with concentrated photovoltaics as their concentrators respond to the same kind of usage. Other areas of developments besides electricity production are district cooling and water desalinisation.

5. WIND ENERGY

5.1. Technological evolution

Wind power is a mature technology in that it already contributes with a significant share in the European energy generation: there are 106 GW of wind capacity installed at the end of 2012 generating 210 TWh during an average year, or 6.5% of the European total[11]. However, the technology is still improving and costs will decrease –especially in offshore applications.

Global installations grew in 2012 by 12% to 45.5 GW, up from 40.5 GW in 2011, and reached 285 GW. The Chinese market shrank for the first time (from about 18 GW in 2010/11 to 14 GW annually), the Spanish market consolidated its reduction, the German market improved and the US market boomed. The new installations in the UK reached 1.9 GW of which nearly 1 GW was offshore About 1 GW was installed in the (so considered) emerging markets of Sweden, Poland, Romania, Brazil, Canada and Mexico. In Europe, markets that performed better than their historical averages include Italy (1.3 GW), Austria and Belgium (300 MW each), Norway and Ukraine. Outside Europe, there was a remarkable capacity growth in India (2.3 GW).

Wind is mostly a global market with a strong local influence: evidence suggests that the turbine manufacturer ranking depends strongly on how their home market performs. For example, in 2012 none of the Chinese manufacturers nor Gamesa (ES) were in the top-5: Instead, General Electric (US) topped a list where Siemens and Enercon (DE) and Suzlon (IN/DE) climbed as well. Most European manufacturers and GE cover different world markets whereas Chinese ones only recently started expanding overseas, with support of the European technology of the companies that they bought, or that they licensed.

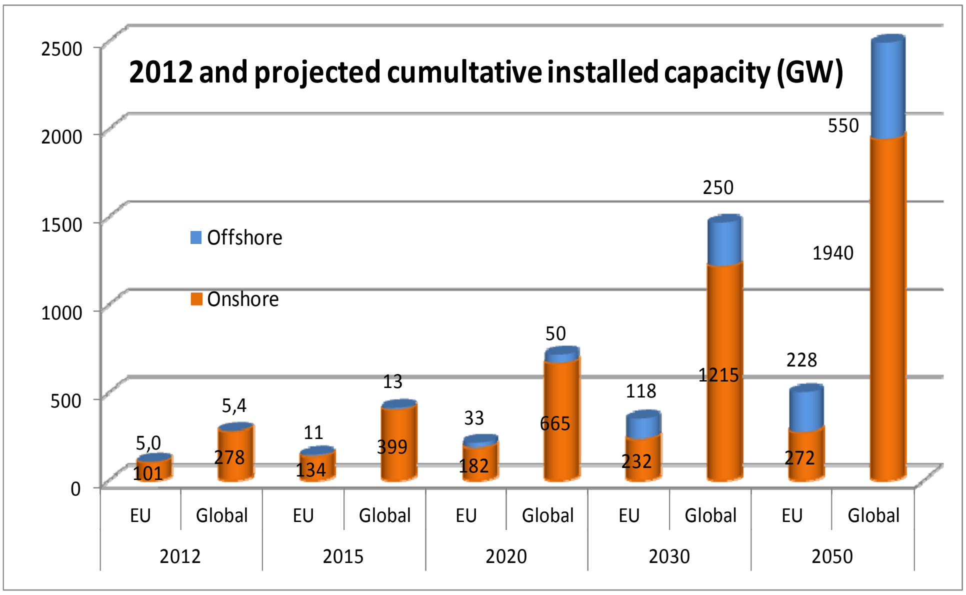

Figure 5.1: Projections of installed capacity to 2050, onshore and offshore, for the EU and globally. Source: JRC analysis.

[11] JRC calculations based on a 23% capacity factor, which is the 2011 average figure for Europe

New European installations are slightly growing at a steady pace. In the last four years between 9.5 and 11.5 GW of wind was added per year, mainly in Germany, in emerging markets and the offshore sector. Figure 5.1 shows current installed capacity and projections for the EU and the world. This scenario is broadly similar to the energy efficiency scenario of the Energy Roadmap 2050, and it differs in that it takes into account the delays to grid extensions that have surfaced recently and which will affect connection of offshore wind farms during the current decade.

5.2. Technology needs [12]

Wind turbines are evolving towards larger rotors, taller towers, lighter nacelles, and more reliable components requiring less maintenance. This evolution requires trade-offs: for example blades are becoming larger and heavier in the quest for larger rotors, but they must become lighter (per unit of length or rotor are) in order for rotors to grow more. The end goal is the reduction in the cost of energy from wind.

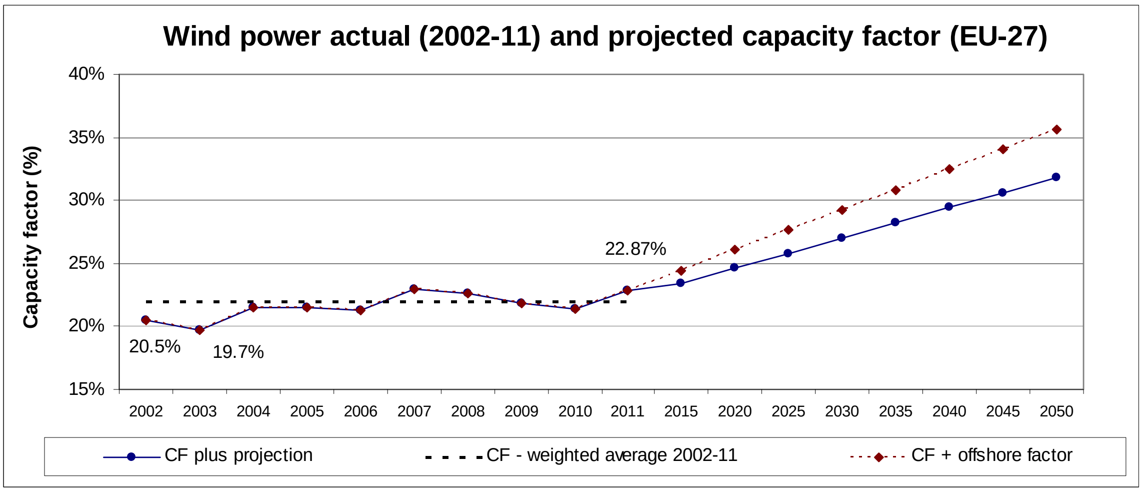

Figure 5.2: Evolution of capacity factors (CF) of the European wind turbine fleet 2002-2011, and projections to 2050. Source: JRC analysis based on data from Eurostat

Wind farms have to improve their efficiency of energy capture, and this is reflected on their capacity factors. Figure 5.2 shows that the actual capacity factor of the EU wind power fleet had an upward trend from 2002 to 2011. This trend will continue to 2050 (blue line). In addition, the brown dotted line takes into account the increased share of offshore installations in the future European fleet. Evidence from Danish offshore wind farms shows capacity factors in the range of 40 – 50%, which are significantly higher than the EU average.

Technological needs include:

[12] Some of the technologies currently in the early stages of development such as kites, those undergoing slow proof of concept (e.g. vertical-axis wind turbines), or not even thought of nowadays, could become mainstream in the 2030-2050 period. However, given the uncertainties in their success of commercialisation, these technologies have not been considered in this report.

Materials[13]

- Development of superconducting materials to enable their use in electricity generators.
- New blade materials that, at affordable cost, are stiffer but lighter, resist fatigue better and are recyclable.
- Blade coatings that decrease sand and water droplet erosion and increase UV light resistance, with self cleaning capability and ice shedding efficiency.
- For towers and foundations, high-strength steels of heavy gauge (thickness above 30mm), with superior toughness suited for welding technology and sustain high loads, at more affordable price levels.
- Also for towers, specialised pre-stressed concrete and innovative, better-performance mortars that can be worked out at a large range of temperatures, very liquid but of quick hardening and, overall, high strength and with other improved specifications.
- Better performing magnets in particular at higher operating temperatures, with higher magnetic power and less use of rare earths.
- High-temperature superconducting (HTS) wire and the corresponding cryogenic materials.
- Silicon carbide (SiC) as a much (energy-) denser base material for power electronics components should reach commercialisation at a reasonable cost.

Models

- Better knowledge of loads, load effects, and electrical effects in the electrical and mechanical parts of the turbine. Separation of load from torque. Appropriate load models.
- Micro- and meso-mechanic modelling on fibre/interface and on fibre arrangements; phenomenological and analytical material models based on damage mechanics to include effects of manufacturing defects and fatigue damage on the complex stress states notably in blades.

Components

- New sensors to support non-destructive condition monitoring.
- Innovative offshore foundations that reduce costs of both manufacturing and installation. This should be treated in a holistic way that includes foundation and turbine installation and the vessels needed for it.
- Substation connections: switchgear, transformers, cables, circuit breakers, etc., for DC substations and for 66 kV AC inter-array cabling.
- SiC switches (IGBTs, thyristors) up to 15 kV.

Processes

- Manufacture facilities for larger forgings.
- Design for manufacture, transport and installation; and for turbine assembly.
- Increase series manufacturing, including automation of manufacturing processes esp. for blades.
- New recycling processes for blade materials at affordable costs.
- Automatic or robotised gas-metal arc welding procedures.

[13] For more information: Scientific Assessment in support of the Materials Roadmap enabling Low Carbon Energy Technologies. Joint Research Centre, European Commission, ISBN 978-92-79-22936-7, 2012.

- Foundry technology for dross-free ductile iron with higher strength and very high wall thickness.
- New surface treatments such as PVD coatings, nitriding treatments and laser treatment to improve gear teeth properties.

Offshore wind is at a stage to strongly benefit from learning-by-doing. Support should include first-of-a-kind sub-structures (foundations) and new cable installations processes, as well as support for the two-four subsequent installations.

5.3. Cost reductions

As any mature technology, the evolution of capital cost in wind installations depends on the market forces more than on technological evolution. Still, in particular for offshore wind, innovation-based cost reductions will have a significant impact in global cost reductions.

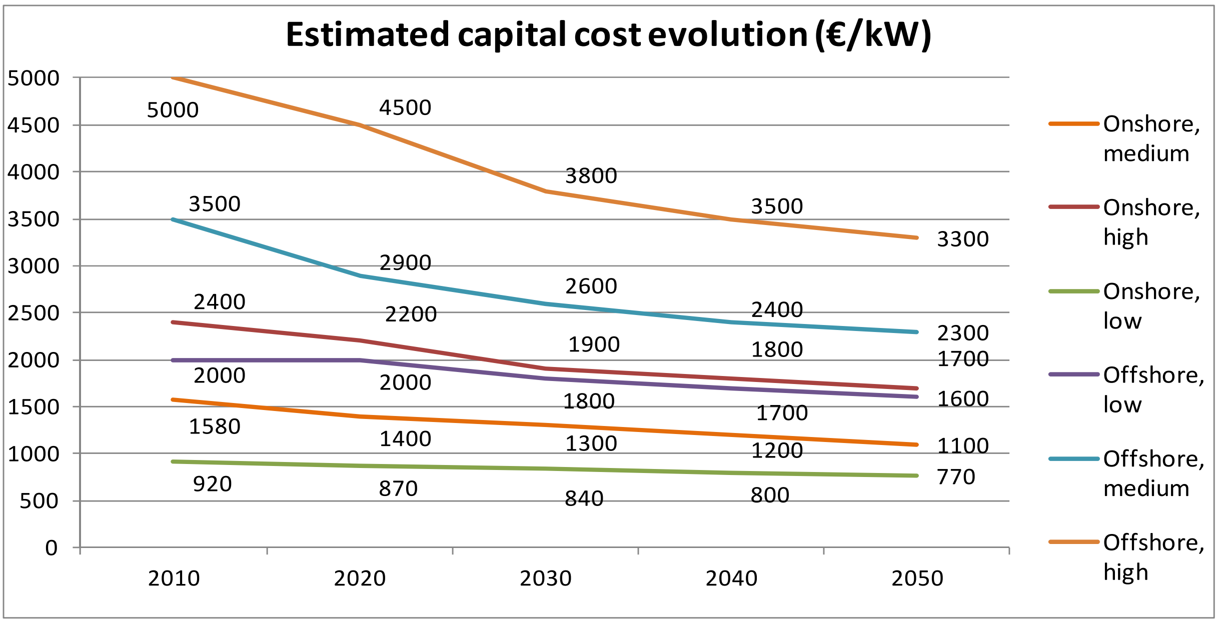

Figure 5.3: Expected evolution of capital cost for new wind power installations, for low, medium and high cost ranges. Source: JRC estimates.

Figure 5.3 shows the expected evolution of capital costs, offshore and onshore, according to the JRC[14]. The base onshore low figure corresponds to an average of countries with traditional low prices such as China and India; onshore high estimates are based on an average of high-cost countries such as Japan and Canada; finally, the onshore medium figure and estimated are based on the average of project costs reported to IEAWind, plus figures for the UK from other sources.

[14] Onshore figures are based on prices reported by IEAWind members, on data from Bloomberg's database, on other industry intelligence and on information collected from industry directly by the JRC

5.4. Soft measures influencing deployment

The application of the latest technological evolutions, providing the lowest cost, is sometimes restricted by local or country regulations, for example mandating shorter towers –which sometimes indirectly limit rotor size- in the building permit. Spatial planning authorities of the Member States could plan long-term, e.g. the ultimate practical potential for wind installations and, as a result, a reasonable deployment path. This would improve the processes of developing wind farms, which can currently take from one to ten years. National and regional authorities could also facilitate project planning. For example, for prospective offshore developments the authorities could, in agreement with developers, set up wind measurement equipment ahead of the consent process so that longer-term data are available which reduce the uncertainty of energy production. With less uncertainty, developers can obtain better debt conditions and the most appropriate turbine and foundations.

The reduction of risks and risk perception reduces LCoE without impacting public budgets. In effect, the interests borne by developers on capital cost borrowing are, in particular for offshore wind, strongly affected by the risk perception that lenders have of the regulatory framework. Where the perception is of regulatory insecurity, i.e. that the government can change the way wind electricity is paid for (e.g. feed-in-tariffs) retrospectively, lenders require higher interest rates and developers require higher returns on investment.

As wind reaches competitiveness with fossil-fuel-produced electricity, the way wind electricity is paid for will need to be reviewed. Variable renewables, and in particular wind and solar, have the particularity that the more the resource is available the more they push down wholesale market prices. Windy/sunny days thus result in high wind/solar electricity produced and, if sold at the market price, developers fail to recover the investment.

As variable renewables increase its penetration of the electricity mix there will be increasing pressure on their integration. The main options to smooth this integration are energy storage, improved interconnections, more flexible conventional power generation plants, and demand management through smart grids. All those options will need to be pursued in parallel because none of them is the perfect solution and because electricity systems are more robust when using a larger mix of both generation and grid management resources that include these.

6. BIOMASS / WASTE POWER GENERATION

6.1. Technological evolution

Biomass plays an important role in energy generation in the EU, with 7.7 % of the EU gross energy demand covered by biomass resources in 2010. The contribution of biomass was more than two thirds (68 %) of all renewable primary energy consumption in 2010 and is expected to reach about 57 % of the renewable energy in 2020. Primary energy production from biomass reached 118 Mtoe in 2010 and should increase to about 180 Mtoe in 2020, according to projections from the national renewable action plans (NREAPs). The total use of biomass is expected to rise significantly until 2050 in the various scenarios of the Energy Roadmap 2050. The biomass use in the reference scenario should reach about 186 Mtoe in 2050. In the decarbonisation scenarios, biomass consumption should reach between 260 and 275 Mtoe in 2050, while in the high RES scenarios the biomass use amounts to around 320 Mtoe. The key issue for bioenergy development is related to the availability of biomass. About 236 Mtoe of sustainably produced biomass could be available in the EU in 2020 and 295 Mtoe by 2030, according to the European Environment Agency, while, according to AEBIOM, the contribution of biomass could reach 220 Mtoe in 2020. The sustainable biomass potential was estimated by the Biomass Futures project at 375 Mtoe in 2020 and 353 Mtoe in 2030. The largest potential is in the agricultural residues (manure, straw and cutting and prunings from permanent crops), followed by forest biomass and waste.

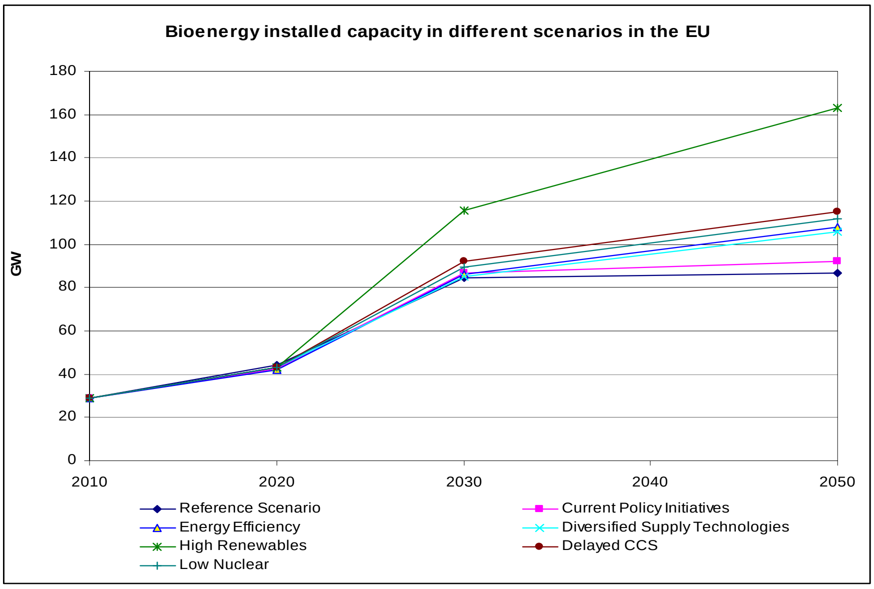

Figure 6.1. Projections of the bioenergy installed plant capacity in the European Union

Biomass electricity in the EU increased from 69 TWh in 2005 to 123 TWh in 2010 and is expected to reach 232 TWh in 2020. The contribution to electricity made by bioenergy will reach 19 % of RES electricity in 2020, according to the aggregated data of the NREAPs. The biomass electricity production should significantly grow to 360 TWh in 2050 in the reference scenario and to 460 – 494 TWh in 2050 in decarbonisation scenarios. Biomass electricity contribution could rise from 2.6% share in power generation in 2005 and 3.7% in 2010 to 7.3% in 2050 in the reference scenario and

9.3-10.9% in decarbonisation scenarios. In the EU, the installed bioenergy power capacity in 2010 was 29 GW. The installed bioenergy power capacity in EU is expected to reach 43 GW in 2020, see Figure 6.1. The installed biomass capacity increases significantly in all scenarios until 2050. Significant growth in biomass power capacity is expected to reach 87 GW in the reference scenario. The growth in biomass installed capacity is much higher in different decarbonisation scenarios, which should reach between 106 and 163 GW in 2050. This is an increase of 3 to 5 times the current (2010) biomass power generation capacity.

