Euro-CASE

European Council of Academies of Applied Science, Technologies and Engineering

Euro-CASE Discussion Paper

Electricity production, transmission and storage – challenges for the future European electricity system

The discussion paper was produced by the Euro-CASE Energy Platform (Technologies) in 2014-16.

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Preface

Euro-CASE and the Euro-CASE Energy Platform

The European Council of Academies of Applied Sciences, Technologies and Engineering (Euro-CASE) is an independent non-profit organization of national Academies of engineering, applied sciences and technologies from 22 European countries. Euro-CASE acts as a permanent forum for exchange and consultation between European institutions, industry and research. Through its Member Academies, Euro-CASE has access to top expertise (around 6,000 experts) and provides impartial, independent and balanced policy advice on technological and innovation issues with a clear European dimension to European institutions and national governments.

In 2013 Euro-CASE launched an Energy Platform which consists of fellows of Euro-CASE Academies from science, engineering and business. The Energy Platform is based on the activities of its member academies that develop policy options and address the need for science-based policy advice. Because of the discussions and the decision about backloading and the ongoing debates the Platform decided to start in a first phase elaborating a policy paper on the reform options for the European Union Emission Trading System (EU-ETS).

In the light of the substantial decisions to be taken in the field of energy at European level as laid out in the Communication "A policy framework for climate and energy in the period from 2020 to 2030" (COM/2014/015 final) it is the aim of the Euro-CASE Energy Platform to work in addition on different scenarios for the development of the European Energy System as well as the technological requirements and constraints for different energy policies. The platform therefore decided to also produce a discussion paper on the European electricity system in 2030; *"Electricity production, transmission and storage – challenges for the future European electricity system"*.

Euro-CASE and its member academies are committed to contribute to the development of a sustainable European Energy System both at the national and on the European levels. Key challenges include issues such as the energy prices and industrial competitiveness in the light of the 2030 targets and the specific interaction of sustainability and industrial policies. A long-term project on the future of the European Energy System is envisioned. http://www.euro-case.org/index.php/activites/item/401-energy.html

Electricity production, transmission and storage – challenges for the future European electricity system

The electricity system has an increasing role in a decarbonized energy system and increased electrification of the energy system is a trend across the global energy system. The growth in electricity demand and capability has the potential of transforming both energy supply and end use.

Electricity has historically been generated with mainly fossil fuels together with hydropower and nuclear power which is why an increased electrification also requires an increased decarbonisation in the future energy production system. A growth in electricity demand and the change in character of the energy supply system require increasingly strategic approaches of how to balance supply and demand. The future energy system is expected to be composed of a combination of central power plants (fuelled with gas, biomass, nuclear power plants and large hydropower plants) and numerous small decentralised plants based on renewable energy like wind, solar and biomass.

Important pre-requisites for a European-wide electrification of the energy system are development of infrastructure, harmonization of the national energy systems, development of the European internal market, and great strengthening of the cross-border collaboration between European countries.

The Euro-CASE Energy Platform aims with this discussion paper to identify and highlight some general new challenges but also possible solutions for the future European electricity system, for the benefit of DG Energy and the European Commission as well as the general energy community and interested public. The report is based on analyses of unified data from existing reports combined with experiences and seminars from the Euro-CASE Energy platform. The target audience for this paper is the society in general but also policy makers and decision makers from the European Commission.

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1 Executive Summary

Even if energy consumption in Europe is decreasing through energy efficiency, the total European electricity usage is increasing due to new markets and uses, for example IT, and also by the perceived increase in electrification in the heating and transport sectors. An increased electrification of the energy system is a trend across the globe and the growth in electricity demand and capability has the potential of transforming both energy supply and end use.

Electricity has historically been generated with mainly fossil fuels together with hydropower and nuclear power. An increased electrification requires further measures to reduce the share of fossil fuels in the future electricity production system. A growth in electricity demand and the change in character of the electricity supply system require increasingly strategic approaches of how to balance supply and demand. The future electricity generation system is expected to be composed of a combination of central power plants, and numerous small decentralized plants.

Important pre-requisites for a European-wide electrification of the energy system are development of infrastructure, harmonization of the national electricity systems, development and evolution of the European internal market, and great strengthening of the cross-border collaboration between European countries. It also requires analysis and homogenization of the subsidies system and an improvement of the EU ETS system, with the objective of replacing the majorities of the subsidies.

Whichever scenario the future European energy system will follow it will consist of mixture of intermittent power and dispatchable power. Fossil fuels and nuclear power will dominate the European electricity system for the next 20-30 years. Even with the renewable proportion expanding massively, a large part of the power generation in Europe will be based on fossil fuels in 2050. Four possible transformation paths to a fossil free energy system can be identified;

- Next generation nuclear (short term, until 2050: GEN III and IV fission reactors, long term, after 2050: ITER fusion reactor).
- More cost efficient renewable electricity production and substantial support of balancing power and storage facilities, including biomass which is a storable renewable energy (in the same way as hydro power with reservoirs)
- Coal or gas with maximum improved efficiency in combination with carbon capture and storage (CCS), or in combination with H2 from Power-to-gas.
- Power-to-gas in combination with hydrogen storage, making use of excess renewable electricity production at very low cost.

The future power system will most likely be a mixture of the four paths. Gas is likely to play an important role in all possible scenarios of the future, especially if EU ETS is working correctly (above 30 €/ton of CO_2). In addition, energy efficiency on the demand side will be important.

Production technologies

The intermittency which characterizes solar and wind power is one of the central challenges in designing the new electricity system. However, although they cause challenges with regards to balancing electricity supply and demand in the current energy system, wind and solar power will be necessary for developing a sustainable energy system in the future.

Also hydroelectric power could be regarded as intermittent due to its unpredictable nature. It is partially true for run-off-the river hydro, even if large rivers allow long duration anticipation and precise prediction. The hydro with reservoirs is storable energy which gives flexibility and stability to the electricity grid. The volume of water available in the reservoirs availability can be anticipated one year in advance. The capacity may be guaranteed.

Hydropower can be generated when needed to meet rapid or unexpected fluctuations in demand due to the storage reservoir of water. There are however limited possibilities for new sites and environmental impacts through land use and conversion.

Harmonization and modification of market rules, and subsidy systems, is important to fully exploit the balancing capability of hydropower, and its support for stabilization of the grid. Integration of electricity markets generally improve the business case for interconnections but different market rules such as having a capacity market connected to energy only markets create suboptimal business cases.

The development of solid (wood), liquid (biofuel), and gaseous (biogas) bioenergy increase the volume of storable energy. Depending on their cost and the value of CO2, they can be used to produce electricity or to directly replace traditional fossil fuels. They are one of the solutions to the increased storage demand.