Currently bioheat is the main bioenergy market, accounting for 73 Mtoe (75 % of the total bioenergy), more than 90% of renewable heating and 13.5 % of total heat generation in the EU in 2010. Biomass will still have the major contribution with 81 % (90 Mtoe) for heating and cooling in 2020. The contribution of biomass used in households is expected to have a moderate increase from 27.0 Mtoe in 2005 to 35.0 Mtoe in 2020, accounting for about 38 % of the biomass used for heating. Direct use of biomass for heating, is expected to rise from approx. 13.5% in 2010 to approx. 33% in 2050 in the High RES scenario. The share of renewables in transport is expected to reach 11% in 2020 in all decarbonisation scenarios and it is expected to rise to 19-20% in 2030 and to 62-73% in 2050. Biofuel consumption rises from 3.1 Mtoe in 205 and 13 Mtoe in 2010 to reach about 18 Mtoe in 2030 and 37-39 Mtoe in 2050 under current policies scenarios. Biofuels contribution to transport sector in decarbonisation scenarios, imply an increase to 25-36 Mtoe in 2030 and 68-72 Mtoe in 2050, with the highest levels being reached in the High RES and Diversified Supply Technology scenarios.

6.2. Technology needs

There are several biomass conversion technologies at different stages of development, based on thermo-chemical (combustion, gasification and pyrolysis) and biochemical/biological (digestion and fermentation) processes.

Biomass combustion. Bioenergy production is largely based on mature direct combustion boiler and steam turbine systems at small- and large-scale for residential and industrial applications. The scale of biomass plants is often limited by available biomass resources, local heat demand and its seasonal variation. Biomass use in small and medium-scale requires further development towards low emission stoves and boiler systems. Future research should focus on the development of advanced control systems and better design. Stirling Engine technology is currently at the pilot-to-demonstration. The Organic Rankine Cycle (ORC) engine can offer technical and economic advantages for small plant capacities and low operating costs. However, electric efficiency is limited, and specific investment costs are high. The biomass ORC process has been demonstrated and is now commercially available.

Waste. Several technologies are available for waste conversion, including thermal or biological treatment. Energy recovery from waste requires certain steps including pre-treatment, waste conversion and energy conversion. Waste gasification with gas cleaning enables energy generation with improved efficiency, in combined cycle applications or syngas reforming. Incineration of MSW is a commercial technology, with effective emissions control. Waste-to-energy plants provide an important contribution to the energy supply. Energy recovery improvements can be achieved through the increase of electrical efficiencies and increased heat utilisation. The major challenges for waste combustion relate to the heterogeneous nature of waste, low heating value and high corrosion risk in boilers.

Biomass co-firing. Biomass co-firing with coal is the most cost-effective and efficient option of bioenergy production. Direct co-firing with up has been successfully demonstrated with a wide range of biomass feedstocks. However, feeding, fouling and ash disposal pose technical challenges that reduce reliability and lifetime of coal plants. Higher co-firing mix will require more sophisticated boiler design, process control and fuel handling and control systems. Higher percentages of biomass can be used in co-firing with extensive biomass pre-treatment (i.e. torrefaction) with minor changes in the handling system. Co-firing of waste poses both a legal barrier and a technical challenge. Waste combustion may only take place in a plant that conforms to the requirements of the Waste Incineration Directive 2000/76/EC (WFD).

Anaerobic digestion. Anaerobic digestion is a commercial and suitable technology for a range of biomass feedstocks. Digestion plants are limited in scale due to feedstock availability. Cleaning of biogas is required before use; biogas can also be upgraded to natural gas quality for injection into the natural gas grid or for direct use in gas engine vehicles. The main challenges for the use of biomethane are the gas purity requirements, infrastructure, supply and gas quality standardization. The main technological development needed is to increase performance and cost effectiveness, enlarge feedstock basis, improve biodegradability, optimise conversion, improve design and process integration. More research is needed on methods to process difficult to degrade feedstocks and the development of new techniques, enzymes and substrates, such as micro and macro algae (freshwater and marine). Anaerobic digestion and gas upgrading can be integrated into new biorefinery concepts.

Landfill gas utilisation. Landfill sites are a specific source of methane rich gas, providing methane emissions from MSW. Landfill sites can produce gas over a 20-25 year lifetime. Collecting this gas can contribute significantly to the reduction of methane emissions and, after cleaning, provides a fuel for heat and/or electricity production. However, due to the requirements to minimise landfilling of organic waste and increase levels of re-use, recycling and energy recovery (Landfill Directive 1999/31/EC), landfill gas is expected to decrease over time in the EU. The plant capacity of landfill gas collection varies from a few tens of kW to 4-6 MW, depending on the size of the landfill site.

Biomass gasification. Gasification is a highly versatile process for biomass conversion to fuel gas (syngas). Biomass gasification is still in the demonstration phase and faces technical and economic challenges. There are several gasification concepts available, depending on the gasification medium, operating pressure and type. Syngas can be used for heat and/or electricity production, or for synthesis of biofuels, e.g. hydrogen, methanol, DME and synthetic diesel via Fischer-Tropsch process, biomethane and chemicals. The BIGCC is a promising high-efficiency concept, although more complex that needs further development. A sophisticated gas purification is needed. The biomass gasification-hydrogen route could be a promising technology for energy production in Integrated Gasification Fuel Cell (IGFC) systems. Although gasification technologies are commercially available, more research needs to be done to achieve large scale commercial use. The key technical challenges and needs for research include process integration and control, gas upgrading, fuel flexibility, reducing complexity and costs, improving performance and efficiency. The critical factors for gasification are the reliability of the gasifier and the cost of the biomass supply. Significantly more RD&D is needed to develop, demonstrate and commercialise IGFC systems.

Pyrolysis. Fast pyrolysis is the conversion of biomass to a liquid bio-oil, solid and gaseous components. There are several technical challenges to the use of bio-oil. More research is needed for improving the quality the pyrolysis oil as bio-oils must be treated before use as fuel and can be upgraded into higher value fuels. However, pyrolysis and bio-oil upgrading technology is not commercially available, although several pilot and demonstration plants are in operation. Research is needed on the conversion process, on the quality and use of the bio-oil, control of bio-oil composition, thermal stability and process reliability. The main challenges concern the development of new techniques and catalysts for bio-oil up-grading.

Further development is needed for process integration; maximize bio oil yield; maximize energy recovery; emissions of pyrolysis oil combustion; cost efficiency.

Torrefaction. Torrefaction produces higher quality solid feedstock (bio-char), with high energy density and more homogeneous composition. Torrefied biomass can create new markets and trade flows as commodity fuel and increase the feedstock basis. No commercial torrefaction plant exists today, but demonstration projects are on the way. Further development of torrefaction is needed to overcome certain technical and commercial challenges. Additional fuel properties (e.g. degree of torrefaction, grindability, hydrophobic properties, resistance against biodegradation) must be defined in a product standard. Development and standardisation of dedicated analysis and testing methods are needed for assessment of end-use performance.

Biorefineries. A key factor in the transition to a bio-based economy will be the development of biorefinery systems. Biorefineries are a promising integrated approach for the co-production of both value-added products (chemicals, materials, food, feed) and bioenergy (biofuels, biogas, heat and electricity) and more efficient use of resources. Biorefineries are largely at the conceptual stage, with potentially interesting new products, routes and process configurations being currently developed. Biorefinery platforms can produce a wide range of marketable products using various thermal, biological and chemical processes. The deployment of the new biorefinery concepts will rely on the technical maturity of a range of processes to produce bio-based materials, bio-chemicals and energy.

Hydrogen from biomass. There are several routes for the conversion of biomass to hydrogen, including chemical, thermo-chemical and biological, at different level of development and not yet economically viable. Processes for hydrogen production include: gasification; pyrolysis; photolytic biological hydrogen; biomass conversion to hydrogen. Photo-biological processes are at a very early stage of development and have obtained low conversion efficiencies. Better understanding of the enzymatic pathways of hydrogen formation is needed. Research is needed to identify more oxygen-tolerant enzymes and new strains of bacteria producing hydrogen. There is a need for significant improvement of conversion efficiency. Further R&D is particularly needed on hydrogen gas separation and purification, for the development of catalysts, adsorption materials and gas separation membranes. Hydrogen storage requires research effort on new materials, adsorption and desorption, recharging. Major challenges refer to the safety issues and developing a hydrogen infrastructure.

6.3. Cost reductions

Several biomass power generation technologies are mature, but most of biomass technologies have difficulties to compete with fossil fuels for a number of reasons. Biomass plants, using complex pre-treatment, handling and feeding systems for biomass feedstock have higher capital and operating costs. Feedstock costs can represent up to 40 % to 50 % of the total cost of electricity produced. Bioenergy is a competitive option wherever low-cost feedstock (e.g. agricultural, forestry, pulp and paper residues, manure or sewage sludge, etc.) and/or when carbon tax or incentives are available. The cost and efficiency of bioenergy generation varies significantly by technology, configuration, complexity and level of maturity. Plant capacity influences the efficiency and cost effectiveness. Bioenergy technologies are at different states of commercialisation from the pilot, R&D or demonstration stage to commercial. Even for individual technologies, different configurations, feedstocks, fuel handling and gas clean-up requirements can lead to very different capital costs and plant efficiency.

The potential for cost reductions of biomass power generation varies, depending on the technology and potential for improvement (Figure 6.2). Many bioenergy technologies are mature and are not likely to undergo significant technological change as there is no much scope for improvement, and cost reductions through scale-up will be modest. The new technologies (gasification, pyrolysis, ORC) that are emerging and have not yet been deployed on a large scale, show significant potential for further cost reduction. Capital cost reductions for biomass co-firing, stand-alone direct combustion technologies (grate/BFB/CFB boilers) will be more modest. AD technologies could benefit from greater commercialisation and some process improvements. The co-production of chemicals, materials, food and feed in biorefineries can generate additional economic benefits for the production of lignocellulosic biofuels, biogas, heat and electricity.

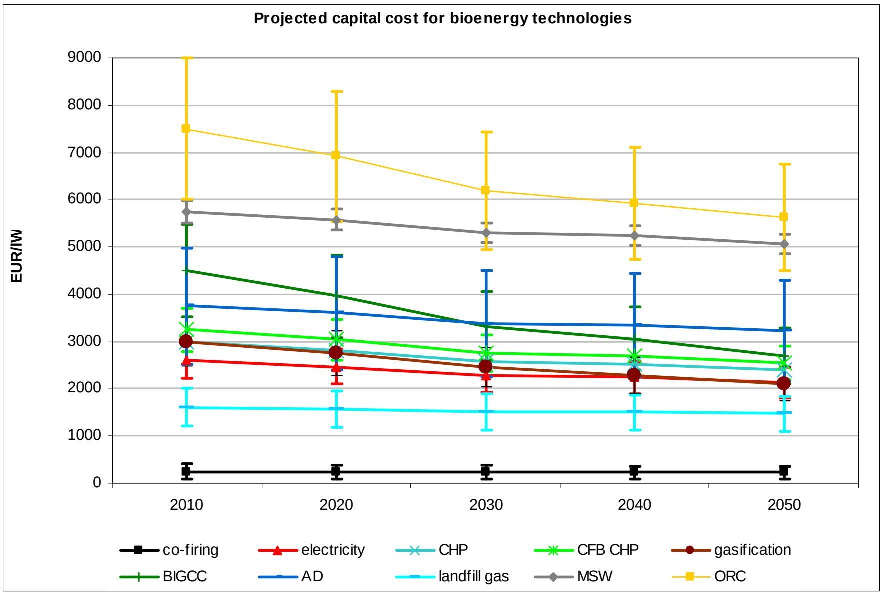

Figure 6.2. Trends in capital costs of bioenergy technologies

6.4. Soft measures influencing deployment

The main barriers to widespread use of biomass for bioenergy are cost competitiveness with fossil fuels and feedstock availability at low cost. Beyond the R&D and demonstration initiatives described above, additional support measures, such as feed-in tariffs and carbon taxes would be critical for the trade-off of advanced technologies.

The main issue regarding the viability of bioenergy lies in the development of a reliable supply chain. Secure, long-term supplies of low-cost, sustainable feedstock is essential to the economics of bioenergy plants. While feedstock cost may be low, increased demand for bioenergy can lead to price increases when competition for feedstock arises. Availability of sustainable biomass production of feedstocks is a critical factor for large scale deployment of bioenergy. Promotion of energy crops (e.g. SRC/SRF and energy grasses) with high yields could increase biomass supply, provided that land-use issues are adequately addressed.

Biomass shows a large variability of physical and chemical properties, making handling, transport, storage and feeding systems more complex and more expensive than for fossil fuels. Additional pre-treatment might be required to meet the quality requirements. Additional fuel properties must be defined in a product standard for pre-treaded biomass, such as wood pellets (process on going) and torrefied biomass. Development and standardisation of dedicated analysis and testing methods are needed for assessment of end-use performance.

Competition between alternative use of biomass for food, feed, fibre and fuel is a major issue for bioenergy deployment. Additional measures are needed to encourage the extension of the feedstock base, such as micro and macro algae (freshwater and marine), to develop new strains and enzymes and new substrates, and to encourage the use of all residues and waste streams. Given the limited amount of biomass, the most efficient use of biomass resources should be pursued.

Various concerns were recently expressed on several sustainability aspects. Sustainability certification of biofuels and bioliquids as well as solid and gaseous biomass should play to play a positive role addressing both direct and indirect effects of bioenergy production. Sustainable land use planning can play a significant role in this issue. The work should continue for the development of harmonised, global accepted sustainability system covering not only biofuels and solid and gaseous biomass, but also agriculture and forestry. This will contribute also to the public acceptance of bioenergy production.

7. CARBON CAPTURE AND STORAGE

7.1. Market evolution

The deployment of carbon capture and storage (CCS) technologies is considered to be the only solution for reconciling the continuous use of fossil fuels, especially for power generation, with the need to reduce greenhouse gas emissions. The important role of CCS in the future European energy system is reflected on the European Energy Roadmap 2050, where it is shown that the lowest cost pathways to decarbonisation require the large-scale deployment of CCS in Europe as of 2030, when the technology is expected to become commercially competitive. Indeed, once CCS technology becomes commercialized, it will draw almost all new investment on fossil fuel power generation, see Figure 7.1. Installed capacity will grow from 3 GW in 2020 to 3 – 8 GW in 2030, 22 – 129 GW in 2040 and approx 50 – 250 GW in 2050, depending on the path of evolution of the energy system, as depicted by the decarbonisation scenarios of the Energy Roadmap 2050. The contribution of CCS in gross electricity generation will rise from 1-3% in 2030 to approximately 5-20% in 2040 and 7-32% in 2050, see Figure 7.2, depending on the shares of RES and nuclear energy in the technology mix: CCS will fill in the gap in baseload power generation in the case of reduced nuclear power capacities (as reflected on the 'low nuclear' scenario, while the very large-scale deployment of RES may hinder CCS deployment ('high RES' scenario). Hence, irrespective of the specific path that the evolution of the energy system will follow, CCS will be an essential ingredient of the post-2020 European power generation technology portfolio. Beyond the power sector, the application of CCS to industrial sectors (e.g. steel, cement, refining) is expected to deliver, according to IEA, half of the global emission reductions required by 2050 from CCS[15].

Europe has been at the forefront of CCS technology development; however is lagging behind in terms of demonstration. According to GCCSI[16], eight of the 16 large-scale CCS integrated projects in construction or operation in the world are located in USA but only two in Europe. However, of the 59 projects under identification, evaluation or definition in the world by January 2013, 17 are located in Europe, 15 in the USA, 11 in China, 4 in Australia and 3 each in Canada and Middle East.

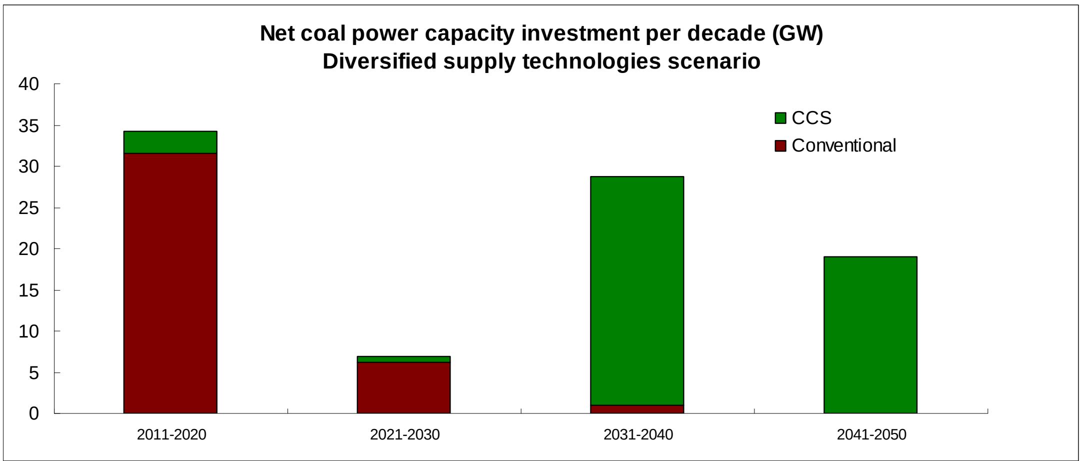

Figure 7.1: Share of CCS capacity in new coal power plants, under the diversified supply technologies scenario of the energy roadmap 2050. Once CCS is commercialized in 2030, it will attract practically all new investment in fossil fuel technologies.

[15] IEA CCS Technology Roadmap, 2009.
[16] GCCSI, The global status of CCS, January 2013 update.

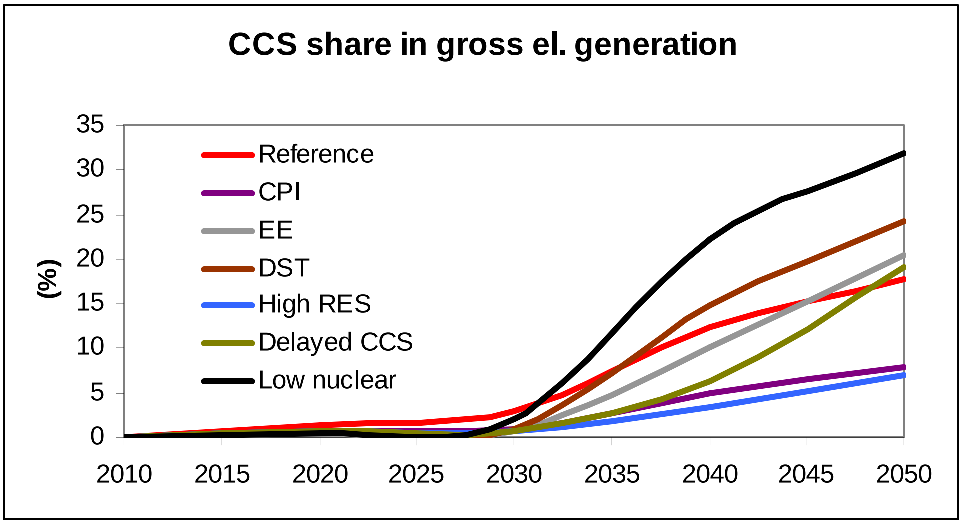

Figure 7.2: Share of CCS in gross electricity generation in Europe according to the scenarios in the Energy Roadmap 2050 (CPI: current policy initiatives, EE: energy efficiency, DST: diversified supply technologies)

7.2. Technology needs

A prerequisite for the commercial deployment of CCS as of 2030 is the demonstration of the technical and economical feasibility of existing technologies in fully integrated up-scaled value chains, that comprise CO_2 capture from power stations and large industrial installations; CO_2 transport via a pipeline network (or ship); and its safe and permanent underground storage in suitable geological formations, such as depleted hydrocarbon reservoirs or deep saline aquifers. A successful demonstration programme will pave the way for the construction of first-of-a-kind types of plant in the early/mid-2020's, laying the foundations for the large-scale roll-out of the technology in 2030 along the timelines envisioned in the Energy Roadmap 2050. One billion euro of funding has already been made available for 6 demonstrations projects by the EU via the European Energy Programme for Recovery (EEPR) and further funding for CCS demonstration may become available from the proceeds of the second call of the NER 300 programme.

Beyond the ongoing demonstration programme, targeted research and innovation activities will be required so that CCS technologies reach and maintain such a level of competitiveness so that the penetration levels described in the Energy Roadmap 2050 are realised:

- The development of innovative capture concepts will pave the way for the second and third generations of CO_2 capture technologies, marked by improved performance (i.e. lower efficiency penalty and cost of capture), which will result in further reductions of electricity costs to levels comparable to or lower than those associated with other future low-carbon technologies. Already, alternatives such as ionic liquid solvents, enzymatic separation and physical separation are emerging. R&D and demonstration priorities should include: the development of more efficient solvent systems and processes for post-combustion capture, e.g. phase change and enhanced carbonate systems; sorption-enhanced water gas shift and novel CO2/H2 separation systems (e.g. membranes) for integrated pre-combustion capture installations; large-scale demonstration of oxyfuel boilers for both the power and the heavy industry sectors and development of second- and third-generation systems like high efficiency circulating fluidised bed reactors and chemical looping. The optimisation of such capture technologies for other carbon-intensive sectors such as the cement, refineries and the iron and steel industries, will enable the European industry to meet its CO_2 emission reduction targets with the lowest possible impact on competitiveness.

- Pilots will lead the development of second- and third-generation technologies that will reduce further the investment and operating costs, as well as the associated energy penalty. They will focus on the testing of new / optimised solvents, sorbents and membranes, new process designs and novel power plant integration schemes for all three capture pathways, post-combustion, pre-combustion and oxy-fuel. These pilots will also address crosscutting issues, such as capture plant flexibility, so that fossil fuel power plants can operate in tandem with intermittent renewable energy sources.
- Demonstration of feasibility of bio-CCS, i.e. using biomass as feedstock, will enhance the CO_2 reducing potential of CCS[17].
- The development of concepts for CO_2 transport will enhance safety and hence public acceptance. These include the design of materials suitable for pipelines handling CO_2 at various compositions, avoiding pipeline rupture and longitudinal cracking.
- Better assessment of storage potential and site characterisation, especially of saline aquifers, will increase the safety of operations and contribute to the optimisation of infrastructure. Activities will include large scale storage demonstrators and pilots and development of models for the behaviour of injected CO2 at various timescales.
- Development of methodologies for pressure management will enable optimal use of the subsurface storage space, co-optimisation of EOR and CO_2 storage, and improved prediction of geologically controlled CO2 leakage mechanisms, which in turn will lead to safe and efficient CO_2 storage exploitation.
- The development of more refined and cost-effective monitoring and modelling techniques will contribute to the assessment of CO_2 migration, diffusion, fluid-rock interactions, and cap rock integrity for verifying storage security. This will lead to enhanced leakage detection and measurement, both in-situ and by remote sensing.
- Development of economically viable technologies, which can use captured CO_2 as feedstock for the production of synthetic fuels and chemicals, will improve the economics of CCS (CO2 utilisation –CCUS-).
- The further improvements of the efficiency of power plants and industrial processes will enable the deployment of CO_2 capture technologies at a minimum overall efficiency penalty. This is addressed in Chapter 9 of this report.

7.3. Cost reductions

Since CCS technologies have not yet been demonstrated on a commercial scale in the power sector, all reported cost figures are only estimates, based on scaling-up of smaller similar components and facilities used in other sectors (e.g. chemical and petro-chemical industry) or on manufacturers' expert judgment. As such, there is a significant uncertainty about near-, medium- and long-term technology costs. A recent cost analysis by ZEP ETP[18] give estimates of the capital costs of power plants equipped with early generations of CCS technology. The costs of a coal plant range from 2450

[17] ZEP ETP and the European Biofuels Technology Platform, Biomass with CO2 Capture and Storage (Bio-CCS), http://www.zeroemissionsplatform.eu/ library/publication/206-biomass-with-co2-capture-and-storage-bio-ccs-the-way-forward-for-europe.html

[18] ZEP ETP, The costs of CO2 capture, http://www.zeroemissionsplatform.eu/library/publication/166-zep-cost-report-capture.html

€/kW (plant with post-combustion capture) to 3325 €/kW (oxyfuel plant). On average, the first generation CCS coal power plant is expected to be about 60-100% more expensive than a similar conventional plant, depending on the capture technology selected, i.e. post-, pre-, or oxyfuel combustion; while the capital cost of a natural gas plant with post-combustion capture can be twice of that of a conventional gas plant with the same capacity. It has been estimated that once CCS power plants start being deployed, costs will decrease at a rate of 12% per doubling cumulative installed capacity, benefiting from R&D activities and the building of economies of scale. Of the CO_2 capture technologies, the costs of oxyfuel-based systems may decrease faster since the industry expects new designs soon after first commercialisation, at a cost of about 2200 €/kW. Figure 7.3 shows the reduction of specific capital investment (SCI) of CCS power plants in the period 2020-2050. It is expected that by 2050, the capital costs of pre- and post-combustion coal plants with CCS will be reduced by almost 20% from those of first market entrants. The corresponding reduction for gas plants is expected to be around 10%.The cost of CO_2 capture for industrial applications will also vary according to application, but may, in many cases, be lower than for power generation due to a higher concentration of CO_2 in the flue gas.

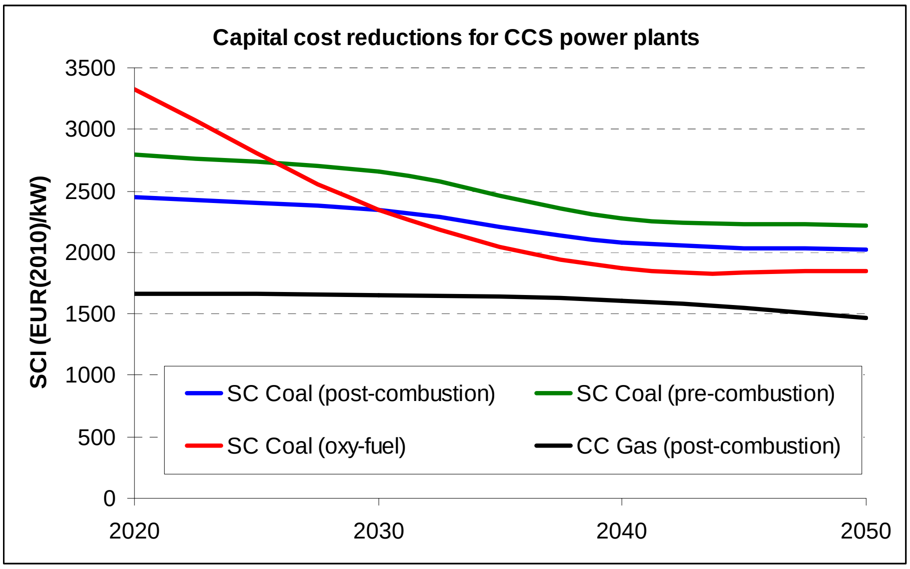

Figure 7.3: Trends in capital costs of supercritical (SC) coal and combined cycle (CC) natural gas power plants with CCS technology (Source: JRC estimates)

7.4. Soft measures influencing deployment

Beyond R&D and demonstration initiatives to address technological gaps, additional measures will be required to facilitate the timely deployment of CCS. The most pressing issue to be addressed is the lack of business case. The current low ETS prices and the lack of any other legal/regulatory constraint, or incentive, hinders investments in CCS, both in demonstration and in bridging the gap to commercialisation, since there is no financial compensation for the additional capital and operating costs associated with CCS, despite the savings that come from buying fewer ETS quotas. This is especially true for the heavy industry, which faces a high risk of 'carbon leakage' due to the global trade of their products. The lack of political commitment to CCS by some Member States, as reflected on the outcome of the first call of the NER300 programme, triggered by the current economic environment, problems in permitting procedures and public opposition only adds to the difficulty of CCS projects to secure public and private financing. Additional financial incentives are hence needed as well as a stable policy/regulatory environment to make a CCS investment as commercially attractive as a conventional fossil fuel plant. It is noted however that the key regulatory issues related to permit/licensing procedures for storage sites and long-term liability have already been addressed by the CCS Directive (2009/31/EC). Securing public confidence in many Member States is another key social and political challenge, as confirmed by a Eurobarometer survey on CCS. While nearly half of the respondents agreed that CCS could help to combat climate change, the survey observed that 61% of people would be worried if an underground storage site for CO_2 were to be located within 5 km of their home. As a result of public opposition, a number of projects that envisaged CO_2 storage in land have been cancelled. This barrier was overcome in same cases when extensive information campaigns took place, or when CO_2 will be stored offshore. Since public perception will have a significant role to play in CCS deployment, measures relating to education on climate change and communication of the main technical economic and social aspects are needed.

8. NUCLEAR FISSION ENERGY

8.1. Market evolution

In the Energy Roadmap 2050 six policy scenarios were studied. In the 'current policy scenario' the share of nuclear power is projected to reduce from 30.5 to 20.7% of the gross electricity production in 2030 and to 20.6% in 2050. For the four decarbonisation scenarios, the share of nuclear in the gross electricity generation varies from 13.4 to 21.2% in 2030 and 2.5 to 19.2% in 2050. For most other recent scenario studies concerning EU-27, the share of nuclear is forecasted to be either stable or slightly reduced by 2050. The construction of new nuclear will vary significantly between Member States. Presently, for example France, Finland, the UK, and Czech Republic plan construction of new reactors, whereas other countries have decided to phase out or stop their nuclear programs, e.g. Germany and Italy.

AREVA is the only European vendor of nuclear reactors. It is one of the global leaders in the industry. Two of its European pressurised reactors (EPRs) are under construction in Finland and France, and two EPRs are under construction in China. Worldwide there are 68 reactors under construction. AREVA is currently competing to sell reactors in the UK, Czech Republic, USA, India etc. Other major vendors competing globally include Westinghouse, GE Energy, Atomstroyexport, Mitsubishi Heavy Industries, AECL, and KHNP. Competition from Chinese vendors as well as from private enterprises selling Small and Medium sized Reactor (SMR) concepts are expected to increase in the future.

Europe and particularly France have large experience with Sodium-cooled Fast Reactors (SFR). Outside Europe, fast reactor programs are pursued in Russia, Japan, India, and China. These countries invest large resources, but Europe has an opportunity to construct the first fast reactor that meets the Generation IV design criteria[19].

8.2. Technology needs

Often nuclear reactor designs are categorised in Generation II, III and IV according to their evolutionary improvements or developments. Most of the reactors operating globally are of Generation II type. Two Generation III rectors are under construction in the EU-27, while Generation IV plants are to be commercially deployed around 2040. Some of the general technology and research needs as well as the specific needs for each Generation of nuclear power are presented below.

General needs

After Fukushima it became apparent that more focus is needed on extreme and rare external safety hazards and the interaction between units on one site in such events[20]. Examples of general technology/research needs are:

[19] GIF, 2002, A Technology Roadmap for Generation IV Nuclear Energy Systems, pp.6, available at: http://www.gen-4.org/PDFs/GenIVRoadmap.pdf

[20] SNETP, 2011, Implications of the Fukushima accident for SNETP, available at: http://www.snetp.eu/www/snetp/images/stories/Docs-Newsflash/Implication_of_Fukushima_SNETP.pdf

- Systematic approach for the determination of safety margins and the risk of occurrence of cliff-edge effects for extreme events beyond the design basis.
- Methodologies to identify extreme and rare events potentially leading to common mode failures of multiple plants system.
- Further develop and validate advanced models and simulation platforms for the analysis of severe accident.

Generation II

The bulk of the Generation II Light Water Reactors (LWR) were commissioned during the 1980's and unless they are granted life time extensions they will be decommissioned in the 2020's, see Figure 8.1. It is expected that most nuclear power plants will extend their operating life time to 50-60 years, as is often the case with similar reactors around the world (e.g. in the USA).

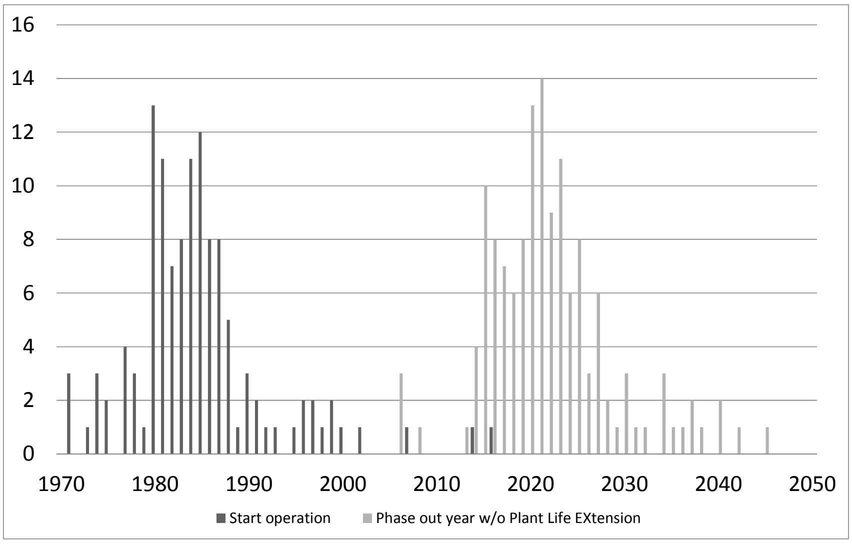

Figure 8.1. Start of operation and planned phase out without plant life extension for nuclear power plants in EU-27

In the period 2010-2030, the successful operation and management of Gen II LWRs beyond their originally foreseen lifetime will be an important driver for R&D[21].

Important issues to be addressed are:

- Increase understanding of ageing mechanisms of materials
- Development best practise guidelines for ageing prevention and mitigation
- Further development and validation of modern computer codes for assessing loading

Generation III

[21] SNETP, 2009, Strategic Research Agenda, available at: http://www.snetp.eu/www/snetp/images/stories/Docs-AboutSNETP/sra2009.pdf

The Generation III LWR reactors are the state of the art of nuclear reactor technology and they are currently being deployed. The designs will be further refined with time based on feedback from operating experience and improvements through R&D.

Generation IV

Within the European Sustainable Nuclear Industrial Initiative (ESNII) three fast reactor concepts are developed. The French project called ASTRID concerns the sodium-cooled fast reactor (SFR). A prototype is planned after 2020 and commercial deployment after 2040. The MYRRHA project of Belgium on a lead-bismuth cooled accelerator driven system plans a demonstrator by 2022. MYRRHA feeds into the development of the lead-cooled fast reactor (LFR) concept. The LFR is expected to be commercially deployed around 2050. A gas-cooled fast reactor (GFR) is also being investigated, but it requires more R&D on fuel and materials, and thus its commercial deployment would be farther in the future.

To achieve commercial availability of SFR by 2040 and LFR by 2050, some of the technology needs identified are[22]:

- Structural materials and innovative fuels that can support high fast neutron fluxes, high temperatures, and guarantee a plant lifetime of 60 years
- Improved safety, and robustness against severe damage, e.g. core designs with moderate void effect and other favourable reactivity feedback effects
- Development of European codes and standards to be used for future construction of Gen IV reactors
- More advanced physical models and computational approaches to achieve more accurate and detailed modelling benefiting from the increase of computational power
- Improved sustainability through a better use of fissile materials, reduction of proliferation risks, and minimisation of long lived radioactive waste.

Nuclear cogeneration using (Very) High Temperature Reactors is another potential area where nuclear power can play a role in decarbonising both the electricity and heat markets[23]. An industrial initiative is being prepared, but since no significant projects exists yet it is not treated further here.

8.3. Cost reductions

Generation III: At Olkiluoto the originally planned start in 2009 of the first of a kind EPR has been delayed by seven years, whereas construction at Flamanville is four years behind schedule. The long delays have caused significant cost overruns. The costs for EPR at Olkiluoto and Flamanville are now estimated at 8.5 billion Euro (5300 Euro/kW_e), which is more than twice their original costs. On the other hand, two EPRs are under construction in China using the experiences learned from the constructions in Europe. The Chinese EPRs are on schedule to be constructed in 46 months. It is likely

[22] SNETP, 2009, Strategic Research Agenda, available at: http://www.snetp.eu/www/snetp/images/stories/Docs-AboutSNETP/sra2009.pdf

[23] SNETP, 2009, Strategic Research Agenda, available at: http://www.snetp.eu/www/snetp/images/stories/Docs-AboutSNETP/sra2009.pdf

that delays and cost overruns would be significantly reduced for the next construction of an EPR in the EU too, see Figure 8.2. In the long term the capital costs are expected to be around 3500 EUR/kW$_e$. The designs will be refined with time to improve economic competitiveness.

Generation IV: According to the Key Performance Indicators indicated by ESNII, the capital cost is expected to be around 4000 EUR/kW$_e$ for the LFR for the Nth-of-a-kind (NOAK) reactors. The aim is to keep capital costs down by plant simplifications and by the use of inherent and passive safety systems. The SFR is expected to have a similar capital costs as the LFR. It should be recognised that for projects of this size and complexity, the uncertainties of these estimates are not negligible.