A comparison of LCOE (Levelized Cost Of Energy) for different technologies show that by 2030 onshore wind is predicted to be the second cheapest, while LCOE for offshore wind finds itself as the most expensive of all power generating technologies, even if its load factor is far better than on shore wind. Other sources do however expect much lower offshore wind costs, due to technological progress, namely for electricity connection and offshore transport.

CCS has a potential to substantially decrease the impact of fossil fuel combustion for the European electricity system. Several factors will however constrain the rate of deployment of CCS; a substantial transport and storage infrastructure will need to be created and the public perception will impact the permitting process of CCS development. There is also a need to develop confidence in the geological processes that will determine the long-term security of the stored carbon dioxide. Also cost, efficiency and water consumption of the CCS technology needs to be improved.

In order to succeed, CCS needs more support from institutions. The future of CCS crucially depends on public understanding and agreement and adequate carbon prices.

The situation of nuclear power has changed following the earthquake and tsunami in Japan in 2011. Instead of being globally regarded as an acceptable technology option for the future, nuclear has faced early shutdown and been questioned in some countries.

In order to include nuclear in the future energy mix in addition to countries where nuclear is already an important factor of capacity such as e.g. France and Sweden there is a need for a decisions on building new nuclear plants. A stable political landscape is critically needed in order for investors to support nuclear. It is also critical that the long term storage of the nuclear fuel waste is developed, fully secured and accepted by the public. The development of new nuclear plants may need long term electricity supply contracts which should be allowed in the European system.

Depending on the type of nuclear technology used in the various countries, nuclear power produces more or less dispatchable power. In France, the flexibility of nuclear power is similar to the flexibility of coal generation (quick decrease, increase by 2% to 5% of plant power/minute). However, the economic value produced is proportional to the electricity produced when the operational cost is flat. The support to the intermittent electricity production reduces the total electricity produced and thereby reduce the profitability of the plant, as is also the situation for coal or gas generation and all dispatchable sources.

The European coal power plants that are currently in use are old and will have to be shut down or refurbished in the next few decades. Regardless of how the rest of the system develops, large investments will have to be made in new thermal plants. The most urgent is to improve the efficiency of the complete chain of electricity generation from coal and lignite (methane collection, desulphurization, denitrification and efficiency of generation toward very high efficiency- from 32% to 47% efficiency).

An additional total amount of 1 000 TW of new thermal power will probably be added until 2030. The thermal power plants in 2030 will consist of old base load plants, new gas combined cycles, some converted and new biomass units and new peak load plants.

Gas utilization will probably increase considerably in the future. Shale gas is one possible source of gas that is explored in parts of Europe, where exploitation is allowed.

Biogas for electricity generation is rising rapidly in Europe. By the end of 2014, more than 17,240 biogas power plants, with a total installed capacity of 8.3 GW, were in operation. The share of biogas of the total EU electricity generation is still very low. [1]

Biomass and waste provided around 5.2 % of the European electricity generation in 2014. [2] Biomass is used primarily in countries with extensive forest industries, where residues such as branches, wood chips and sawdust can be used to produce electricity and heat. Countries with large agricultural industries and industries that produce waste products that can be used as biofuels also have potential to increase their use of biomass[3].

Many of the coal-fired boilers can be fired with a part or fully with biomass. It is easy to burn wooden biomass in a coal fired boiler if it is milled down to typical sawdust size. Moisture content does not matter[4].

Transmission & Distribution

In the future electricity system, both the transmission system at high voltages (115 kV or above) and the distribution systems at low voltages need to be optimized and integrated with large scale storage facilities. Transmission refers to the electricity transferred from the generating power plants to the electric substations while the distribution system carries electricity from the transmission grid to the end user.

When increasing the renewable electricity production in Europe, interconnections between countries will be more important. Large wind power capacities in countries like Germany and Denmark need to be balanced with storage capacities in for example hydro power in countries like Norway or mountain regions as Alps.

Since an increased portion of intermittent renewable power will be introduced to the electricity system, demand on the regulation and flexibility of the transmission and distribution system will increase. The future grid needs to better match supply and demand of electricity. Smart grid technology such as home energy controllers, peak shaving, virtual power plants and storage capabilities (both small and large scale) are solutions that will transform the system to a smarter electrical grid. The fact that also the transport system is being increasingly electrified emphasizes the need for an electricity system transformation. To build a more efficient grid, Smart grid technologies are increasingly applied.

On the transmission level, one of the complicating factors is the reluctance of citizens to accept new high voltage transmission lines. The necessity of new connection is not sufficiently explained and therefore debated. Various alternative solutions are used such as subterranean DC lines (between Spain and France) or submarine DC lines (several projects from France to Spain, UK, and Ireland). The cost is higher by far, but it could still be an affordable option. Here smart grid solutions can play an important role to cut peak demand (peak shaving), to displace demand when production is at low cost and possibly minimize the need for new physical transmission infrastructure.

The transmission and distribution business is highly regulated. The smart grid development in general is thus strongly driven by regulation. Here the work to develop "smart regulation" is very important, a regulation addressing services, technology, innovation and user participation of the grid transformation. Another critical success factor is the ability to adopt technology development is other areas for use in smart grid applications. As mentioned the key technologies are here IT Technology, sensors and power electronics.

Electrical Storage

The various technologies of electricity storage are characterized by their power output but also by the amount of energy that can be stored. The majority of the electrical (capacity) or chemical storage may store a few hours with a maximum of 7 hours. It is the same for most pumped hydro storages, with some exceptions of up to 20 hours. A low wind period may last several days and sometimes more than one week. The low solar production in winter lasts

[1] European Biogas Association webpage
[2] Gross electricity generation, Eurostat Database
[3] Vattenfall, 2014
[4] Strömberg, L, 2014.

for several weeks. For longer need of storage, it is possible to use more biofuels and to develop power to gas technology to produce hydrogen and then methane in combination with CO_2.

Another development of electricity storage is mobility (cars, and later airplanes). The positive impact in terms of GHG emission is evident if the electricity used is fossil free. This development is associated with home electricity storage to better take advantage of the battery.

It could be argued that it is necessary to adjust the development of intermittent electricity generation to the actual capacity of storage developed. This in order to create an economically sustainable business model. The further development of electricity storage technologies will be important for all applications, from large-scale generation and grid ancillary services all the way down to customer and end-user sites.

Energy storage might need to be a field of its own right, not just an add-on to renewable. It is most likely that further work on the market-terms is required; with incentives for storing energy and building these systems. Each storage technology has advantages and disadvantages and in the future a mix of these carriers will probably be used.

A future electricity sector relying heavily on power production from renewable resources will most likely require substantial energy storage.

To stimulate development in energy storage technologies and their integration in energy systems the following series of initiatives are possible ways forward.

- Energy storage should be supported as a separate field of research
- Demonstration of connections between grids, such as the power-to-gas concept
- Design of market terms for integrating energy storage in electricity markets
- Regulatory settings should be developed to favour the effective coupling of the power, heat and gas infrastructures
- DC development namely for transmission, including interconnection

End-users could also become active players in the future electricity system by being turned off or on depending of the need of the system.

Market observations

The European electricity system is at a crossroads, as national capacity markets and support systems for renewables are pushing for more regional planning and nationalization[5] of the electricity markets. Whereas European common polices stress transnational energy infrastructures and regulation, which makes it possible for energy to flow freely over national borders. The EU is promoting an integrated European electricity market, with the implementation of network codes and a European market model. An observation is that in order for the EU targets to be reached a harmonization of the market including subsidies could be required.

Balancing generation and consumption will pose a challenge for the future electricity system. The challenges, as can be seen, consist of utilizing existing resources efficiently as well as of dimensioning the system optimally in order to sustain a reliable supply and avoiding locked in generation and price collapses. Plausible solutions are the expansion of the European transmission grid, increased usage of both thermal and electrical storage, placed in different parts of the energy system and demand control, where industrial consumers as well as households and large commercial facilities are connected.

One trend is access to peak load capacity will partly replace transmission capacity. Properly handled, capacity markets can be implemented without any additional costs for the customers. The increased cost associated with paying for capacity will be balanced by reduced electricity prices of the same magnitude. With a larger share of intermittent power, electricity prices will, in the long run, vary more, a volatility that could be reduced with the introduction of a European Internal Market together with a capacity market.

The existing electricity generation system will for a long time influence the structure of the system and even with the renewable proportion expanding massively a large part of the power generation in Europe will be based on

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fossil fuels and nuclear power for the next 20-30 years. To achieve a fossil free energy system, there are different transformation paths such as the next generation nuclear, more cost efficient renewable electricity production and CCS. The future energy system will most likely be a mixture of the three paths. Gas will also play an important role in all possible storylines of the future with a transition from fossil gas to biogas. Considering security of supply, development of European shale gas resources seems inevitable.

The actors in the electricity system will face different challenges in the transformation. The transmission system operator has to expand the network fast enough when facing long lead times and uncertainty regarding the location of the new power sources. Investments in storage facilities can reduce the investments but there is an obvious risk that renewable power will be trapped-in in some regions and cross-border collaboration is a key in mitigating this problem. Plausible ways forward are to create economic incentives required for the necessary dispatchable power, stimulate effective investments in the networks and create potential flexibility of demand to be utilized such as smart grid solutions. Additional, a market which rewards not only energy but also installed capacity might needs to be developed in order for the new system to be competitive and provide security of supply.

These solutions are often referred to as Capacity mechanisms and are designed to support investments to ensure security of supply. Many of these mechanisms have an impact on the internal electricity market, involve state aid and are subject to EU State aid rules.

One example is an Electricity Only Market (EOM) were all decisions made by electricity consumers and power providers are based on spot prices. For investments in the first place to become profitable on an EOM, shortages must occur, or high risk of such, for a minimum number of hours. This particular type of investment in power plants, utilized only during a short period of time and highly dependent on high electricity prices at the specific time they are operated, will be the most insecure investments in the power market, a risk that can be reduced by the design of support systems like feed-in premiums and design of markets for ancillary services.

An alternative is to create a capacity market (CM) in the EU, or in certain countries. On a capacity market one can procure the desired capacity, possibly up-section in different types of power and consumption flexibility. Since under capacity is much costlier than excess capacity, the procured capacity on a capacity market should be done with a certain spare margin. In practice, one should procure as much capacity so that the risks of shortage are negligible.[6]

However, with an energy-only market (EOM) there are few incentives for large investments in peak load power plants. The incentives to invest in high-tech, clean technology are especially low and a high power rating and low electricity production tends to give plants with low investment cost and high fuel cost. If thermal power plants are to provide the peak load energy needed, open cycle turbines with natural gas, LNG or light oil will probably be the major choice.[7]

Conclusion

The current European electricity system is predominantly supplied by fossil fuel, nuclear, and hydro power. The European thermal power fleet (coal, nuclear and gas) is aging and 2/3 needs to be replaced within the next 30-40 years. CCS technology is currently facing profitability issues.. The instability in long term policies is halting investors into the European power sector. Nevertheless perspectives of power-to-gas could help CCS. The future sustainable solution is to go beyond storage and to emphasize more directly on “Carbon re-Use”.

- ➔ Large changes are needed and unavoidable in the near future to improve supply sustainability and safety.
- ➔ If the expansion rate of sustainable electricity production is not increased rapidly, nuclear power seems to be a non-avoidable option in case of failure of CCS. New nuclear power plants need to be planned promptly if they should be ready in time to replace the current old capacity before its end of life.
- ➔ Stable and long term policies need to be developed in order to attract investment to the energy sector (attractive business models are needed).

The equalization of sustainability, security of supply and competitiveness (energy triangle) and the focus on non-regret options is paralyzing European development.

[6] *NEPP 1*
[7] *Strömberg,L. 2014*

- ➔ Use and develop gas as an intermediate solution in the transformation of the energy system (transition from fossil gas including shale gas to biogas).
- ➔ Accept temporary tradeoffs for the long term security, competitiveness and sustainability of supply.

Solar PV is expanding rapidly and is very unevenly distributed between the European countries. Wind power is unevenly distributed in Europe and for the time being, mainly located onshore. Major expansion in the wind power sector is planned to take place offshore.

- ➔ Research is needed in order to lower the costs for offshore wind.
- ➔ Expansion of renewable intermittent energy in Europe can be very costly and require storage capabilities and / or interconnections between countries. Time is required to optimize the system. For the time being, development of intermittent renewable has no significant impact on GHG emissions.
- ➔ Regulation needs to be adjusted to promote storage, the possibility of a capacity market should be investigated.
- ➔ Increase the electricity share coming from hydropower in order to utilize its potential as balancing power and storage. (an attractive business model is needed)
- ➔ Transmission requirements between countries need to be correlated to the renewable electricity share in the country.

2 Introduction

The introduction chapter describes the background of this paper and the European electricity system as well as the scope and method used. This chapter ends with a short reflection about the COP21 conference and its implications.