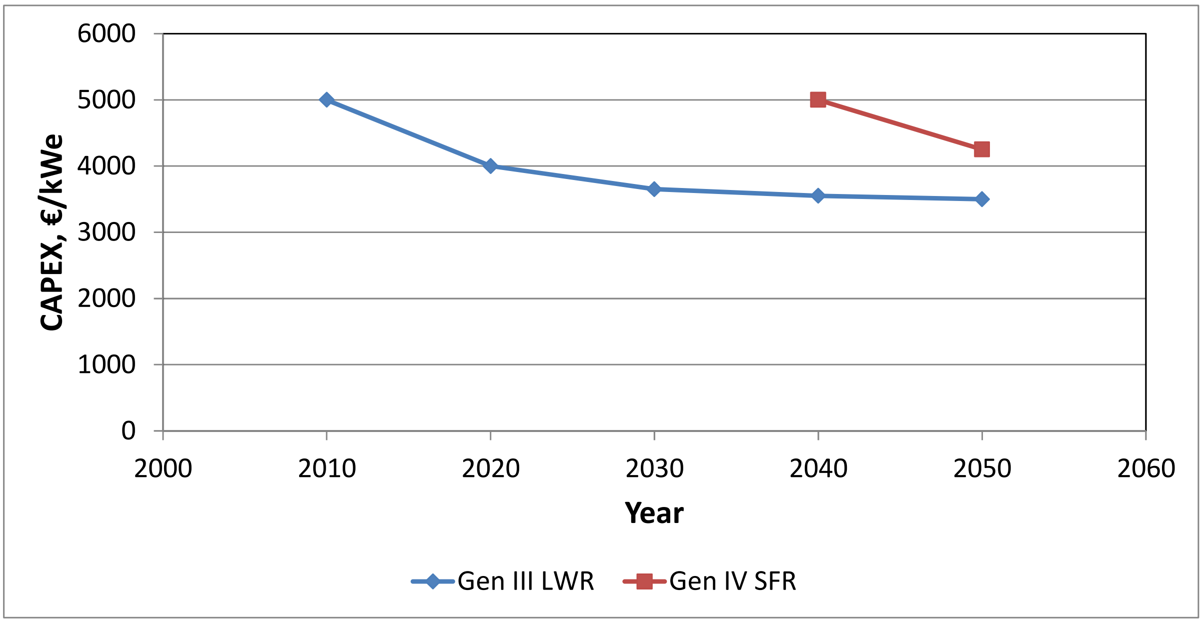

Figure 8.2. Capital cost trends for Generation III and IV nuclear reactors.

8.4. Soft measures influencing deployment

Non-technological measures could have an important effect for the market trajectories of nuclear power. The following areas would help the nuclear industry:

- Access to favourable financing to increase certainty for investors and make more resources accessible to research programmes.
- Streamline the licensing process in the Member States through common regulatory requirements, which could shorten the time from investment decision until reactor operation.
- Harmonisation of European plant life extension justification methodologies.
- Harmonisation of European methodologies for a new type of probabilistic safety assessment, e.g. extreme events like earthquakes, and sharing of data.
- Extend training of qualified engineers and scientists in the nuclear domain.

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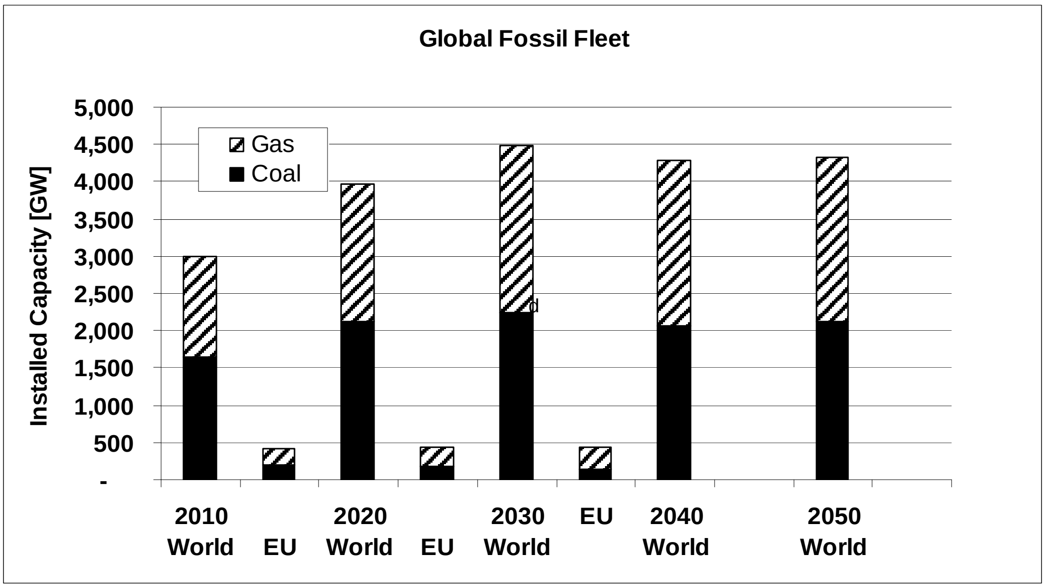
9. ADVANCED FOSSIL FUEL TECHNOLOGIES

9.1. Market evolution

Coal and gas fired power stations will likely remain in the European generation technology portfolio, with the latter having a higher potential if a safe and secure extraction of hydrocarbons from unconventional resources will become possible, even in scenarios with a very high share of RES-E generation[24]. Their role will be to provide backup in times of no supply from variable RES-E as well as flexibility in case of rapid supply and demand changes. The technology portfolio consists of continuously improved steam and gas turbines (and combinations thereof as e.g. CCGTs). On a worldwide level, fossil fuels are expected to remain the most important source of power generation representing more than 40% of capacity additions by 2035 and providing well over 50% of electricity in 2035[25]. Only 9% of these additions are expected to happen in the EU. Scenarios taking into account a decarbonisation of the European power system assume no more growth in global installed capacity post 2030 reducing the market to replacement installations which however remains significant. Roughly 1,300 GW of coal and 1,200 GW of gas plant capacity will be added between 2012 and 2035 representing about half of the then installed total capacity. The European and – to a lesser degree – the global fossil fuel mix are expected to continue shifting from coal to gas which is expected to overtake coal in terms of installed capacity by 2030.



Source: JRC elaboration on IEA WEO 2012, New Policies Scenario; IEA ETP 2012, 4DS[26]

9.2. Technology needs

Stream turbines for coal plants

[24] See e.g. EWI: 'Flexibility options in European electricity markets in high RES-E scenarios, Study on behalf of the International Energy Agency (IEA), Cologne 2012.

[25] World Energy Outlook 2012, New Policies Scenario, page 182

[26] IEA Energy Technology Perspectives 2012

Today, the majority of the European fleet of coal power stations still uses subcritical steam turbines that have thermal efficiencies of below 40% (LHV). No new deployment of this technology is expected in Europe apart from selected cases of retrofitting or reactivating mothballed stations. During the last decade[27], 92% of new coal plants in Germany and 53% of new coal plants in Poland were built using supercritical technologies reaching thermal efficiencies of 45% and 43% in case of hard coal and lignite fuel respectively. Outside Europe, subcritical technology still enjoys a market share above 50% of new builds in China, India and the United States.

The next evolutionary step in the development of steam turbines for coal power stations is to raise the steam temperature to 700°C achieving a thermal efficiency of up 50%. The 700°C technology necessitates the switch from iron-based to nickel-based alloys as only the latter are able to withstand the higher temperatures. A number of pilot projects to test components under real life conditions have been initiated within projects funded by the EU and member states, such as e.g. the COORETEC[28] program. The full commercialisation is not expected before the decade of 2020-30.

Integrated Gasification Combined Cycle (IGCC)

IGCC is a technology originally developed for the treatment of refinery residues and not with a focus on power generation. Worldwide, only 17 of the currently operating 137 IGCC plants[29] are used for power generation and only 6 of these use coal as their primary feedstock.

A number of new projects with a capacity above 500 MW, i.e. double the size of currently deployed plants, have recently been announced in Europe[30] but no final investment decision has been communicated so far. In the USA, one large scale project began test operation in 2012[31]. IGCC technology is currently disadvantaged by higher costs and the lack of a comparable experience (compared with the coal steam turbine plants). The prime objective of R&D is the demonstration of the commercial viability of this (otherwise mature) technology for power generation from coal.

Once the large scale deployment track for this technology takes off, an improvement of the power block would be a main target as current plants in general use less advanced gas turbines compared to state of the art combined cycle natural gas (CCGT) plants. A roadmap is currently developed by the European Turbine Network within the FP7 project H2-IGCC[32] with the aim of integrating most recent (H-class) gas turbines into an IGCC allowing a net thermal efficiency of up to 50%. A recent study by Shell[33], one of the leading providers of gasifier technology, suggests thermal efficiencies of 48.5% for new built projects.

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[27] Finkenrath, Smith, Volk: CCS Retrofit – Analysis of Globally Installed Coal-Fired Power Plant Feet, IEA 2012

[28] www.cooretec.de

[29] According to the US DOE database on gasification plants, located at www.netl.doe.gov/technologies/coalpower/gasification/worlddatabase/

[30] Christer Björkqvist, European Turbine Network-ETN, Progress Towards Implementation of IGCC-CCS in Europe, ICEPAG, 2010

[31] Duke Energy, Sustainability Report 2011-12

[32] www.h2-igcc.eu

[33] Prins et. al: Technological Developments IGCC for Carbon Capture, Chemical Engineering Technology 2012, 35, No3, p. 413-419

Gas/oil steam turbine power plants

Gas power plants with steam turbines have also been deployed in Europe mainly in the 1970s but their relatively low thermal efficiency of ca. 40% challenges their competitively against CCGTs or even open cycle gas turbines. This can be observed by decisions of some European utilities to mothball such units[34]. Plant manufacturers have moved to gas turbine technology since the 1990s.

Gas turbines and combined cycle gas turbine plants (CCGT)

Gas turbines have been used for more than 50 years, mainly for peak power generation but also in combination with combined heat and power systems. Investments in open cycle gas turbines are ongoing in Europe.

The CCGT combines two building blocks: a gas and a steam turbine. In current CCGTs, the steam is generated by the exhaust gases of the gas turbine. The deployment of combined cycle gas turbine power plants gained significant momentum in the 1990s when progress in materials allowed gas turbines to achieve temperatures exceeding 1500°C allowing this combined process. The performance of gas turbines and the CCGT plants using these turbines has continuously improved since then. Thermal efficiencies of gas turbines deployed in the 1990s are typically around 35%, resulting in a CCGT efficiency of up to 55%. Gas turbines of this type are still used for open cycle gas turbine applications today. Today's most advanced gas turbines have a power rating of 375 MW and thermal efficiencies of 46%, allowing CCGT efficiencies above 60%. The bulk of investment projects today however use improved F-class gas turbines resulting in slightly lower CCGT efficiencies of ca. 58%.

Research and development towards higher efficiencies is ongoing in different industrial initiatives. The goal for a CCGT is to reach a combined thermal efficiency of 63% by 2020. The future development of gas turbines is expected to take place in a competitive market environment including public R&D support as e.g. within the 'AG Turbo' or the US DOE gas turbine programme. Closely related to this are activities with the aim to adapt newest generation (H-class) gas turbines to syngas in IGCCs (see the abovementioned H2-IGCC-project).

9.3. Cost reductions

Steam turbines

Stable capital costs can be expected for new build steam turbines for both hard coal and lignite plants. The technology is mature and it shows a rather small learning rate of ca. 5% per doubling of capacity[35]. Improvement of technology (such as an increase in steam parameters) is happening incrementally and the rate of new deployment is relatively constant. As the global cumulated capacity of deployed coal plants (including all technologies such as e.g. IGCC) is expected to double by 2030, a 5% reduction in capital costs could be expected by then. Constant costs of 1700 $€_{2012}$/kW

[34] See e.g. the decision by Statkraft to mothball the Emden unit in Germany: http://www.statkraft.com/presscentre/press-releases/statkraft-adjust-generation-in-germany.aspx

[35] Junginger (Editor) et. al.: Technology Learning in the Energy Sector, Lessons for Policy, Industry and Science, 2010

and 1850€$_{2012}$/kW for coal and lignite respectively are however assumed for the European Union anticipating more ambitious environmental targets and taking into account a more expensive and highly qualified workforce.

IGCC

As the potential for improvement of the compound IGCC system is the result of the potentials of its components (gasifier, gas cleaning unit and power block), learning rates similar to CCGT technology, i.e. a 10% reduction of capital costs per doubling of capacity, can be assumed given similar components. Taking into account the very small installed base of plants today such a learning rate would lead to a significant cost reductions. Two scenarios are presented in Figure 9.1: the high cost scenario assumes an IPCC share of 5% of all new coal plants, the low cost scenario a share of 25% of all new coal plants by 2035. It is further assumed that learning would take place in a single investment wave starting past 2020. No further reduction in costs is assumed between 2030 and 2050. It can be seen that IGCC costs could fall below those of coal plants equipped with steam turbines however only if every fourth project would make use of this technology.

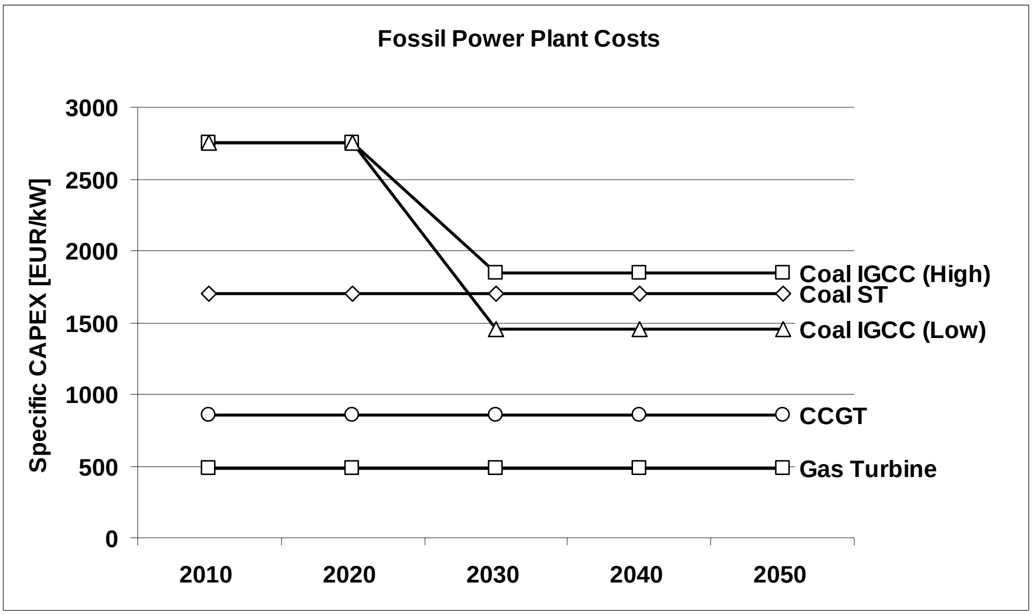


Figure 9.1: Capital cost trends for conventional fossil fuel power plants (Source: JRC estimates)

Gas turbines and CCGT

Large gas turbines suited for combined cycle plants are a mature technology but provided only by a limited number of European, American and Japanese manufacturers. Observed learning rates have stabilised at 10% per doubling of capacity after a phase of more rapid price declines observed in the 1990s[36].

The cumulated capacity of deployed gas fired plants (including CCGTs and OCGTs) is expected to grow in most energy scenarios. According to the New Policy Scenario of the IEA World Energy Outlook, the cumulated installed capacity will double by 2035. This would result in a cost reduction of 10% (on world markets). As in the case of steam turbines, constant specific capital costs are assumed postulating higher than average environmental requirements and higher labour costs for Europe.

9.4. Soft measures influencing deployment

Investment decisions by utilities as well as R&D decisions by manufacturers related to fossil fuel plants have so far been made purely on competitive grounds. Key drivers for future directions will be given by the commodity markets and energy system requirements, such as:

- Gas and carbon emission prices determining whether gas-fired plants will be designed for baseload, cycling or backup generation.
- The total system intermittency resulting from RES-E penetration levels and integration measures such as storage deployment, larger scale interconnection and demand response measures
- The total generation mix including the share of coal, nuclear and hydro power stations

The challenging business case for new build fossil power plants in markets with an increasing level of RES-E, depressed power prices and low running hours and a reduced investment appetite from the side of utility investors faced with strained balance sheets might lead to a lack of investments even in capacity that is needed from a system security of supply perspective. A number of Member States have started to address this problem by considering the introduction of capacity payments to plants and the European Commission has launched a public consultation on that matter[37]. A reform of power markets allowing both RES-E and conventional generation to compete on a level playing field will be one of the regulatory challenges for a high RES-E system.

All abovementioned barriers could be overcome by the end of the decade when demand for new generation capacity can be expected to pick up again and strong price signals for CO_2 would provide a competitive advantage to low carbon investments.

[36] Junginger (Editor) et. al.: Technology Learning in the Energy Sector, Lessons for Policy, Industry and Science, 2010

[37] http://ec.europa.eu/energy/gas_electricity/consultations/20130207_generation_adequacy_en.htm

10. MARINE (WAVE & TIDAL) ENERGY

10.1. Market evolution

Currently, the installed capacity of marine (wave and tidal) energy technologies on the global level is limited to few MW (excluding tidal barrage projects). These installations are demonstration projects. Table 10.1 gives an example of marine energy technologies installed in European waters.

Table 10.1: Examples of marine energy technologies installed in European waters

Developer	***Projects to date***
Pelamis Wave Power, UK	2 Units of 750 kW at EMEC, UK
Ocean Power Technologies, USA	2 Units of 40 kW in the USA and 150 kW unit is Scotland
Seabased, Sweden	Multiple 30 kW devices in Sweden
Aquamarine Power Oyster, UK	One unit of 315 kW and another of 800 kW at EMEC, UK
AW Energy WaveRoller, Finland	One unit of 300 kW in Portugal
Voith Hydro Wavegen, UK and Germany	One unit of 300 kW in Mutriku, Spain and 500 kW unit in the UK
WavEC, Spain	One WavEC Pico Plant of 400 kW in Azores
Dave Dragon, Denmark	One unit of 20 kW in Denmark
Wello Oy, Finland	One Penguin WEC unit of 500 kW at EMEC, UK

The installed capacity of marine energy technologies in the EU in 2020 will reach 2253 MW, according to the National Renewable Energy Action Plans: 1300 MW in the UK, 380 MW in France (including the 250 MW La Rance tidal barrage plant), 250 MW in Portugal, 100 MW in Spain, 135 MW in Portugal, 75 MW in Ireland, 10 MW in Finland and 3 MW in Italy.

In the longer term, it is estimated that marine energy would cover 5% of the EU power generation in 2050, i.e. approximately 250 TWh of marine energy electricity. Assuming that such plants operate on average during 3500 hours a year, the required installed capacity of marine energy in the EU could reach 71 GW in 2050. The 2030 installed capacity would be around 15 GW and the capacity in 2040 around 35 GW.

10.2. Technology needs

The potential of marine energy is undeniable. Wave and tidal energy can play an important role in Europe's future electricity supply as it relies on vast resources and a low-carbon footprint. Moreover, its development would contribute significantly to the economic growth of coastal regions, and represents an opportunity for the European industry for technology exports. Nevertheless, the very early stage of marine energy technologies implies that many technological challenges lie ahead.

Research has already led to the development of a wide variety of marine energy conversion technologies. This is an on-going effort and new concepts can be expected in the future. Many proposed systems have not yet been tested under real operation conditions. The evolution from design to lab and from lab to the water will allow a variety of technologies to compete and eventually to bring viable marine energy systems to the market. The priority of the sector is the demonstration of concepts, which should include testing of single units under real operation conditions, but also up-scaling to the array level. Accumulation of short- and long-term operation data, such as performance, component and system reliability, operating and maintenance needs, etc,. is a required input for design optimization and cost savings.

Europe is currently world leader in marine energy development and demonstration. This includes the development of marine energy conversion concepts, system design and engineering, and single- and multiple-device testing, aiming to demonstrate commercial viability. The European test centres, e.g. the European Marine Energy Centre (EMEC), the Wave Hub, the Biscay Marine Energy Platform (BiMEP) and the Danish Wave Energy Centre (DanWEC), are state of the art facilities. However efforts have to intensify to accelerate development and eventually deployment of marine energy in Europe.

According to CarbonTrust, the capital cost breakdown for a tidal energy device in a medium- or large-scale farm would be as follows: 30% for the rotor and power train, 25% for the structure, 16% for installation, 13% for off-board electrical equipment, 12% for generator and other on-board electrical equipment and 4% for design, engineering, management and insurance. The capital cost breakdown for a wave energy device in a medium- or large-scale farm would be as follows: 41% for the device, 17% for installation, 14% for transmission, 10% for decommissioning, 7% for moorings, 4% for commissioning, 5% for design, engineering and management and 2% for insurance. R&D activities to achieve cost reductions should focus on the components with the highest costs.

Another R&D priority for marine energy technologies is the increase of capacity factors. The capacity factor of current technologies is roughly around 2000 full operation hours a year. It is estimated that R&D and demonstration can increase annual operating hours to 3000 in 2020 and on the longer run a typical range would be 3500-4000 h/y. Once such capacity factors are achieved, the cost of generated electricity will decrease to levels that make the technology competitive with other low-carbon technologies. System viability is also very relevant as off-shore operation and maintenance is very costly. Hence, R&D needs to focus on this issue.

Accurate resource assessment is also necessary for the successful deployment of marine energy in Europe. There is a need for a high resolution, accurate European marine energy atlas, which should be updated regularly.

10.3. Cost reductions

The current costs of both wave and tidal energy are considerably higher than conventional and other renewable energy generation technologies. This is not surprising, given the early stage of technological maturity of these technologies, particularly since projects are constrained to demonstration of individual devices and thus there are very limited economies of scale. According to

CarbonTrust[38], the current costs are due to high uncertainties and lack of know how. The cost of devices decreases through deployment at choice sites or dedicated test sites. Reduction cost efforts are focused on new generation devices by means of increasing the energy yield in deeper waters and greater swept area per unit of support structure and foundation and per unit of capital costs and operating and maintenance costs.

Cost reduction in wave and tidal energy will be achieved through design improvement, optimizations in applied materials and mass production. These factors will lead to significant reductions in investment costs, increase of the capacity factor, higher reliability and extended lifetime.

At the current early stage, wave and tidal technologies still offer a wide variety of different designs. For instance, current wave energy converter technologies include the following types: attenuator, point absorber, oscillating wave surge converter, oscillating water column, overtopping, pressure differential, bulge wave and the rotating mass type, among others. Tidal energy converts include, among others: horizontal and vertical axis turbines, oscillating hydrofoil, enclosed tips, helical screw and tidal kite. In the future, it is expected that the current technological diversity on the R&D and demonstration level will crystallize to standard solutions with strong synergies so that significant cost reduction through the learning rate would be achieved with the increase in the cumulative installed capacity.

Figure 10.1 presents the cost reduction curve for wave and tidal energy during the period 2010 to 2050, based on JRC estimates.

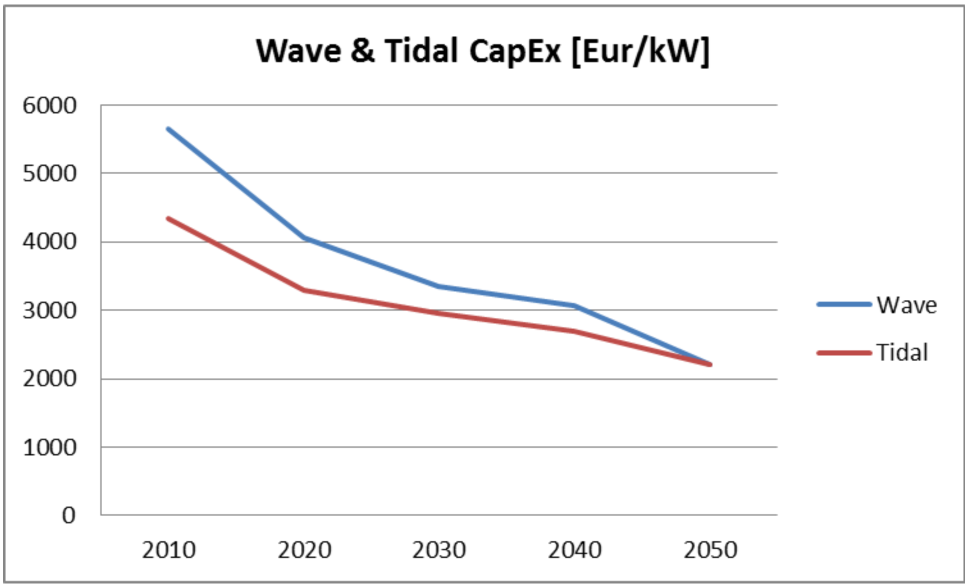


Figure 10.1: Estimated trends in capital costs of marine energy technologies

[38] Carbon Trust 2011, “Accelerating marine energy”, July 2011, http://www.carbontrust.co.uk /publications/pages/publicationdetail.aspx?id=CTC797

10.4. Soft measures influencing deployment

Once marine energy technologies are demonstrated, subsidies or feed-in tariffs will be required. These should target the acceleration of the deployment of marine energy technologies in Europe. This acceleration would bring cost reductions and lead eventually to the emancipation of the technology from financial support.

The deployment of marine energy in Europe will necessitate new infrastructure, such as the upgrade and extension of the grid and the building of ports and maintenance vessels. Thereby the synergies with other offshore energy technologies (offshore wind, offshore oil and gas platforms) have to be assessed and implemented, while the coexistence with other marine activities like marine transport and fishing should be harmonized. Legislative measures to provide the needed infrastructure, facilitate grid-connection and feed-in priority for marine power generation are also required as marine energy systems do not provide electricity on demand.

11. FUEL CELLS AND HYDROGEN

11.1. Market evolution

Commission roadmaps do not present penetration figures by 2030 and 2050 for fuel cell and hydrogen (FCH) technologies, nor is such information readily available from literature. Market evolution numbers are based on projections of the evolution of the energy, transport, industrial and residential systems, based on assumed scenarios towards a low-carbon economy. In these projections, FCH technologies, with zero CO_2 performance at the point of use and high energy efficiency, are recognized as essential contributors to the required decarbonisation in all economy sectors, yet deployment projections of FCH technologies have only been found in the IEA Energy Technology Perspectives[39]. The numbers in Table 11.1 comply with a scenario that ensures an 80% chance of limiting long-term global temperature increase to 2°C, and assume a high penetration of hydrogen (2DS hi-hy scenario).

Table 11.1: FCH projections according to the IEA 2DS hi-hy scenario

	2030	2050
Share of H2 in energy mix in industry sector (%)	0	7
Share of H2 in energy mix in buildings (%)	0	5
H2 as fuel for transport (%)	0	15
FCEV in passenger vehicle stock (%)	2	25

In addition to the applications listed in this table, hydrogen is expected to play an increasing role in large-scale energy storage in grids to balance the intermittent nature of renewable electricity. Projected market deployment figures for large scale hydrogen storage are not available at present.

The rate of progress in FCH technology deployment is complex as it varies across a range of technology applications and geographical regions with different policies and incentives for promoting market penetration. In the last years, fuel cell markets for stationary generation, backup power, and material-handling applications continued to expand as the operational effectiveness and efficiency of the technologies increases. Industrial interest is steadily rising for other applications where FCH technologies still need to improve performance and reduce cost to be competitive with the capabilities and cost of incumbent technologies. A 2012 McKinsey survey among EU stakeholders[40] identifies the following years for “major FCH applications to become commercial”:

[39] IEA, Energy Technology Perspectives 2012 – Pathways to a Clean Energy System
[40] Survey results on the trends in terms of investments, jobs and turnover in the Fuel Cells and Hydrogen sector – McKinsey, Oct. 2012

transport	cars	2015
	buses	2016
	material handling vehicles	2014
	auxiliary power units	2017
	refuelling stations	2015
energy	power generation	2016
	industrial CHP	2017
	domestic CHP	2017
	backup/UPS	2013
	portable	2015
H2 production	large scale electrolysis	2015
	from biofuels	2016
	from conventional fuels	2016
H2 storage	mass storage for electricity	2018

Respondents to the survey indicated that the expected turnover till 2020 will grow strongest in the area of hydrogen production and storage.

In line with these expected dates of commercialisation, industry has started transitioning away from primarily R&D-based to becoming commercial. In 2012 the global turnover for fuel cells and hydrogen has reached more than US$ 1 billion[41], up from US$300 million in 2005[42], with the highest growth in the stationary sector. The market is expected to be worth $15.7 billion in 2017[43], and a recent US study estimates that the global market could be between US$ 43 billion and US$ 139 billion annually over the next 10 to 20 years[44]. In the market segment with the highest visibility, namely passenger vehicles, a recent study[45] shows the following figures:

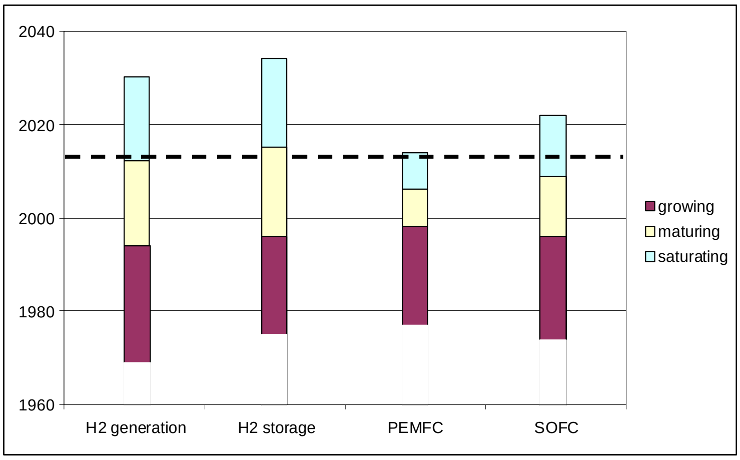
41 Pike Research, The Fuel Cells and Hydrogen Industries: 10 trends to Watch in 2013 and Beyond
42 2007 FCH JTI Impact Assessment
43 Pike Research, Fuel Cells Annual Report 2012
44 US DoE Hydrogen and Fuel Cells Program Plan, September 2011
45 Polymer Fuel Cells – cost reduction and market potential, Carbon Trust, Sept. 2012

	2020	2030	2040
Number FCEV EU	0.44-0.9 M (0.1-0.3%)	9.0-16.0 M (3.4-6.0%)	66.1-92.4 M (24.7-34.5%)
Number FCEV global	1.9-3.8 M (0.1-0.3%)	43-77 M (3.3-6.0%)	491-691 M (24.4-34.4%)
PEMFC market value EU	$bn 1.14-1.5	$bn 14.2-19.5	$bn 30.6-34.5
PEMFC market value global	$bn 4.1-6.1	$bn 68-94	$bn 231-261

11.2. Technology needs

FCH technologies are not stand-alone technologies, but performant enablers for energy generation, conversion and use processes in the power, transport and industrial sectors. Because of their cross-cutting application potential, and the associated need for including them in the relevant energy chains, it is very difficult to quantify the contributions of FCH technologies to the market trajectories for 2020, 2030 and 2050 of energy technologies covered in the SET-Plan.

As indicated above, commercial roll-out of a number of FCH technologies is expected in the 2015-2020 time frame. Evolution beyond 2020 is assessed through technology forecasting: integrating growth models with bibliometric analysis of publications and patent data available till end-2008, development curves (growing-maturing-saturating) obtained for "generic" FCH technologies are shown in the figure below[46].



In line with present experts' assessments of the status of FCH technologies, the analysis shows that fuel cells have progressed further in their development, whereas hydrogen production, and particularly hydrogen storage still have a way to go. Considering the model-extrapolated date for

[46] Chen et al., IJHE, 36(2011)6957-6969

reaching saturation, fuel cell technologies, resp. hydrogen technologies are expected to reach volume market penetration in the 2020, resp. 2030 time frame.

To achieve volume market penetration, the technology advances needed are both incremental and stepwise. Incremental performance improvements are required in electric conversion efficiency and durability of fuel cells and in efficiency of conventional hydrogen production, both for central and for distributed generation. For hydrogen transport and delivery, energy requirements for compression and/or liquefaction should decrease and material compatibility issues addressed. To reduce costs, these incremental performance improvements must be accompanied by the establishment of large-number manufacturing capabilities.

Step-increases in capacity and performance are needed for hydrogen production methods. This covers the application of CCS to production from fossil fuels, biomass gasification, new emission-free production processes such as low temperature solar, fermentation and photo-electrochemical processes, as well as efficient MW-size electrolysers for intermittent large-scale hydrogen production from excess renewable energy. Also for on-board hydrogen storage incremental progress is unlikely to be successful: novel on-board storage technologies (hybrid gas and solid state, cryocompressed) are needed for meeting costs and energy density targets in order for FCEVs to become fully competitive with future efficient passenger cars.

With maturity of FCH technologies expected to be reached in the 2020-2030 time frame, moving towards the 2050 deployment status will primarily depend on a timely and successful integration of hydrogen and fuel cells in appropriate locations of the energy, transport and industry chains, and in their contribution in facilitating the interconnection of these chains (e.g. power2gas). The identification and exploitation of the integration potential of FCH technologies in linking these chains require a regionally-diversified systems approach and consideration and exploitation of other technologies, in particular ICT.

11.3. Cost reductions

Cost reductions go hand in hand with progress in performance and with technology learning. In terms of efficiency, durability, safety and emissions, FCH technologies are already competitive with incumbent technologies in a number of applications. However, notwithstanding considerable progress over the last years, cost-competitiveness has not yet been achieved and cost reduction is now a major driver in technology development. Expected cost evolutions for major FCH technologies compiled from different sources are shown in Figure 11.1. The projected cost reductions are related to incremental technology performance improvements in efficiency and durability and level off as technology maturity is reached. Cost reduction factors of 2-3 from the current level are expected, with further cost decreases relying on large-number manufacturing. Cost projections cannot be included for technologies which still require a step-increase in capacity and performance.

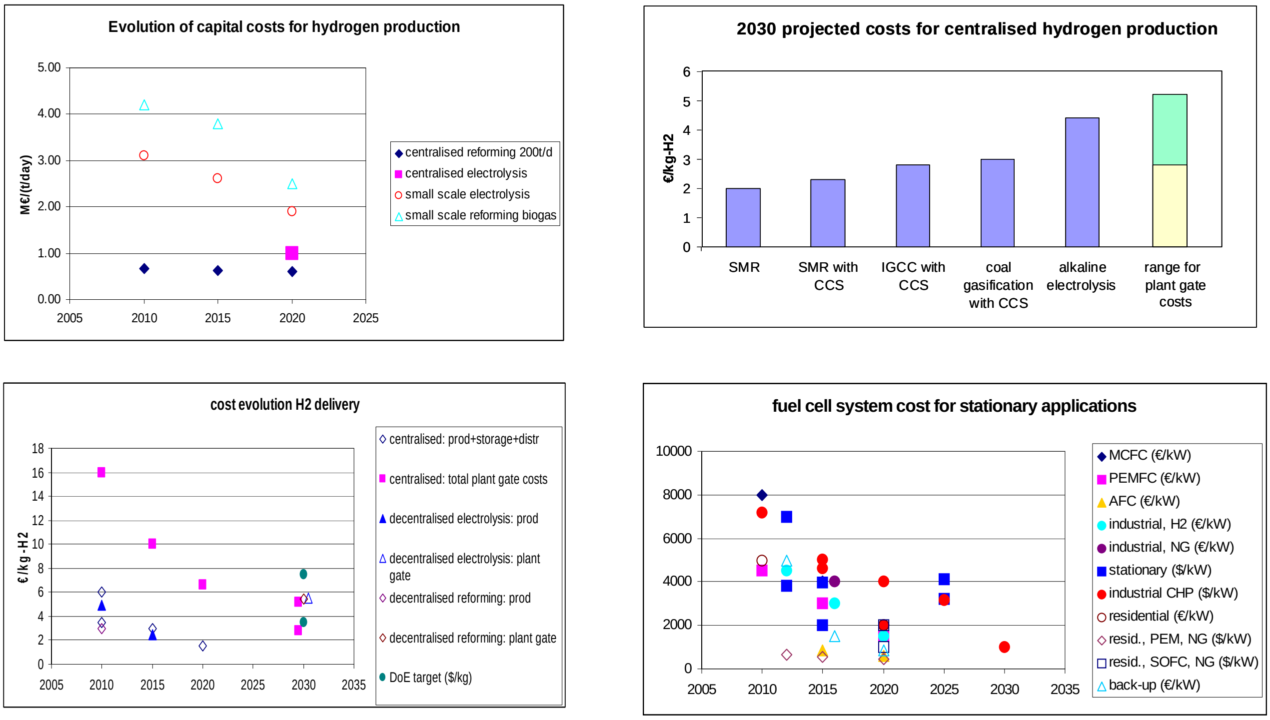


Figure 11.1: Trends in cost reductions for FCH technologies

11.4. Soft measures influencing deployment

Accompanying measures, in addition to support for research, development and technology innovation, are needed to address barriers and/or challenges faced by FCH industries, which lie at four main levels:

- The potentially huge environmental and energy security benefits of FCH applications accrue to society at large and are difficult to be monetized by individual technology providers and consumers.
- FCH technologies must compete globally with well-established incumbent technologies. Continued cost reduction for enlarging market share requires significant investment in advanced manufacturing processes. Consequently the financial risk for early movers is high and lack of cash-flow during the first phase of deployment is to be expected.
- The FCH sector is dispersed across different activity areas (energy, transport, industry, residential), actors and countries, which hampers the build-up of critical mass needed for self-sustained commercial activity.
- Mass volume deployment of FCH technologies beyond 2030 critically depends on their timely and successful integration in energy, transport and industrial chains. In particular, the deployment of large-scale hydrogen storage within the power generation system is considered very challenging.