In December 2011, the EC released the Energy Roadmap 2050, a strategy paper that explores how the goal of the EU - to reduce greenhouse gas emissions to 80%-95% below 1990 levels by 2050 – can be achieved without disrupting energy supplies and competitiveness. It shows that achieving a high degree of decarbonisation is possible. The document is based on a set of seven different scenarios (the scenarios differ in the energy mix and combine varying shares of renewables and the importance given to energy efficiency and new technologies such as CCS). By means of these scenarios and their impact on prices and costs conclusions for necessary policy frameworks to allow for an almost carbon-free energy system can be drawn. Ultimately, this should support member states to make the required policy choices.[8]

The Roadmap is a strategy paper; Substantive legislation such as directives that could influence the architecture of the energy markets in the future is still to be written.[9] As the EU may not intervene in the member states' energy mix it can be argued that "[…] adopting a roadmap for restructuring the energy sector seems contrary to the distribution of powers on energy policy laid out in Article 194 (2) of the Treaty on the Functioning of the European Union"[10]. Implementing the Roadmap would mean a reduction of the member states' sovereignty over energy policy - thus assuming more influence and control on the part of the EU than the present state of play allows for. Therefore, the success of this planning instrument will depend mainly "[…] on the willingness of the member-states to agree to a deeper Europeanisation of energy policy […]"[11].

The year 2020 is now approaching and the next step in EU's climate and energy policy needs to be defined. An outline for the successor to the EU framework for climate and energy for 2020 has already been proposed by the EU Commission. In its communication "*A policy framework for climate and energy in the period from 2020 to 2030*" put forward in January 2014, the Commission sets the following goals:

- to reduce EU domestic greenhouse gas emissions by 40% below the 1990 level by 2030 (binding at EU level);
- to increase the share of renewable energy to at least 27% of the EU's energy consumption by 2030 (EU-wide binding renewable energy target).[12]

In February 2014, the European Parliament voted in favour of *three binding targets* for 2030, adding a 40 % target for energy efficiency.[13] EU leaders agreed to decide on the framework no later than October 2014. Following a review of the Energy Efficiency Directive, the Commission also proposed a new energy efficiency target of 30 % for 2030. [14] As of October 2014, the European Commission decided this to be to be 27 %.

In designing the policies that will shape the European energy system of 2030, the lessons from the current framework should be taken into account. It is clear that the EU ETS did not fulfil what it was intended for and a reform is necessary, an issue which is discussed in the Euro-CASE policy brief on reform options for the EU ETS. With regards to technology and innovation, the progression towards the 20-20-20 targets set up by the "*2020 climate and energy package*" provides useful information in designing the next framework. Meeting these targets has so far shown mixed results. While the 20 % reduction in EU greenhouse gas emissions as well as raising the share of EU energy consumption produced from renewable resources to 20 % is likely to be achieved, a 20 % improvement in the EU's energy efficiency remains a challenge.[15] The Energy Efficiency Directive (EED) adopted in 2012 aims at ensuring that actions leading to higher energy efficiency is taken, particularly in the areas of energy performance of building, energy services and cogeneration. The EED is an important part in reaching the EU 2020 20 % energy efficiency

[8] *European Commission 2011*
[9] *Langsdorf, 2011*
[10] *Fischer & Geden 2012*
[11] *Fischer & Geden 2012*
[12] *European Commission, 2014a*
[13] *Erbach, 2014*
[14] *European Commission, 2014b*
[15] *EEA, 2013*

target and it establishes "*legally binding goals for the Member State's efforts to use energy more efficiently at all stages of the energy chain- from the transformation of energy and its distribution to its final consumption*"[16].

The 2030 framework should consider the long term perspective. Indeed, the *EU Energy Roadmap 2050* is a key input in finalizing the EU framework for 2030. Most notably, the framework should take into account the CO_2 emissions target of achieving an 80 % - 95 % reduction compared to 1990-levels by 2050[17]. The different decarbonisation scenarios presented in the Roadmap to achieve this target share common elements irrespective of the chosen energy mix. Among them are a growing demand for renewable energy, an increased role for electricity and the importance of energy savings.

The EU's competences in the field of energy policy have developed only slowly over time. Although two energy based institutions, the European Coal and Steel Community (1952) and the European Atomic Energy Community (1957) stood at the beginning of the European integration process, the EU founding treaties did not contain a specific provision on EU intervention in the energy field. This circumstance hindered enhanced cooperation and led the Community to resort to using competences related to developing the Single European Market (SEM) and European environmental policy and linking them with energy issues to adopt legally-binding measures affecting the energy sector. In addition, the heterogeneous interests of the member states based on different energy mixes and energy market structures also constrained attempts at developing more cooperation in the field of energy. It was only in 2009 when the Treaty of Lisbon entered into force that a legal basis for EU intervention in the field of energy was introduced[18]. Henceforth, the EU can intervene at European level to (a) ensure the functioning of the energy market; (b) ensure security of energy supply in the Union; (c) promote energy efficiency and energy saving and the development of new and renewable forms of energy; and (d) promote the interconnection of energy networks (Art. 194.1, TFEU).

Whereas particularly point (b), ensuring energy supply security, can be described as innovative as the issue was formerly dealt with at the national level, there are limits to the EU's performance. The EU may, for instance, not intervene in the member states' energy mix and the general energy supply structure[19].

Renewable energy resources such as solar and wind power will be necessary for developing a sustainable energy system in the future with a substantial decrease in emission of carbon dioxide. However, they cause challenges with regards to balancing electricity supply and demand in the current energy system. Even with increased energy efficiency and growth in their installed capacity, wind and solar power will though not suffice to meet future demand. Therefore, other sources of energy such as thermal and hydro power should be integrated in the system.

The intermittency which characterizes solar and wind power is one of the central challenges in designing the future energy system. The intermittency makes it hard to balance the energy system which is currently designed only to balance the electricity demand side but will in the future also have to balance electricity production.

Therefore, dispatchable power from for example gas turbines will be increasingly important in the new system. An effective energy system constitutes several methods of handling the intermittency of solar and wind power. Energy storage, smart grids as well as efficient transmission and distribution, are technology areas which reduce the balancing challenge and also improve the sustainability of the system. Also, energy self-production/self-consuming as developed in Germany and ideas relevant to smart building/cities will improve energy efficiency and probably reduce need to fully connect to the grid. Additional, a market which rewards producers for not only energy but also installed capacity needs to be developed in order for the new system to be competitive and provide security of supply.

End-users could also become active players in the future electricity system by being turned off or on depending of the need of the system.

The energy triangle

[16] *European Commission, 2013d*
[17] *European Commission, 2013*
[18] *Langsdorf, 2011*
[19] *Ibid.*

The sustainability of the future European energy system is though not the only aspect to consider. The EU energy and climate policy should enable three necessary goals: European competitiveness, European security of supply, and sustainability. The 2020 framework with its strong focus on sustainability has shown that it is not easy to balance the three needs. In fact, one of the key lessons from the present framework is that the 2030 framework should be designed in a comprehensive manner so that its policies and instruments ideally reinforce each other and aim at achieving all three objectives.

It is essential to avoid counter-productive policies. An example from the current framework illustrating the type of situation that should be avoided in the 2030 framework is that the EU targets for energy efficiency and renewable energy undermined the efficiency of the ETS[20].