Market forces alone are insufficient to overcome these barriers. Hence a purpose-oriented coherent framework consisting of tailored and time-phased actions, policies and incentives that target public and private market actors, is needed. The following components of such a framework can be identified:

- Globally harmonised standards and regulations to ensure safe, compatible and interchangeable technologies and systems. This will also contribute to cost reduction.
- Increased awareness among the public, among private and public actors in the energy, transport, industrial and residential sectors, and among policy-makers at local, regional, national and EU level, of the performance potential and societal benefits that hydrogen as flexible energy carrier and fuel cells as modular and highly efficient energy converters offer over incumbent technologies.
- Policy measures that value the societal benefits and ensure a level playing field enabling the uptake of FCH technologies, including public financial support, in particular for infrastructure development in the energy and transport sectors.
- Improved alignment of views and coordination of activities of private FCH stakeholders and public institutions, aiming at equitable risk-sharing particularly in the stages of initial commercial roll-out.
- New business models that allow the deployment of large scale hydrogen storage in future smart-grid based energy systems

12. ELECTRICITY STORAGE TECHNOLOGIES

12.1. Market evolution

The market for electricity storage can be broadly divided in two segments: *large scale storage* used for energy time shifting on transport grid level and *decentralised* storage supporting services on distribution grid level. Currently, the market is comprised mainly of the first segment which is dominated by the mature technology of pumped hydro. The equally mature compressed air energy storage (CAES) has not yet been deployed on a large scale. Roughly 42 GW of pumped hydro storage are currently installed in Europe (EU combined with Switzerland, Norway and Turkey)[47] with an additional capacity of 5.5 GW under construction.[48] Only two CAES facilities exist worldwide of which one is located in the EU (Huntorf, Germany build in 1978); and the second one was built in Alabama, USA in 1991. Three new grid scale CAES projects, one of which in the EU are in an advanced state of development or have secured financing. The potential for new pumped hydro or compressed air energy storage in Europe could be more than four times the current capacity[49]. Market needs however are likely to be smaller if competing sources of flexibility are taken into account: studies see an additional 50% [50] to 100% of installed capacity by 2050[51] i.e. 20 – 40 GW of additional bulk storage for Europe.

The currently less developed market for decentralised storage technologies such as batteries is driven by developments on the level of power distribution and consumption. A trigger for the mass deployment of (Li-ion) batteries would be the electrification of road transport. This could make battery storage available for grid applications: both directly in the form of vehicle-to-grid concepts or in form of grid-connected Li-ion (or more conservative lead acid) batteries. Other \technologies such as NaS batteries, Redox-flow batteries, or flywheels are currently deployed in pilot projects competing with lead-acid and Li-ion systems for provision of grid services. Even though *hydrogen* does not play a significant role in the current electricity system, it offers the broadest spectrum of potential applications of all storage technologies: from stand alone systems comprised of electrolysers and fuel cells to an integrated power-to-gas concept allowing the transport and storage of wind energy from coastal regions to the inland consumption centres [52].

12.2. Technology needs

Pumped Hydro storage

Pumped hydro storage, as well as hydropower in general, is a mature technology, now used for more than 100 years. It is the only storage technology deployed on a large scale today.

Compressed Air Energy Storage (CAES)

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[47] Eurelectric: Hydro in Europe, powering renewables
[48] Source: Platts
[49] The STORE project identifies 180 GW of additional PHS capacity in Europe, www.store-project.eu
[50] EWI: 'Flexibility options in European electricity markets in high RES-E scenarios, Study on behalf of the International Energy Agency (IEA), 2012.
[51] Eurelectric Power Choices
[52] See e.g. the Power to Gas Initiative launched by the German Energy Agency dena: http://www.powertogas.info

CAES is a technology made of mature building blocks. The concept is based on the compression of air by means of electric energy, storing the compressed air in an underground cavern and expanding the air, now mixed with natural gas in a combustion chamber to drive a gas turbine. Alternatively, in an adiabatic CAES, the expanding air recovers the heat generated during compression from a thermal storage so no natural gas is needed in the process. Demonstrating the Adiabatic CAES on large scale is the main R&D target for this technology. The ADELE project (located in Stassfurt, Germany) aims at developing a 360 MW generation plant with 3h of storage.

Batteries

Storage in form of electrochemical batteries is occasionally deployed in electricity grids, mainly for short time action such as frequency control. There is a large variety of mature to innovative technologies that can be classified by their chemical composition. The most prominent of these are:

- Lead-acid batteries are a mature technology mainly found as starter batteries in car. This technology is increasingly deployed for power grid applications such as capacity firming or spinning reserve. The main R&D goal is to improve the lifetime in terms of discharge cycles.
- Li-ion batteries represent the state of the art in small rechargeable batteries. They are widely used in consumer electronic devices, such as computers, digital cameras, and cell phones, as well as military, space and electric vehicles. Recently, Li-ion systems in the range of up to 1 MW have been installed by ENDESA to provide frequency control in the Canary Islands[53].
- NaS batteries are used for stationary grid applications. A system with 1MW is currently tested in the Pegase demonstration project on Reunion Island, launched in 2011. The aim is to provide mainly frequency control to a system with a high share of PV and wind power generation.
- Flow batteries (Zn-Br, Vanadium Redox) separate the electrolyte from the cell stack and thus decouple the power system from the energy capacity. The storage capacity can be increased by adding more electrolytes allowing discharge rates of up to 10 hours. This technology could therefore also be a candidate for time shifting services. A total of [54] demonstrator projects[55] have already been deployed in Europe, the US, Japan, Australia with 7 more projects to be realised, all of them located in the USA.

Hydrogen

R&D measures focus on the entire hydrogen value chain. The main goals are the demonstration of feasibility, optimisation of possible concepts and most important the achievement of cost competitiveness. Further details are given in the chapter on hydrogen and fuel cell technologies.

Flywheels

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[53] http://www.endesa.com/en/saladeprensa/noticias/Documents/agosto12-Proyecto%20Store1%20(DEF)-en.pdf
[54] Source: Bloomberg New Energy Finance
[55] Source: Bloomberg New Energy Finance

Flywheels for electricity grids are currently a niche technology. They store energy in mechanical form, i.e. in rotating masses. With storage capacities typically in the range of 15 min and almost immediate response capability, they are suitable for frequency control. One particular application is in small or remote power systems with intermittent RES-E. Endesa initiated the construction of a flywheel in the Canary Islands with a maximum power of 0.5MW providing 18MWs of energy as a complement to the abovementioned Li-ion storage project.

Other storage technologies

Further storage technologies are superconducting magnetic energy storage and super capacitors. The first technology stores energy in magnetic, the second in electric fields. The advantage of both technologies is to store electricity directly allowing very fast response times. Those technologies are in early phases of demonstration.

12.3. Cost reductions

The Figure 12.1 shows the current range of costs (in €/kW of rated power) for storage technologies in different stages of maturity distinguished between power generation, transmission & distribution and end-user application. Additional costs (not shown in the Figure) arise from the energy reservoir of the storage and are given in €/kWh. Costs for mature technologies are rather well understood while technologies that were only occasionally deployed in the past or are in different stages of demonstration phases bear a high level of uncertainty.

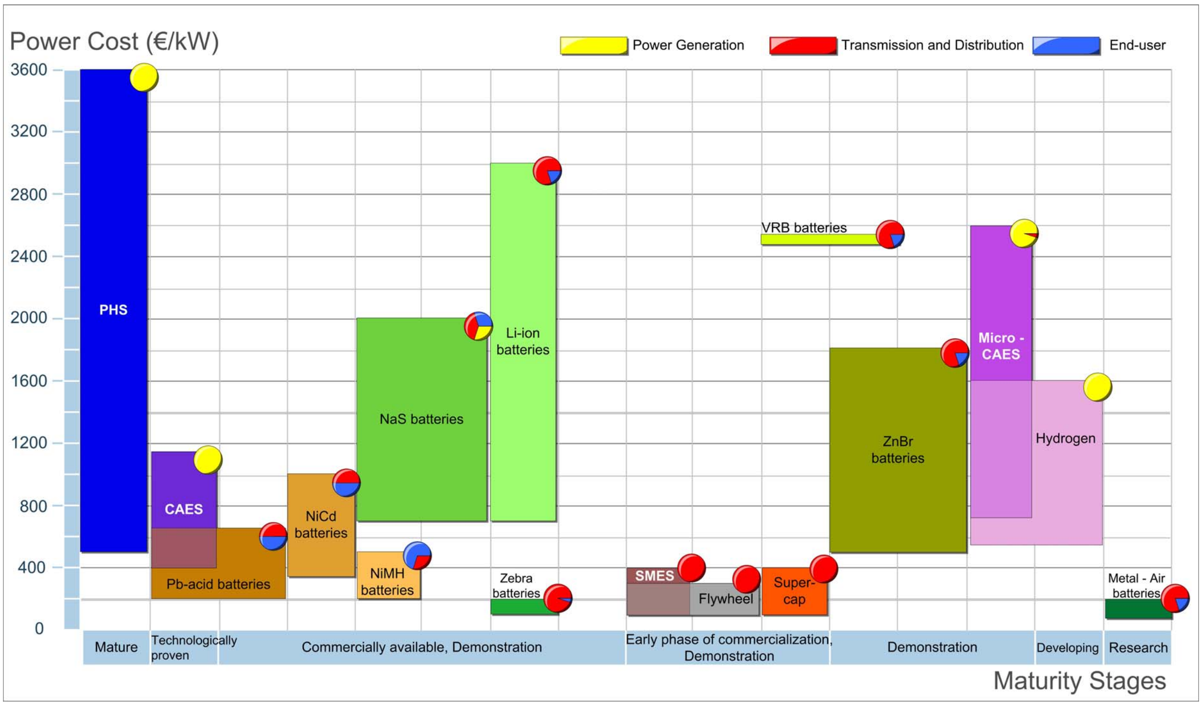

Figure 12.1: Cost of storage technologies. Source: SETIS Technology Map – 2011 update

Pumped Hydro storage

Costs for pumped hydro stations are in the range of 500 -3600 €/kW for the power production equipment and 60 – 150 €/kWh for the reservoir. The large range is given by costs of civil works which may vary depending on the geographical conditions. Stable costs can be assumed as this is a mature technology.

Compressed Air Energy Storage

The costs of this technology are given by the compressor and turbine and the excavation of the storage cavern. Estimates range between 400 - 1150 €/kW for the power conversion unit and 10 – 120 €/kWh for the storage unit. All components of such a system are mature today, however the system integration may leave room for cost improvements over time.

Batteries

Lead-acid batteries are the most economically attractive technology for decentralised storage with power costs of 200 - 650 €/kW and energy costs of 50 - 300 €/kWh. The maturity of the basic concept and the dependency on lead as a commodity leaves room for cost reductions mainly in the power electronics block so assuming constant cost would be safe.

With power costs of 700 – 3000 €/kW and energy cost of 200-1800 €/kWh, Li-ion batteries cost more than double than lead-acid batteries with estimates spreading widely. Prices are set on a highly competitive market. Some financial analysts see prices to fall to the lower end of the range implying current overcapacities and anticipating a shakeout resulting in a further market consolidation[56].

As NaS batteries, flow batteries, hydrogen systems and flywheels – while commercially available - are currently restricted to a very limited market.

12.4. Soft measures influencing deployment

R&D support for storage technology

Direct financial support would help develop less mature technologies and unlock their untapped technological potential. Different storage technologies are not necessarily in competition with each other if they are able to provide different services and in particular if they can be used in different value chain steps of the power system, The dynamic evolution of the future power system including more intelligent and complex distribution networks could benefit from a portfolio of storage technologies. For this reason an equal and fair support to less mature technologies according to cost-efficiency criteria could be beneficial for the development of technologies.

Support to large scale storage investments

In the current environment consisting of depressed demand, relatively low commodity and carbon prices and an increasing supply of RES-E, the arbitrage business case faces severe challenges such as investments in peak power generation in general. Also lower prices for natural gas over longer time periods could challenge the time shifting business as storage competes with gas turbines for a number of services. The currently strained finances of some potential investors combined with a regulatory framework that does not always recognise the role of storage in the transition to a decarbonised power system, are a major barrier to the deployment of this technology. For this reason direct support to investments, together with the setting up of market mechanisms to recover investments, e.g. capacity payments, could lower

[56] http://www.rolandberger.com/media/pdf/Roland_Berger_Li_Ion_Batteries_Bubble_Bursts_20121019.pdf

the burden for investment decisions. A number of Member States have started to address this problem by considering the introduction of capacity payments to plants and the European Commission has launched a public consultation on that matter[57]. Moreover, revisited RES-E incentive schemes that adapt dynamically with progressive high RES deployment and take power system needs into account could be an additional measure.

Competition of storage with other solutions

Storage is one of several instruments able to provide flexibility to a system with a high share of RES-E. It competes with other technologies such as flexible fossil fuel generation, demand-side response technologies, grid extension allowing power flows over larger regions, or a non usage of some of the excess RES-E as anticipated by a number of studies on systems with a very high degree of RES-E[58]. **C**ompetition in this sector is a source of efficiency, which would benefit from a level playing field for the different technologies. Market distortions, resulting from support of particular technologies to the detriment of others bear the risk to promote and perpetuate sub-optimal technological solutions..

Regulatory ambiguities

One particular challenge originates from the fact that storage can provide a number of different services for both generation (e.g. peak shaving through arbitrage) and transmission (e.g. reserve power, congestion management). Storage thus falls into both the regulated and the unregulated domain of European energy markets. The risk that storage installations providing services to the regulated domain would act as a non-regulated agent (and vice versa) has been identified and addressed by different stakeholders[59]. Adequate measures for promoting storage need to be created if such conflicts of interest are to be avoided, in particular: regulate potential cases of abuse of asymmetric information e.g. from transmission and distribution system operators, and guarantee the unbundling of the power system.

[57] http://ec.europa.eu/energy/gas_electricity/consultations/20130207_generation_adequacy_en.htm
[58] See e.g. abovementioned EWI-IEA study
[59] See e.g. http://www.eurelectric.org/media/53340/eurelectric_decentralized_storage_finalcover_dcopy-2012-030-0574-01-e.pdf

13. ELECTRICITY NETWORKS TECHNOLOGIES

13.1. Market evolution

The electrical network is usually divided into the longer distance and higher voltage transmission network and the medium distance and lower voltage distribution network. In this framework, the synergies in the evolution towards a smart distribution grid and to a smarter transmission network are crucial, considering the steep changes to occur at distribution level, simultaneously with the introduction of new technologies and the development of further interconnections at transmission level. Therefore, in order to take advantage of those synergies, the coordination of their evolution is crucial.

Advanced electricity networks not only allow for a higher intake of variable RES generation, but also entail an increase in energy efficiency, thanks to the effective integration of ICTs. Smart grids provide, in this framework, critical options for the development of the present and future European energy infrastructure[60]. Advanced electricity networks will require the deployment of many different technologies: from power electronics to communications protocols. Smart meters, which provide utilities with a secure, two-way flow of data, are a key component for smart grids, but alone do not assure its development.

Furthermore, it is worth noting that electricity networks should be considered in the context of the relative markets and the various stakeholders interconnected. Smart grids support the development of the electricity markets, enabling the unbundling of the operators, providing more capable cross-border links, and supporting the involvement of all the stakeholders, down to the consumer/prosumer level. Moreover, they create establish a platform for the existing and future entrants in the market to develop innovative energy services.

The evolution of electricity networks in the next decades will be determined by several factors (which at the same time will be enabled by suitable networks):

- the deployment of sustainable energy resources, given that the share of renewable energy sources (RES) in EU-27 gross power generation is expected to more than double, from 14.3% to 36.1%, between 2005 and 2030;
- the optimal integration of distributed generation (DG), distributed energy storage systems (DESS) and demand side management (DSM) systems.
- the integration of electric vehicles (EV), their magnitude in terms of load and general energy consumption, and their potential use as a storage medium

13.2. Technology needs

In terms of the several components for smart grids, the maturity of the industrial proposals has been expanding in the last few years. The most immediate challenges are: 1) the smart integration of distributed renewables and the empowerment of open and dynamic retail and services markets at the distribution level, and 2) the reliable long-distance transport and balancing of massive amounts of renewable electricity at the transmission level. From the viewpoint of technologies, the following appear to play a decisive role:

1. Technologies for long-distance connections, including High Voltage Direct Current (HVDC) grid technologies. HVDC, has advantages over high voltage alternating current in terms of long distance and underwater transmission, featuring few losses, increase in transmission capacity, quick change in power flow direction, and no increase of short-

[60] European Commission, 2010a. COM(2010) 677 final - Energy infrastructure priorities for 2020 and beyond - A Blueprint for an integrated European energy network, European Commission, 2010.

circuit power at the connection points. HVDC, both point-to-point and the under-development multi-terminal HVDC, are building blocks needed for the development of future electricity networks, enabling e.g. offshore wind farms.

2. Technologies for increasing the controllability of the networks, including Flexible AC Transmission Systems (FACTS), which are advanced power electronics devices that allow increased efficiency at several levels (e.g., transmission capacity, power flow control, losses reduction, voltage support). FACTS, already in use in transmission lines, are in the process of being deployed also at distribution level under the designation of D-FACTS or Custom Power. In terms of synergies between technologies, the case of the joint deployment of energy storage and FACTS is well documented. This synergy allows the optimization of the power transfer capacity ratings and higher flexibility in the network.

3. Technologies for enabling new grid and consumer-driven services, including:

    a) ICT/telecom networks, essential for the deployment of smart grids, since they empower the effective communication between all interconnected actors and components. It includes telecommunication and remote control technologies, centralised or decentralised data management systems and solutions for the processing of metering data. An enhanced data exchange, with dedicated ICT platforms supervising the information flows between the electricity system players, may strengthen the capabilities for fault prevention, asset management, generation control and demand side participation, among others.

    b) Smart metering, which empower both distribution utilities and producers-consumers (prosumers), who can gain greater awareness of their consumption and generation. Positive results are more efficient consumption, e.g. benefiting of real time price responsiveness, and in load shifting according to the needs of the power system. Installation of smart meters coupled with Demand Side Management (DSM) enables the rationalisation of energy consumptions, supporting a more responsive and flexible load. DSM will play an important role in load shifting and peak shaving; it demands bidirectional communication and a partial control of some of the customer resources, usually heavy loads. The deployment of DSM is an important step for the economically sustainable power balancing of the future smart grids, particularly in extreme situations.

4. Future planning, operation and maintenance approaches, including:

    a) Innovative smart grid architectures such as active distribution networks, microgrids, and virtual power plants. These have different characteristics, which may overlap sometimes. Active distribution networks, including microgrids, include DG, ICT technologies, distributed energy storage, appropriate protection schemes, power electronics, such as D-FACTS, and demand side management. Microgrids present black start capability and/or intentional islanding mode features. Virtual Power Plants (VPP) can be divided in two subtypes. The technical virtual power plant (TVPP) uses resources either physically connected by the local distribution network or located in the same geographical area. The commercial virtual power plant (CVPP) integrates resources that can be more dispersed, and that may even be linked to each other only at transmission level, being thus housed in separate distribution networks.

    b) Technologies and business processes for the integration of Distributed Generation (DG), renewable electricity, demand response, storage and electric vehicles, including new market architectures, and off-line tools for forecasting, asset management, grid development planning, development of emergency responses and training of operators. This should include relevant standards to ensure interoperability. Of relevance will be multi-energy grids (e.g. interconnecting electricity, gas, heat). DG's output is not constant as it may vary with natural resources changes or with the thermal output desired for combined heat and power (CHP) systems.

13.3. Expected cost and benefits

The evolution of the power networks in support of the European strategy towards a low-carbon energy future will require significant investments. Given the economic potential of the Smart Grid and the substantial investments required, there is a need for a methodological approach to estimate the costs and benefits of Smart Grids, based as much as possible on data from Smart Grid pilot projects.