The triangle below exemplifies interactions where policies may reinforce several of the objectives. It is these types of areas that the 2030 framework should identify in order to"*maximize synergies and deal with trade-offs between objectives of competitiveness, security of supply and sustainability"*[21]

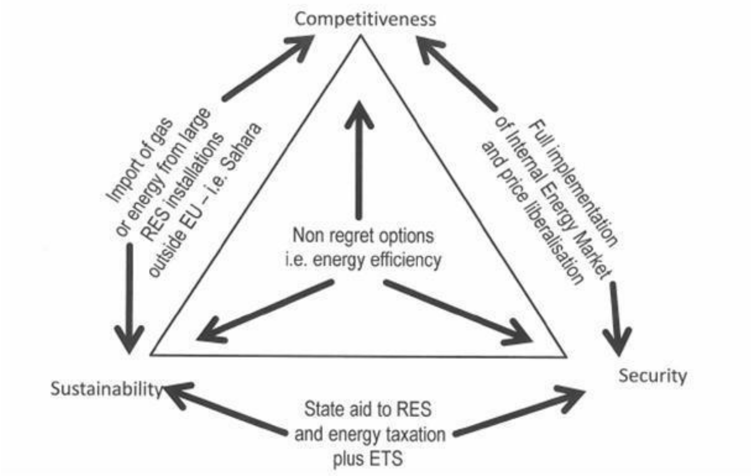

Figure 1 - Energy triangle with positive interactions[22]

The purpose of this report is to summarize the status of the different electricity producing technologies in Europe and highlight some observations and challenges they face in terms of sustainability, competitiveness, and security of supply. Regarding the energy triangle the paper's scope allow some key areas of the European electricity system to be highlighted, describing some of the major negative sustainability effects, addressing but not thoroughly quantifying security of supply and discussing the key implications of supply and demand as well as cost structures of production technologies. Subjects such as the cost effectiveness of the implied trajectory of the EU energy system are not included but would be a possible future research area. It should be mentioned that observations and potential trajectories, using the energy triangle, is based on the conditions and knowledge of a traditional system, a future European Electricity system might differ through cheaper cutting edge technologies, with implications that are hard to quantify.

The energy triangle concept resembles but is not equal to the "Energy Trilemma" model (energy security, energy equity, and environmental sustainability) developed by the World Energy Council (WEC). The "Trilemma" model *"entailing complex interwoven links between public and private actors, governments and regulators, economic and social factors, national resources, environmental concerns, and individual behaviours"* is used as a framework for future energy systems and transformations by developing understanding of effective policies and strategies. If the

[20] *d'Oultremont, 2014*
[21] *Ibid.*
[22] *Ibid.*

Energy trilemma model would have been used it might have underlined other aspects and contexts of the different production methods which would be interesting in future papers.[23]

Reflections on COP21

On the inauguration day, 150 heads of states or governments were present to show their personal commitment to climate and to the result of this meeting. After two weeks of intense global but also frequent bilateral negotiations, on Saturday December 12 2015, a common statement was voted called "Adoption of the Paris Agreement". The full document contains an introduction, 6 chapters with 19 pages and an annex, Paris agreement, containing 29 articles in 12 pages.

The agreement will come into effect in 2020 if it is ratified by at least 55 countries responsible for more than 55% of the greenhouse gas (GHG) emissions on our planet. Verification of signatures will take place between April 22, 2016 and April 21, 2017 in the office of the United Nations in New York. The agreement will be open to further adhesions immediately after the date of April 21, 2017.

French Presidency of the COP21 had begun unofficially in Warsaw. During Warsaw and Copenhagen climate meetings, it had been decided a new principle of the future agreement: contrary to the Kyoto protocol principle, there would be no longer a willingness to determine a quantitative objective for the greenhouse gas emissions. It was decided to propose for the approval of parties a voluntary declarative system in which each state would declare their action plan to curb the GHG emissions of its own country. The national contribution proposed by each country would be recorded on a global register. At the time of the vote, 150 countries had determined their national contributions. Such an option presented a significant diplomatic advantage because it never limited the sovereignty of each nation as the home contribution would be really free of any external constraints.

This new option is not really binding. For instance, the article 13-3 of the Paris agreement says: "The transparency framework shall build on and enhance the transparency arrangements under the Convention, recognizing the special circumstances of the least developed countries and small island developing States, and be implemented in a facilitative, non-intrusive, non-punitive manner, respectful of national sovereignty, and avoid placing undue burden on Parties".

However, individual national contributions, recorded in the registry, are now identified by all citizens of the planet and the future follow up of the action plan will be known to all. It will be the judgment of the citizens of various countries which will apply constraints. Incidentally, there are countries where inhabitants decided to attack the government under the law of their country because the climate engagements were not respected, at least in their appreciation.

Additionally, under the Paris Agreement (item 4-19) each state should publish the path it will follow to continue curbing the GES emission in its country, in order to allow for consolidating all the trajectories and for elaborating a global evolution of the planet.

It is worth observing that the initial « Projet of decision » dated December 12, 2015, aimed at reducing GHG emissions to 1.5 °C : :" Emphasizing with serious concern the urgent need to address the significant gap between the aggregate effect of Parties' mitigation pledges in terms of global annual emissions of greenhouse gases by 2020 and aggregate emission pathways consistent with holding the increase in the global average temperature to well below 2 °C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5 °C…"

The above citation does not express a global commitment but rather a wish. It is almost certain that the objective of 1.5 °C will not be reached if individual states (Parties) do not exceed their initial pledges. Nevertheless, this value of 1.5 °C is a goal for all to attain.

The process is now launched with the idea that a collective stance will encourage individual countries to demonstrate their willingness to assume their responsibility in the climate evolution shared effort. During the COP 21, no country

[23] *World Energy Council, webpage 2016*

denied that climate is its problem. The Paris agreement is a collective fundamental progress and a diplomatic step forward.

A revision of the national contributions of the parties will occur every 5 years, and the revisions are supposed to propose a further progress, and not a step back.

The COP 22 in Marrakech will propose the rules to insure the follow up of national engagements: measurements, control, transparency, committees of experts, champions, as described in the Paris agreement. All these points are of extreme importance for the future credibility of the process.

Among the 195 countries (parties), many have no means and knowledge to measure and publish their $C0_2$ emissions. CO2, which comes from the combustion of fossils, is relatively simple to determine on the basis of the quantities of coal and hydrocarbons, solid, liquid or gaseous, imported or extracted in the country, and consumed in the country. For the time being, the GHG emissions are not recorded in the country of their extraction but in the country of their combustion. However, the major part (except for chemical use) of the fossils extracted is burned and, finally, it is the extraction which should be progressively curbed. In the Paris agreement, the article 13-11 mentions "For those developing country Parties that need it in the light of their capacities, the review process shall include assistance in identifying capacity-building needs."