The Commission 'Proposal for a Regulation of the European Parliament and of the Council on Guidelines for Trans-European Energy Infrastructure' (Com/2011/658) proposed as one of the criteria of eligibility for Smart Grid projects their economic, social and environmental viability, which calls for a definition of a comprehensive impact assessment methodology, including a CBA. The survey on Smart Grid projects across Europe carried out by the JRC in 2011 and 2012 concluded that there are only a few projects that have conducted some form of CBA. Though many studies have touched upon the subject of Smart Grid benefits, it is difficult to find studies which have attempted to develop a systematic approach to the definition and evaluation of the costs and benefits of Smart Grid projects and which have tested their approach on real case studies.

While some projects may not have shared their data for confidentiality reasons, many others simply did not have such data because a detailed CBA was beyond the scope of the project, which often predominantly focused on evaluating technologies, applications and solutions. Another reason may be the lack of an established CBA methodology for Smart Grid projects. For that reason JRC issued in 2012 "Guidelines for conducting a Cost-Benefit Analysis of Smart Grid projects".

This lack of formal evaluation of Smart Grid projects based on their investment needs and resulting benefits has been linked to three main reasons[61]:

- Smart Grid projects are typically characterised by high initial costs and benefit streams that are uncertain and often long term in nature. In fact, many Smart Grid benefits are systemic in nature, i.e. they only come into play once the entire smart electricity system is in place and new market players have successfully assumed their roles.
- Smart Grid assets provide different types of functions to enable Smart Grid benefits. A variety of technologies, software programs and operational practices can all contribute to achieving a single Smart Grid benefit, while some elements can provide benefits for more than one Smart Grid objective in ways that often impact each other.
- The active role of customers is essential for capturing the benefits of many Smart Grid solutions. Especially at this early stage of the Smart Grid development, consumer participation and response are still uncertain and relevant behavioural information (e.g. load profiles) is often not (yet) accessible to utilities.

[61] Jackson, J., 2011. "The Utility Smart Grid Business Case: Problems, Pitfalls and Ten Real-World Recommendations". Prepared for the 2nd Annual Evaluating the Business Case for Smart Grid Investments, 20-21 October 2011, Orlando, US

13.4. Soft measures – How to overcome the barriers to large-scale deployment

Whilst the smart grids deployment is at its first stage in Europe, stakeholders and market players perceive multiple uncertainties and barriers.

Standards are crucial for the evolution of the market of electricity networks. It is expected that the common European framework that will result from the mandate M/490, given by the European Commission to the European Standardization Organisations CEN, CENELEC and ETSI, will establish or update a set of consistent standards. This framework should integrate a variety of digital computing and communications technologies and electrical architectures, and associated processes and services, achieving interoperability and enabling or facilitating the implementation in Europe of the different high level Smart Grid services and functionalities. Resulting from the mandate M/490, the standardization bodies developed a technical reference architecture, a first set of Use Cases mapped against standards, and a first set of consistent standards. These standards (with reference to 24 types of Smart Grid systems, including more than 400 standard references, and coming from more than 50 different bodies). are a key step for the deployment of smart grids in Europe.

Technically, now that standards have been identified, there is an increasing need for the demonstration of the interoperability among the several components constituting a Smart Grid. From the smart meter, to the interaction between electricity grid and electric vehicles, full interoperability will ensure that any new device can be integrated into the Smart Grids system.

The regulatory framework is also perceived as a significant barrier to the large scale deployment of smart grids: it is generally agreed that a stable and predictable regulatory context would allow, among others, the development of a sound financing environment for smart grid initiatives. This would also pave the way for new business models involving wider participation of consumers and prosumers in the market. Uncertainty and the need of building confidence in future business models may therefore be another consequence of a regulatory framework that presents space for a future inclusion of smart grid features. Moreover, it is possible to identify a debate arising amongst several market stakeholders concerning the control of the different assets involved. Furthermore, regulation can also mitigate the impact of high level initial costs, which hinder the short term deployment of smart grids, due, among others, to the traditional conservative approach from utilities. To solve this issue a more secure investment environment for utilities with long-term quantifiable benefits, including revenues coming from grids enhancement, would be helpful.

Social barriers, besides technological and regulatory barriers, aggravate the general situation. On one hand, there is a need for information about smart grids and their features that can trigger consumer awareness and engagement, which in turn can enable faster and more effective deployment of smart grids (as an exemplary initiative, a smart grid contest was launched in 2011 to “accelerate and encourage open innovation and build up the international Smart Grid community”). On the other hand, concerns about consumers’ protection, both in terms of privacy and security need to be taken in consideration. The expected roll out of extensive smart grid programmes in Europe calls for a continuous development of skills and knowledge, through a wide and effective communication to the public and the workforce. Finally, efforts in overcoming the barriers perceived would be vain without coordination among all the actors involved (policy-makers, researchers, industry and finance players, consumers).

14. ENERGY INTENSIVE INDUSTRIES

Technology developments can assist the European energy intensive industry to reduce its energy consumption and carbon footprint. This chapter focuses on three important European industries, the iron & steel, the pulp & paper and the cement sectors. The greenhouse gas (GHG) emissions from the iron and steel industry during the period 2005 to 2008 on average amounted to 252.5 Mt CO_2 eq. In 2008 the CO_2 emissions from the pulp and paper and in the cement industry amounted to 38 Mt and 157.8 Mt CO_2, respectively. The emissions of these three energy intensive industries represented 9% of the total CO_2 emissions of the EU, or 44% of total CO_2 emissions of the industry sector.

14.1. Market evolution

14.1.1. The iron and steel industry

There are two main routes to produce steel. The first route is called the "integrated route", which is based on the production of iron from iron ore. The second route called "recycling route", uses scrap iron as the main iron-bearing raw material in electric arc furnaces. In both cases, the energy consumption is related to fuel (mainly coal and coke) and electricity. The recycling route has significantly lower energy consumption (by about 80%).

The "integrated route" relies on the use of coke ovens, sinter plants, blast furnaces and basic oxygen furnace converters. Current energy consumption for the integrated route is estimated to lie between 17 and 23 GJ per tonne of hot-rolled product. The lower value is considered by the European sector as a good reference value for an integrated plant. A value of 21 GJ/t is considered as an average value throughout the EU. The "recycling route" converts scrap iron in electrical arc furnaces. Current energy consumption for this case is estimated to lie between 3.5 - 4.5 GJ per tonne of hot-rolled product. The lower value corresponds to a good reference plant. The higher value corresponds to today's average value within the EU.

Alternative product routes to the two main routes are provided by direct-reduced iron technology (which produces substitutes for scrap) or the smelting reduction (which like the blast furnace produces hot metal). The advantage of these technologies compared with the integrated route is that they do not need raw material beneficiation, such as coke making and sintering and that they can better adjust to low-grade raw materials. On the other hand, more primary fuels are needed, especially natural gas for direct reduced iron technology and coal for smelting reduction.

The growth of the EU27 iron and steel production can be estimated to be 1.18% per year up to 2030. This would imply a production of around 260 Mt crude steel in 2030. The increase in the production is estimated to be covered mainly by an increase in the recycling route. The production from the integrated route will stay around their current values.

Today, over 40% of steel is traded internationally and over 50% is produced in developing countries. In 1998, the EU was responsible for 23% of global steel consumption, whereas in 2008 its share in consumption had dropped to 16% due to the increase in the demand for steel in the developing countries (i.e. China, India and Russia). Apparent crude steel consumption in the EU increased at an average rate of 2% in the period of 2000-2008, but it fell drastically in 2009 by around 30% due to the financial crisis. The production of crude steel in the EU in 2008 was 198 Mt, representing 14.9% of the total world production (1327 million tonnes of crude steel). Ten years earlier, with a slightly lower production (191Mt crude steel), the same European countries accounted for a 24.6% share. The main difference is that the Chinese production grew more than fourfold over this period (from 114 Mt to 500 Mt crude steel).

14.1.2. The pulp and paper industry

There are two main routes to produce different types of pulp: from virgin wood or from recycled material. The pulp produced in either way is subsequently processed into a variety of paper products. For virgin pulp making, two main kinds of processes are used – chemical and mechanical pulp making.

Recycled fibres are the starting point for the recycling route. Europe has one of the highest recovery and utilisation rates of fibres in the world (66.7% in 2008[62]). There are large variations on the energy profiles for different technologies. Raw wood use differs by almost four times between the different paper grades, and energy use differs by a factor of two. However, in general terms, it can be said that mechanical pulp making is more electricity-intensive and less heat intensive than chemical pulping. The electricity/steam consumption ratio at paper mills enables an efficient use of co-generation of heat and power (CHP). Nowadays its electricity production amounts to almost 46% of its electrical consumption.

Specific primary energy consumption in 2008 was 13.4 GJ/t, based on the overall totals of energy and production data, this specific consumption includes 2.04 GJ/t of specific net bought electricity. Half of the energy used by the industry (54.4% in 2008) comes from biomass and approximately 38% from natural gas.

In a business-as-usual scenario, there is still some room for improvement because the average values of the 10% of best performers (benchmark levels) have 50% and 30% lower specific CO_2 emissions than the highest values and the average, respectively. However, tapping this potential improvement requires the replacement of today's machines by new ones. However, due to the high cost of new machines, this will take time and is dependent on machine age, investment cycles, sector developments and availability of capital. The prime candidates for improvements are the boilers followed by the most energy-intensive part of the paper production, the drying of the paper.

In 2008, the EU paper and board production (reported by the 19 CEPI-associated countries[63]) accounted for 25.3% (98.9Mt) of world production (North America 24.5% and Asia 40.2%). Europe also represents about 21.6% (41.6 Mt) of the world's total pulp production. From 1991 to 2008, the EU pulp and paper production (in CEPI countries) had an average annual growth of 0.4% and 1.9% for pulp and paper respectively, whereas the number of pulp and paper mills has decreased around 40%. This process of consolidation of the sector has led to fewer and larger companies with a large number of relatively small plants specializing in niche markets. Overall, the pulp and paper sector keeps growing at a steady pace with a changing product mix and new grades developing as a

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[62] Recycling rate: "Recovered Paper Utilization + Net Trade", compared to Paper and Board Consumption

[63] CEPI is the Confederation of European Paper Industries (CEPI), and its mission is to promote the member's business sector by taking specific actions notably, by monitoring and analyzing activities and initiatives in the areas of industry, environment, energy, forestry, recycling, fiscal policies and competitiveness in general. Its associated countries are: Austria, Belgium, Czech Republic, Finland, France, Germany, Hungary, Italy, The Netherlands, Norway, Poland, Portugal, Romania, Slovak Republic, Slovenia, Spain, Sweden, Switzerland, United Kingdom

consequence of long-term societal changes (tissue, because of the ageing population and hygiene needs, packaging, etc.). The situation of the sector in the future will also depend largely on the extent to which export markets advance, e.g. the competitiveness of the sector in a global perspective.

14.1.3. The cement industry

Clinker, the main component of cement, is obtained throughout the calcination of limestone. 63% of the CO_2 emissions emitted during the fabrication of cement come from the calcination process, while the rest (37%) is produced during the combustion of fossil fuels to feed the calcination process. Four processes are currently available to produce the clinker: wet, semi-wet, semi-dry and dry. The heat consumption of a typical dry process is currently 3.38 GJ/t clinker where 1.76 GJ/t clinker is the minimum energy consumption for the thermodynamic process, about 0.2 to 1.0 GJ/t clinker is required for raw material drying (based on a moisture content of 3 to 15%), and the rest are thermal losses. This amount (3.38 GJ/t clinker) is a little more than half of the energy consumption of the wet process (6.34 GJ/t clinker). The average heat consumption of the EU industry was 3.69 GJ/t clinker in 2006. The average thermal energy value in 2030 can be expected to decrease to a level of 3.3 to 3.4 GJ/t of clinker; this value can be higher if other measures to improve overall energy efficiency are pursued (cogeneration of electric power may need additional waste heat).

Current European average of electrical consumption is 111 kWh/t cement, most of it (around 80%) consumed for grinding processes. The main users of electricity are the mills (grinding of raw materials, solid fuels and final grinding of the cement) that account for more than 60% of the electrical consumption and the exhaust fans (kiln/raw mills and cement mills) which together with the mills account for more than 80% of electrical energy usage. The uptake of CCS technology by the cement industry would mean a significant increase of power consumption.

The alternative fuels consumption increased from 3% of the heat consumption in 1990 to almost 18% in 2006. If the current trends remain, the substitution rate could reach 49% in 2030 with savings of 0.30 EJ (7.3 Mtoe) in 2030. The achievement of a clinker to cement ratio of 0.70 in 2030 (possible if current trends are held) would mean savings of 0.054 EJ (1.3 Mtoe) in 2030. Taking into account all these trends, it is estimated that between 2006 and 2030, the cost effective implementation of remaining technological innovation can reduce thermal energy consumption by 10% and CO_2 emissions by 4%.

The EU cement industry production in 2006 (267.5Mt) represented 10.5% of the total world production, the weight of European cement industry in 2008 decreased to a 9% of world production (254.7Mt),. The cement consumption in Europe peaked in 2006 with 265.9Mt. In 2008 consumption decreased to around 2005 (246.6Mt) level. In the former EU15 the number of cement plants with kilns decreased by 31 between 1995 and 2006, while the number of grinding plants in the same 15 countries increased by 19 over the same period. These numbers reflect the competition faced by the European industry: in 10 years 12 % of the cement plants with kilns closed and the number of grinding plants (to convert imported clinker into cement) increased by 28 %.

14.2. **Technology needs**

14.2.1. The iron and steel industry

Exploiting the advantages of the recycling route (with direct CO_2 emissions an order of magnitude lower than the integrate route) will require an outstanding end-of-life management to ensure that all steel contained in scrap can be recycled in an effective way.

An early market roll out after 2020 of the first technology considered in the ultra low CO_2 steelmaking project (ULCOS project, supported by the EU) could further reduce CO_2 emissions. The ULCOS project is the flagship of the industry to reach a decrease of over 50% of CO_2 emissions in the long term. The first phase of ULCOS had a budget of € 75 million. As a result of this first phase, four main processes have been earmarked for further development:

- Top gas recycling blast furnace is based on the separation of the off-gases so that the useful components can be recycled back into the furnace and used as a reducing agent; and in the injection of oxygen instead of preheated air to ease the CO_2 capture and storage (CCS). The implementation of the top gas recycling blast furnace with CCS will cost about € 590 million for an industrial demonstrator producing 1.2 Mt hot metal per year. The tentative timeline to complete the demonstration programme is about 10 years, allowing further market roll-out post 2020.
- The **HIsarna** technology combines preheating of coal and partial pyrolysis in a reactor, a melting cyclone for ore melting and a smelter vessel for final ore reduction and iron production. The market roll-out is foreseen for 2030. Combined with CCS the potential reduction of CO_2 emissions of this process is 70-80%. A pilot plant (8t/h, without CCS) was commissioned in 2011 in Ijmuiden, the Netherlands.
- The **ULCORED** (advanced direct reduction with CCS) iron is produced from the direct reduction of iron ore by a reducing gas produced from natural gas. The reduced iron is in solid state and will need an electric arc furnace for melting the iron. An experimental pilot plant is being planned in Sweden, with market roll-out foreseen in 2030. The potential reduction of CO_2 emissions of this process is 70-80%.
- **ULCOWIN** and **ULCOSYS** are electrolysis processes to be tested on a laboratory scale. There is a need to support this ULCOS research effort with a high share of public funds, and to lead the global framework market towards conditions that ease the prospective deployment of these breakthrough technologies.

It is important to notice that, compared to the conventional blast furnace, the first two breakthroughs ULCOS-BF and HISARNA would result in a reduction of CO_2 emissions of 50-80% and at the same time a reduction of energy consumption by 10-15%. One important synergy in the quest to curb prospective CO_2 emissions through the ULCOS project is the share of innovation initiatives within the power sector or with any other (energy-intensive) manufacturing industries that could launch initiatives in the field of CCS (e.g. cement industry).

14.2.2. The pulp and paper industry

There are potential emerging and breakthrough technologies in the pulp and paper industry, although most are currently at a standstill. These can be grouped in the following families:

- The *bio-route* is the route towards integrated bio-refinery complexes producing bio-pulp, bio-paper, bio-chemicals, bio-fuels, bio-energy and possibly bio-Carbon Capture and Storage (bio-

CCS). Some of the bio-route concepts are in the European Industrial Bioenergy Initiative (EIBI). In fact, as part of this initiative, there is a first large-scale demonstrator, a bio-DME (dDimethyl ether) plant in connection to a pulp mill, under construction in Sweden. Also, one of the flagships planned for this Initiative is led by a Finnish pulp and paper company, Part of this route is also the further development of gasification of black liquor, which aims at producing a combustible mixture of raw gases on the one hand and separating out the inorganic pulping chemicals on the other hand for their subsequent use in the pulping processes. Lignoboost**,** another bio-route concept, is a complete system that extracts lignin, a component of wood from kraft black liquor. This lignin can be used as a biofuel with a relatively high heating value and could also be used as feedstock to produce innovative chemicals.

- *Innovative drying technologies*. Some drying technologies such as “impulse drying”, the “Condebelt” process, or the “steam impingement drying” have only had a first-of-a-kind implementation, and have not been replicated. The first European commercial facility with a condebelt® process entered in operation in 1996 at the Pankaboard mill in Pankakoski, Finland. There is a second case of implementation of this technology in 1999 in South Korea. Research and demonstration regarding innovative drying technologies seems to be at a standstill.
- *Mechanical pulping*. There is ongoing work, at laboratory studies level, to optimise the production of mechanical pulp focusing mainly on the wood yield preparation and more efficient refiner plates (less energy consumption at the same productivity levels).

Under the European Commission’s Sustainable Bio refineries call, the European Union is contributing to the four projects funded under the European Commision’s Sustainable Biorefineries Call (Star-COLIBRI, SUPRABIO, EuroBioRef and BIOCORE) with € 51.6 million of a total budget of € 79.1 million. Also, part of the support needed to develop the bio-route can be channeled through the European Industrial Bioenergy Initiative with projects. However, the large investments needed for the transition from pilot plant to full scale application may require an additional push to allow the industry to cross the apparent “valley of death” in which much of the research is at present. A number of these investments bring financial risks that mills cannot take in the current economic conditions and for which assistance is needed. Furthermore, several large scale technologies are competing in the same field, where it is not clear yet which one will be the winning technology. For those commercially-available drying technologies, the market seems to doubt their potential so far, since very few new machines have been deployed. Next to the investment cost factor, trust or reliability of new technologies seems to be an issue.

One important synergy in the quest to curb CO_2 emissions could be exploited through sharing innovation initiatives with the power sector or with any other (energy-intensive) manufacturing industries that could launch initiatives in the field of CCS (e.g. iron and steel industry, cement industry…).

14.2.3. The cement industry

As a mature industry, no breakthrough technologies in cement manufacture are foreseen that can reduce significantly thermal energy consumption. Alternative technologies are currently being researched such as the fluidized bed technology; however, although improvements can be expected, it is not foreseen that such technologies will cover the segment of big kiln capacities. On the other hand, CCS has been identified as a prominent option to reduce CO_2 emissions from cement production in the medium term. Currently, the main evolution of the sector to improve its energy and environmental performance is towards higher uses of clinker substitutes in the cement, higher use of alternative fuels such as waste and biomass and the deployment of more energy efficiency measures. A significant number of energy efficiency measures are currently being proposed; however their deployment is quite site-specific rendering difficult an assessment of the gains that can be expected. It is noted that many thermal energy reducing measures can increase the power consumption.

14.3. Cost reductions

According to the ETP 2012[64], achieving in the EU from today to 2050 their 2DS scenario would require an additional investment of € 7.8 trillion (35%) more than under a scenario (6DS) in which controlling carbon emissions is not a priority. The IEA's 2DS scenario aims to reduce energy-related carbon dioxide (CO_2) emissions by 50%, compared to 2005 levels. During this period the additional investments of the European's industry is € 265 billion, (3.4% of the additional € 7.2 trillion). To achieve the 2DS scenario, the total investments needed in the European industry reach € 331 billion in the first 10 years (€ 32 billion more than the investments required under the 6DS scenario). The difference in the requirement of investments in both scenarios is increased after 2030 due to the higher costs of reducing emissions intensity, particularly with the implementation of CCS. These investments are the requirements in industrial production plants for the five most energy-intensive sectors (iron and steel, pulp and paper, cement, aluminium and chemicals and petrochemicals).

The additional investment needs offer significant fuel savings as a result of investment in low-carbon technologies. In the industry sector, the fuel savings are estimated at 6 times the additional investments costs. In the EU, up to 2050, the total additional savings amount to € 1.59 trillion.

Some examples of technological options that can become a reality by 2020 for marginal abatement costs of the order of 40-60 €/t CO_2 are the remaining BATs in all sectors of the industry. That price can also trigger the implementation of top-gas recycling blast furnace in the iron and steel industry. Marginal costs around 100-130 €/t CO_2 by 2030 can set off black liquor gasification in the pulp and paper industry. Values of 140-170 €/t CO_2 could bring about CCS in the cement industry. Eventually, by 2050, marginal cost of 170-200 €/t CO_2 could lead to new cement types and to hydrogen smelting and molten oxide electrolysis in iron and steel.

14.4. Soft measures influencing deployment

The three energy intensive industries considered in this chapter are affected by risks of carbon leakage under the terms of the former European Union Greenhouse Gas Emission Trading System (EU ETS). The revised Directive provides for 100% of allowances allocated free of charge, at the level of the benchmark to the sectors exposed. However, even with this new provision the industry is still calling for new measures to level the global playfield.

Despite the high penetration of cogeneration in some of the industries considered in this chapter, there are sectors with a high potential to tap, For example, in the pulp and paper industry, it is estimated that only 40% of CHP potential capacity has been installed. The barriers to the further

[64] Energy Technology Perspectives 2012. Pathways to a clean Energy System. International Energy Agency, 2012.

expansion of CHP are common to all the industries. One of those barriers is the ‘spread price’, the difference between the price of the fuel used by the CHP and the price of the electricity generated.

In the iron and steel industry, no significant advance to decrease CO_2 emissions is possible without the development of breakthrough technologies, as proposed by ULCOS. The main lever of energy savings for steel production is led by further increases in the recycling rate. However, further increases in the recycling rate beyond the 60% in 2030 will be stifled by the availability of scrap. Such high recycling values will increase the impurities and reduce the overall steel quality. Recycling has high emissions of heavy metals and organic pollutants due to the impurities of scrap. These issues will become a more pressing issue to be solved urgently.

In the pulp and paper industry, in the short and long term perspectives, the availability of raw materials (wood and recycled fibre) will be crucial. Currently, there is an increasing pressure on biomass availability. For their main virgin feedstock, wood, the pulp and paper industry is competing with other bioenergy producers; almost 5% of the EU gross energy demand is covered by biomass resources. In fact, the biomass was almost two thirds (65.6%) of all renewable primary energy consumption in 2007. At the same time, waste paper is exported at large scale mainly to China, where new large paper mills use this resource. This leads to shortages in recycled fibres for some European paper producers. Also, the trend by many municipalities to decrease the availability of waste to be recycled by the energy intensive industries may further hamper reaching higher levels of efficiency.

In the cement industry, one of the main barriers to the deployment of energy efficiency measures and CO_2 mitigation technologies in the cement industry in Europe is related to energy prices. High energy price favors investment in energy efficiency and CO_2 emissions abatement, however at the same time higher energy prices may lead towards more and more imports from non EU countries to the detriment of a European production. The market penetration of cements with a decreasing clinker to cement ratio will depend on six factors, i) availability of raw materials, ii) properties of those cements, ii) price of clinker substitutes, iii) intended application, iv) national standards and vi) market acceptance. It is noted that a cement that can be fit for purpose in one country can often not be placed in some other countries due to differences in national application documents of the European concrete standard. Therefore a way to encourage the use of these cements would be the promotion of standard harmonization at the EU level.

15. BUILDINGS AND ENERGY

The building sector is associated with around 39% of the final energy consumption in Europe. Several studies[65] have shown that the energy saving potential of this sector is substantial and can bring significant benefits at individual, sectoral, national and international levels. In line with the European Commission's objective to move towards a low-carbon economy, an array of European Directives (EPBD 2002/91/EC, EESD 2006/32/EC, RESD 2009/28/EC, EPBD 2010/31/EU, EED 2012/27/EU) is in place in order to exploit this potential. This policy framework can act as a catalyst for the market transformation in the building sector and can offer great opportunities for various technologies to be widely deployed in the market.

15.1. Market evolution

More stringent building energy codes, as a result of the first Energy Performance of Buildings Directive (Directive 2002/91/EC), mean that the market can shift its focus to more sustainable construction techniques and materials, energy efficient building components and designs. As energy codes have adopted a performance-based perspective (as opposed to a prescriptive one, based on individual measures), integrated solutions and packages can be better promoted in buildings. Moreover, the cost optimality methodology – introduced as part of the recast Directive 2010/31/EU – is expected to shift current building code requirements to cost-optimal levels, taking into account the whole lifecycle of measures. This can help transform the current industry's conservative approach for short-term profit maximization, which acts unfavourably towards energy efficient components.

Nearly zero energy buildings – a requirement of the recast Directive 2010/31/EU for all new constructions by 2020 – mean that a combined deployment of high performance constructions, energy efficient installations and renewable energy measures should take place at a large scale. The experience gained from current exemplary voluntary standards[66] acting as leading market concepts can be used to draw lessons and prepare the grounds for the necessary market transformation. Recommendations are given in the JRC report “Evaluating and Modelling Near-Zero Energy Buildings; are we ready for 2018.” Technologies based on fossil fuels will progressively have a lesser importance in buildings, while improving the skills of the workforce and ensuring high compliance levels will be a prerequisite for the successful realisation of these nearly zero energy buildings.

Estimates show that 75% of the existing stock in the developed countries will still be used in 2050. A large share of these buildings is inefficient, and reducing the energy use of the overall stock in the long term critically depends on the measures taken in these buildings. This highlights the need of boosting the renovation market. In light of the new Energy Efficiency Directive (2012/27/EU), Member States should renovate at least 3% of the surface of their central government building stock as well as establish roadmaps for mobilising investment in the refurbishment of their national

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[65] E.g., Fraunhofer-ISI, 2009. Study on the Energy Savings Potentials in EU Member States, Candidate Countries and EEA Countries - Final Report, s.l.: European Commission; WBCSD, 2009. Energy Efficiency in Buildings, Transforming the Market. , s.l.: World Business Council for Sustainable Development; Urge-Vorsatz, D. et al., 2012. Best Practice Policies for Low Energy and Carbon Buildings. A Scenario Analysis. Research Report Prepared for the Global Best Practice Network for Buildings, s.l.: Central European University (CEU) and Global Buildings Performance Network.

[66] Examples include the German PassivHaus, the Swiss Minergie and French Effinergie standards

building stock. This process would mean that more collaboration between different companies and industry actors should be established in order to join forces and offer combined or holistic renovation packages.

15.2. Technology needs

There is a wide range of technological solutions that can be used to drastically reduce the energy consumption of the building stock. The energy consumption of a building is influenced by several factors, such as geometry and orientation of the building, performance of building envelope, efficiency of building installations as well as usage patterns, energy management and occupancy behaviour. The philosophy that supports the reduction of energy consumption in buildings can be followed in three steps:

1. Application of energy saving measures (e.g. improve insulation of building envelope).
2. Increase of energy efficiency of building installations and use of renewable energy resources to cover remaining energy needs.
3. Optimization of usage patterns and occupancy behaviour.

It is widely accepted by the expert community that existing technologies can already reach significant energy reduction levels. Instead, it is rather non technological barriers which prohibit the deployment of energy efficient measures as buildings are complex systems, involving and a large number of actors and a variety of technologies.

Step 1

The building envelope (i.e. building shell) plays a key role in reducing the energy demand of a building. It is the interface of the outdoor climate conditions (temperature, solar radiation and wind) during summer/winter months with the indoor climate (comfort level, air quality and light), thus affecting the living and working conditions inside a building. A building designed with a low compactness ratio, optimum orientation combined with passive heating and cooling techniques benefits from reduced summer heat gains and winter heat losses. Moreover, the use of daylight can significantly reduce lighting needs. The heat transfer through the building envelope can be optimised by applying the right level of insulation, where low U-values (high thermal resistance) of 0.1-0.15 W/m^2K can be reached. The avoidance of thermal bridges – junction points where insulation is discontinuous – at the design level is a critical structure design option which minimises the risk of additional heat loss or condensation. Multiple (air- or argon-filled) glazing can reduce thermal transmittance to 0.7 W/m^2K. Improved building envelope air-tightness in combination with heat recovery ventilation systems can obtain levels of 0.4 – 0.6 ACH (air changes per hour) with an energy efficiency of the installation over 80 %.

Step 2

Building installations should include a highly efficient generation system, an effective and efficient distribution system as well as effective controls on both generation and distribution systems. Condensing boilers offer a high thermal efficiency (at least 85%) compared to non-condensing boilers, while biomass boilers may offer an alternative option. Measures such as heat recovery systems can reduce the energy consumption of HVAC systems as they use heat exchangers to recover heat or cold air from the ventilation exhaust and supply it to the incoming fresh air.

The integration of renewable energy technologies (solar, biomass, geothermal) has also an important role in buildings. Renewable energy technologies such as active solar thermal and solar electrical systems should be favoured and in addition to biomass boilers, heat pumps, whose main operating principle is to absorb heat from a cold place and release it to a warmer one, can be used for space heating and hot water purposes. Solar thermal collectors can convert incoming solar radiation into heat for space heating or hot water purposes, while roof-top photovoltaic installations (solar electrical) can produce electricity to cover the remaining energy needs in a building.

Step 3

Smart technologies entering the built environment range from control automisation to smart metering devices for increased communication with utilities and end-users. Numerous applications for innovation and requested technologies for the built environment offer opportunities to reduce the energy consumption and to control the energy demand/supply balance through intelligent management (ICT). The building will be considered as the cornerstone of the future energy system in our society. Proper integration of renewable energy technologies and electrical vehicles in this built environment will lead to a more efficient use of available energy resources.

Further technological developments will increase the availability of options while allow even higher performance levels to be achieved in buildings. Innovative integrated technologies (ventilated facades and windows, solar chimney and new insulation materials) can also contribute to a further decrease in overall energy consumption. Up-scaling the diffusion of current energy efficiency technologies in the market can help foster the penetration of promising new innovating technologies.

16. SMART CITIES AND COMMUNITIES

16.1. Introduction

In the EU in 2011, Eurostat reports that "68% of the population lives in urban areas, which consumes 70% of energy"[67], accounting for 75% of the EU's total greenhouse gas emissions (GHG)[68]. In the world, more than half of the mankind is living in urban areas and it is estimated that cities will host 70% of the world population by 2050[69]. This evolution will inevitably put pressure on resource consumption and environmental issues in urban areas.

However, cities are becoming active in developing strategies for better and more sustainable living conditions. Indeed, Smart Cities are commonly defined as an evolution of the present cities, where the increased inclusion of technology and of information and communication technologies (ICT) in particular, drives towards more sustainable growth and better quality of life for the citizens[70].

According to a 2007 research paper[71], smart cities can be ranked along six smart axes: economy, mobility, environment, people, living, governance. Energy and energy technologies underpin most of them, and energy efficient technologies will play a fundamental role in shaping the cities of the future.

Although there are no smart cities yet[72], urban areas are evolving into smart cities from different angles: for the energy point of view, utilities and energy actors are engaging in smart energy services and networks; from the transport point of view, cities are supporting electro-mobility and public transport companies are experimenting smart systems to improve their services; from the building side, energy efficiency, including more efficient heating and cooling systems, is strongly promoted in new and renovated buildings. Overall, information and communication technologies are pivotal and they play a central role in the integration of the various city networks and services.

Estimations of the benefits achievable through the deployment of smart cities in the coming decade anticipate up to 50% reduction in energy consumption, 20% decrease in traffic and 80% improvement in water usage[73].

16.2. Technology needs

Smart Cities technology is not a single technology but rather the combination of multiple, existing technologies. Smart Cities are at the intersection of ICT, energy and transport. They boost the adoption of more efficient energy technologies: in buildings, with more efficient buildings see Chapter 15, like nZEB (near zero energy buildings), improved electrical appliances, as well as heating and cooling systems; in the electricity distribution grid that becomes a smart grid, see Chapter 13; in transport, with the introduction of electrical mobility solutions and the necessary infrastructure. Multiple technologies are integrated through information and communication technology, which is the main enabler of the smart cities evolution, based on existing technologies and developing new and innovative cross-functional

[67] Eurostat (2011) Regional yearbook 2011: European cities. Urban areas are over 10 000 inhabitants.
[68] C(2012) 4701 final, COMMUNICATION FROM THE COMMISSION SMART CITIES AND COMMUNITIES - EUROPEAN INNOVATION PARTNERSHIP
[69] UN (2004), World Population to 2300
[70] Intelligent Operations Centre for Smart Cities (IBM, 2011), Integrated City Management Platform (Schneider Electric 2012), Urban Interoperability Platform (Indra, 2013), Connected Urban Development concept (Cisco, 2009), Intelligent City Network concept (Accenture, 2009), Oracle City Platform (Oracle, 2013).
[71] Giffinger (2009) Smart cities Ranking of European medium-sized cities
[72] Hollands (2008) Will the real smart city please stand up?, City, 12 (3), p. 303-320.
[73] Elfrink (Cisco) (2012) Interview with McKinsey's Rik Kirkland, www.mckinsey.com

applications and services for the benefit of the citizens and the environment. A large number of sensors, as well as monitoring and communication technologies will be deployed, that will reinforce the need for data analysis systems and capabilities, cloud computing facilities, data centres, servers, etc. Moreover, increased numbers of devices will be in exchanging data via M2M (machine-to-machine) communication and leading to the future "Internet of things". Due to the expected fast speed of deployment of ICT, improving their energy efficiency is becoming crucial. The European Commission supports and promotes voluntary agreements to increase energy efficiency in ICT, such as the codes of conduct which includes, among others, data centres, digital TV, broadband communication equipment, external power supplies[74].

The Commission proposed to set up a European Innovation Partnership (EIP) on Smart Cities and Communities in 2012[75]. A high level group, supported by a sherpa group, has been set up with representatives from industry, cities, regulators, the bank-sector and other stakeholders, The high level group will advise the commissioners for Energy, Transport and the Digital Agenda on and should agree on a Strategic Implementation Plan for the EIP in the autumn of 2013. The combination of technology development and innovation with the EIP as a deployment mechanism will result in a pipeline of long-term, sustainable solutions for European cities

Furthermore, the Smart Cities Stakeholder Platform, gathering a multitude od stakeholders is preparing the Ten Years Rolling Vision along four main axes: energy efficiency and buildings, energy supply and networks, mobility and transport, finance and planning. EERA Smart Cities (the alliance of European research organizations) is developing the research activities of Joint Research Programme that focuses on energy efficiency and the integration of renewable energy sources,.

In addition technology requirements are increasingly defined at local level by the cities leaders. This bottom-up trend is also confirmed by the success achieved by voluntary programmes like the Covenant of Mayors initiative or the Green Digital Charter[76] . These projects are landmarks for the sustainable development of cities, promoting at city level the 2020 European energy and climate targets and the adoption of the Green Digital Charter.

Smart Cities are complex systems; many technological challenges are foreseeable. However, it is recognised that one major technological challenge is the adoption of standards to ensure connectivity and interoperability and to stimulate industrial competition. Moreover, it is also imperative for the future of smart cities to demonstrate the potential for scaling successful pilot projects up to the citywide scale and to replicate results.

16.3. Market evolution

The Smart cities market is not just one single market, but rather the convergence of several existing markets, such as buildings and home appliances, energy management, industrial automation, services to the citizens, transport and security, with the common denominator of information and communication technology for their integration. Consequently, the main smart cities market players come from the ICT sector or from the infrastructure sector.

Worldwide, pilot projects are on-going (Amsterdam, Malaga, Dubai) that address specific areas of the future cities. According to recent studies, the smart cities market is expected to grow steadily. Pike Research estimates a growth in annual spending from $ 6.1 billion today

[74] http://iet.jrc.ec.europa.eu/energyefficiency/ict-codes-conduct/data-centres-energy-efficiency

[75] C(2012) 4701 final, - Communication on Smart Cities and Communities European Innovation Partnership

[76] The Covenant of Mayors (www.covenantofmayors.eu) , the Green Digital Charter (www.greendigitalcharter.eu) supported by the NiCE project (Networking intelligent Cities for Energy Efficiency, http://www.greendigitalcharter.eu/niceproject).

to $ 20.2 billion in 2020[77], with half of the growth expected in developing countries; ABI Research evaluates the smart cities market value at $ 8.1 billion annually in 2010 and will reach $ 39 billion by 2016[78] and a cumulative spending of $ 116 billion between 2010 and 2016[79].

16.4. Soft measures

The potential for development of smart cities not only relies on technology evolution. Non-technical issues also need particular attention. Because of the complex mix of technologies and networks involved, it is crucial for instance that a forward-looking vision is developed by the city administrators, along with the integrated planning of networks and services and a consistent long-term ICT plans. A long-term planning is an opportunity to support the creation of new "ecosystems", where different actors are brought together to cooperate and to combine assets and knowhow for more sustainable solutions at city level.

Regulation will also play a strategic role. It is expected to promote the development and adoption of standards for an open and constructive competition. Particular emphasis should be put on data issues, in order to improve and secure data exchanges. Moreover a forward looking regulation is expected to pave the way towards the definition and the application of favourable incentive schemes.

On the financing side, smart cities projects require massive funding. Public-private partnerships are proposed as valuable options that not only bring together the large financing means needed to wide scale smart cities projects but also combine the different stakeholders and contributions needed for successful smart cities projects.

[77] Pike Research (2013) Smart cities report

[78] Differences in figures are the results of the different interpretations of the smart city and confirm that there is a need for common definitions and standards.

[79] ABIresearch (2011), Smart city data