For the others, GHG emissions and in particular for methane, the analysis is far more complex, and should involve natural and anthropic emissions and removals, namely by dry soils[24].

One important step could therefore be to compare the national contributions of the parties, member states of the European communities, to analyse their convergences or divergences, to analyse the systemic result of all these contributions together, and to compare the consolidated contribution with the objectives expressed by the European communities for GHG emission. Furthermore to improve the measurements and previsions of the GHG emission of the European community, with specific approaches for CO2, CH4, NO_x etc. in order fulfil the Paris agreement.

Attributing a price to a ton of CO_2 is one of the action tools to diminish GHG emissions. Alongside with the Kyoto system, European ETS functions technically well and could be an example in conjunction with other systems which are being and/or will be developed worldwide; it could be interconnected to them.

The issue of competitiveness' loss of industries subjected to the EU ETS, in comparison to others not dependent on ETS, is an area to be analysed, at least in case of industries which have not received their free emission allowances. One important point is that the CO_2 price, in the present situation, might be too low for its intended purpose. One proposal, depending on the necessity of a price signal calls for a price collar in the EU ETS with lower and upper boundary.

The Intergovernmental Panel on Climate Change (IPCC) was invited (Decision draft II-21) to provide a special report in 2018 on the impacts of global warming of 1.5 °C above pre-industrial levels and on related worldwide greenhouse gas emission pathways. Beside considerations on temperature, it would be useful to dedicate more efforts (measures, historical and paleontological studies, modelling) to the potential evolution of water resources in various regions of the world, namely in those regions or countries where water resources are the main subject of concern. A first step in could be to have a global approach (historical analysis, measures, modelling) of the evolution of the water resources in the European continent, and to propose financial and scientific support to the countries of Africa to do the same there.

One summarizing reflection to be made about COP21 and its implications on the European electricity system is that even though most climate areas have been previously targeted, measured and quantified, this agreement and many participants' intentions are for continued but also increased pace on the transition from energy sources with climate and environmental impacts to more sustainable alternatives. The transition will also affect the electricity

[24] NATF, 2013

transmission and distribution as well as electrical storage and the interconnectivity with other areas of the energy and transport system.

3 Production

The Production chapter displays the current electricity production in Europe, as well as major energy sources; coal, hydro, natural gas, nuclear, solar, solid biofuels ,waste and wind.

Each energy source is briefly described and mapped, with current production, capacity and share of European electricity production. Furthermore future development and critical success factors is showcased as well as an energy triangle analysis of each source. The chapter ends with an observation of the future European electricity system.

An increased electrification of the energy system is a trend across the global energy system[25]. The growth in electricity demand has the potential of transforming both energy supply and end use.

Current trends include both electrification of heat in the form of heat pumps and electrification of the transport system. Increased electrification of buildings using heat pumps is an approach to improving buildings energy efficiency. The usage of heat pumps for heating and cooling of space and water allow electricity to further displace natural gas. Even geothermal energy and solar thermal requires electricity in order deliver heat.

Electrification of the transport system is another source for increased electricity demand. The transport system in combination with improved fuel economy and new vehicle technologies will reduce the oil use significantly in the transport sector since this sector today is heavily oil-dependent.

Electricity has historically been generated with mainly fossil fuels together (coal 23,6 % and 11,4 % natural gas) with hydropower (18,6 % in 2014) and nuclear power (26,2 % in 2014) which is why an increased electrification also requires an increased decarbonisation in the future energy production system. A growth in electricity demand and the change in character of the energy supply system require increasingly strategic approaches of how to balance supply and demand. The future energy system is expected to be composed of a combination of central power plants (fuelled with gas, biomass, nuclear power plants and large hydropower plants) and numerous small decentralised plants based on renewable energy like wind, solar and biomass.

Important pre-requisites for a European-wide electrification of the energy system are development of infrastructure, harmonization of the national energy systems, development of the European internal market, and great strengthening of the cross-border collaboration between European countries.

The current European Electricity system is made up of numerous national and regional European electricity markets depending on scope e.g. are six regional wholesale electricity markets. As previously described in the introduction chapter, the EU's competences in the field of energy policy have developed slowly over time. To increase the harmonization and electricity exchange, EU's current internal energy market strategy requires the removal of trade barriers, the approximation of tax and pricing policies and measures in respect of norms and standards etc.[26] Different electricity market designs are further discussed in the Market observation chapter.

Intermittent or Dispatchable Power

There are several ways to group and compare energy sources, if they are weather dependent or not, if they are renewable or not etc. One way to compare different energy sources is if they are intermittent or dispatchable. An intermittent energy source's output varies according the availability of the resource. Dispatchable power, on the other hand are flexible since their output can be turned on or off on demand. [27]

The intermittency which characterizes solar and wind power is one of the central challenges in designing the new energy system. However, although they cause challenges with regards to balancing electricity supply and demand

[25] *Energy Technology Perspective, 2014*
[26] European Parliament webpage
[27] *IEA, 2008*

in the current energy system, wind and solar power will be necessary for developing a sustainable energy system in the future. The intermittent power is unevenly distributed in Europe which puts greater pressure on transmission between countries. Also hydroelectric power, run-off the river, is regarded as intermittent due to its unpredictable nature. The availability of hydropower is however much higher than of solar and wind power. The availability of hydropower with reservoirs is considered as energy storage. Also the hydropower is very unevenly distributed in Europe, giving countries like i.e. Norway, Sweden and France a storage capacity which can balance the intermittency of wind and solar.

Even with increased energy efficiency and growth in their installed capacity, wind and solar power will not suffice to meet future demand. Therefore, other sources of energy such as thermal power or nuclear have to be integrated in the electricity system. Thermal power includes electricity generated from coal, gas, nuclear, biomass and waste.

The volatility of wind and solar power makes it hard to balance the energy system which is currently designed only to balance the electricity demand side but will in the future also have to balance electricity production. Therefore, dispatchable power from for example gas turbines will be increasingly important in the new system.

Global warming will have serious consequences for Europe and might as well affect its electricity production. Intermittent power and weather dependent energy sources such as solar, wind, hydro but also biofuels might be affected. Generally the climate change will affect the predictability of the weather as well as the frequency of extremes such as droughts and floods as well as desertification, changes in sea level and higher temperatures. This will affect mentioned energy sources, with i.e. hydro power already facing water scarcity in Southern and Eastern Europe as well as the Alps region, biofuels facing droughts and desertification in the south of Europe etc. This might lead to that intermittent and weather dependent energy sources become even more "unpredictable" in the future.[28]

3.1 Electricity Production in Europe

The European electricity generation, 3278 TWh (2014), predominantly consists of four major sources of fuel; more than one quarter of the net electricity generated in Europe in 2014 came from nuclear power plants (26.2 %), while almost double this share (40,9 %) came from power stations using combustible fuels (such as natural gas, coal and oil). Among the renewable energy sources, the highest share of net electricity generation in 2014 was from hydropower plants (18.6 %), followed by wind turbines (7.6 %) and solar power (2.8 %).[29]

The graphs below show installed electricity capacity in GW in EU to the left and produced electricity in TWh to the right. As can be seen there is a large difference between installed capacity percentages for the renewable energy sources compared to the fossil combustible fuels. This means that in order to replace the existing power fleet, the European total installed capacity needs to increase significantly from todays 1017 GW.

[28] *European Commission webpage, 2016*
[29] *Entso-E, Yearly Statistics & Adequacy Retrospect 2014, 2015*

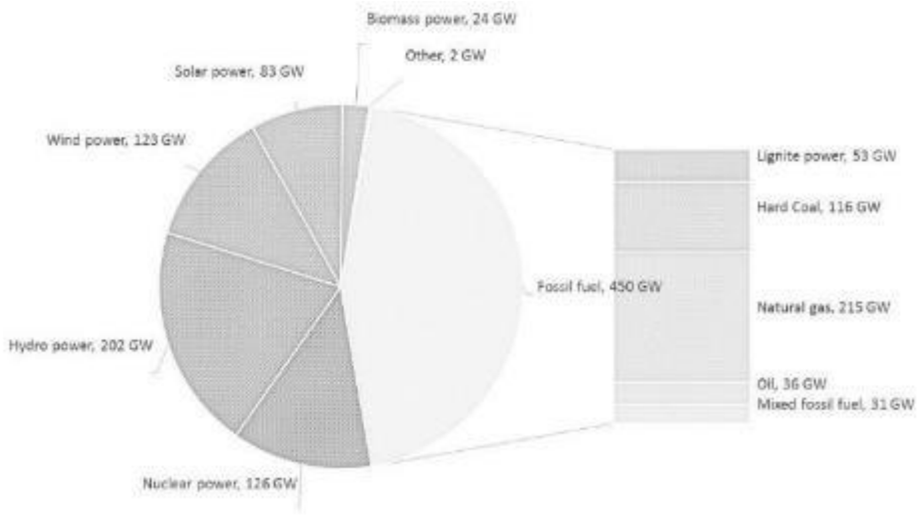

Figure 2 – Composition of European installed power capacity in 2014[30]

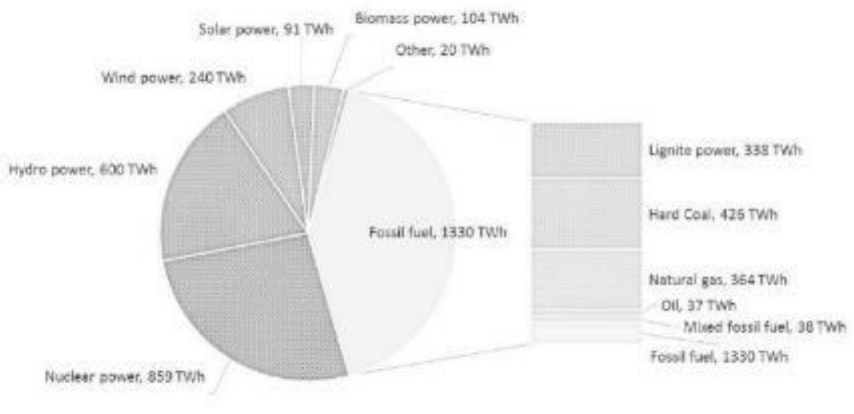

Figure 3 – Composition of European produced electricity in 2014[31]

France and Germany are the top countries in terms of electricity production from nuclear power followed by UK, Spain and Sweden. The significance of nuclear power was particularly high in France, Hungary and Slovakia in 2014 where it accounted for more than half of the national production of electricity. Germany have permanently shut down eight of its reactors and pledged to close the rest by 2022 as a consequence of the Fukushima nuclear disaster and France is today in a national debate over a partial nuclear phase-out whereas other countries (e.g. UK, Poland andHungary) are planning to construct new plants.

Germany, Spain and the UK are the top three countries with respect to largest installed capacity of wind power in 2014. Norway, France and Italy are the countries with the largest amount of hydro power.[32]

As highlighted earlier however, thermal power constitutes a large share of the European electricity fleet. The age of these power plants are of importance when looking at the development of the European power system. This gives an indication of when they need to be replaced and the shape and efficiency they might have. The graph below show the age structure for the existing thermal power capacity, the total installed thermal capacity is 600 GW and the graph show the minimum age distributed over four regions. As can be seen, almost 400 GW is at least 20 years old[33]. This means that the majority of the thermal power fleet needs to be replaced within the next 30 - 40 years.

[30] *Entso-E, Yearly Statistics & Adequacy Retrospect 2014, 2015*
[31] *Entso-E, Yearly Statistics & Adequacy Retrospect 2014, 2015*
32 Entso-E, Yearly Statistics & Adequacy Retrospect 2014, 2015
[33] *NEPP, 2014*

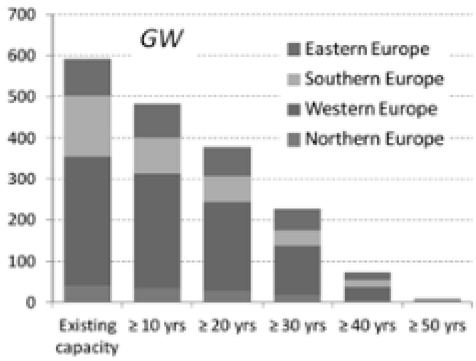

Figure 4 – Age structure of the European thermal energy capacity[34]

The renewable share of the electricity production in Europe has increased steadily since the mid-nineties, mainly consisting of wind power in the beginning. Other renewable electricity production sources have however started to claim a larger share during the mid-two thousands. Between 2002 and 2014, the relative importance of renewable energy sources in net electricity generation grew from 13 % to 32,7 % (18,6 % hydro, 7.6 % wind and 2.8 % solar). [35]

The following graph show how the total installed capacity has developed from 1995 up till 2013, and also how the share of intermittent and wind power has specifically developed.

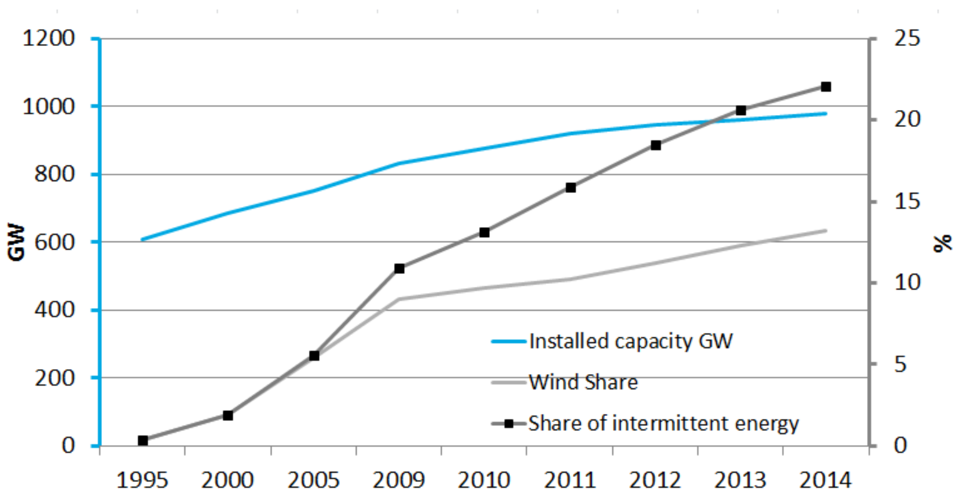

Figure 5 – The development of total installed capacity and the share of renewable energy development in Europe, specifically wind power[36]

EU has been increasingly reliant on imports, particularly of oil and gas, as a result of the downturn in the primary production of hard coal, lignite, crude oil, natural gas and more recently nuclear energy. On average, 2014, 53 % of EU total coal consumption and 18 % of total gas consumption used for electricity and heat were imported[37]. Above 53 % of the EUR-28 gross inland energy consumption in 2013 came from imported sources. [38] This dependency of energy imports forms the backdrop for policy concerns relating to the security of energy supplies which may be threatened if the imports come from a few partners. Almost 77 % of the EUR-28 imports of natural gas in 2013 came from Russia (39 %), Norway (29, 5 %) and Algeria (12, 8 %)[39]. The EU import of crude oil comes predominantly from Russia (34 %) followed by Norway (12 %). The European Commission has stated that LNG (Liquefied natural gas) is

[34] *NEPP, 2014Ibid.*
[35] *Entso-E, Yearly Statistics & Adequacy Retrospect 2014, 2015*
[36] *EU Energy Factbook, 20132015*
[37] *Eurelectric, 2015*
[38] *Eurostat webpage*
[39] *Ibid.*

one possible solution to satisfy European energy security needs. By using the increasing LNG export capacity of countries such as USA, Australia etc. and increase the import capacity and interconnectivity of Europe, the EU strategy aims to build capacity, almost replacing current conventional gas imports.[40] One example is the LNG terminal in Klaipeda, Lithuania that gives the Baltic States the opportunity to reduce their dependence on Russian gas. *"The EU's recent energy stress tests showed that the LNG terminal could ensure supplies to all protected customers in the three Baltic states, in the case that Russia cuts off its gas supplies*"[41]

Shale gas is another possible source of gas that is explored in parts of Europe. USA is at present the only country with large scale shale gas production which among other things has provided the country with competitive gas and electricity prices comparing to Europe.[42] The political situation in Europe is somewhat different and the public across many countries is opposed to this technology, more about this in the gas section below.

Energy Poverty in Europe

Energy Poverty is often described as a situation when households or individuals do not have adequate resources to provide their homes with energy, i.e. in the form of electricity and/or heating.[43] In 2012, 10, 8 % or 54 million citizens of the European Union belonged to this group.[44] This problem was especially highlighted in the southern and central parts of the European Union and often due to rising energy prices, poor living conditions or low incomes. Energy poverty is one of the issues targeted by the EU's Third Energy Market package but where the actual responsibility lies with the national governments to identify and protect vulnerable individuals and households. Some research suggests that the best way to deal with this issue, in the short term is to do financial interventions but in the long term energy efficient measures such as retrofitting buildings, raising awareness and transparent and comparable prices are needed. [45]

European commission has so far promoted a better exchange between countries through best practices and is set to set up a series of recommendations on how to decrease the vulnerability such as energy efficient measures.[46]

Electricity production and environmental concern

All electricity production faces environmental concerns, from both renewable and non-renewable sources. If it is not the actual production of electricity, it could be the production of the production units that emits emissions. One example is the production of Solar PV There are issues on how the modules are produced and the levels of emissions vary with geography, manufacturer and by chosen technology. News about toxic emissions poising water and air, unacceptable worker conditions etc. has forced many manufacturers to update their business standards but there are uncertainties in how environmental regards are looked after. There is also greenhouse gas emissions, associated with production and the "energy payback" (how long it take for the module to pay back its production energy) ranges from six months to two years, depending on the electricity production mix supporting the production and where the solar PV is later used.[47]

Additional issues for e.g. wind power but also other electricity production units is that they often have local environmental concerns, sound pollution and other effects to the local biodiversity. Another example is large scale hydropower that often utilize large reservoirs of water, allowing it to meet sudden demand fluctuations but also controversial since it affect water availability and the local ecosystem.

These examples show that all production of electricity have environmental concerns and it is a complex issue to include them in deciding which production mix is best suited for a future electricity system in Europe. More research

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[40] *European Commission, 2016a*
[41] *Dailymail websitewebpage*
[42] *Financial Times webpage*
[43] *The actual definition can vary between different countries.*
[44] *Number represents citizens who couldn´t keep their homes warm, with corresponding numbers for poor housing conditions or late payments of utility bills*
[45] *Insight_E, 2015*
[46] *European Commission, energy poverty*
[47] *IEEE Spectrum webpage*

might therefore be needed on this area, where not only carbon emissions but also other environmental concerns are taken into account.

Environmental issues are concerned by the rapid progress of Carbon Capture, Storage and Use. Anticipating the interest of carbon use will by-pass, to some extends, the drawbacks of carbon storage issues. Carbon use and recycling is today a very active and promising field of research

3.1.1 Solar Power

Electricity from solar power can be produced through photovoltaic cells (PV) or through concentrated solar power plants (CSP). Also the combination of the two, concentrated photovoltaic (CPV) can be used to generate electricity. The technology that is most widely used in Europe is solar PV.

Solar PV

Solar photovoltaic cells (PV) are generally made from modified silicon, or other semi conductive materials, that absorb and convert sunlight into electricity. There are three basic types of PV modules: monocrystalline, polycrystalline, and thin-film.

The two first basic types of solar PV modules can be called traditional solar cells. The third one, thin-film, which have layers of micrometer thick material can be categorized as second generation solar cells. Because of their flexibility, thin film solar cells can double as rooftop shingles and tiles, building facades, or the glazing for skylights. The third generation solar cells are being made from a variety of new materials besides silicon such as plastic lenses or mirrors to concentrate sunlight onto a very small piece of high efficiency PV material (CPV mentioned above).

The net electricity generation in Europe in 2014 was 92 TWh of solar power, which corresponds to a share of 2.8 %.[48] In 2002 the share of electricity generated from solar power was only 0.01 percent. The installed solar PV capacity continues to grow and in 2014, the cumulative capacity base in Europe was 82,8 GW.[49] UK took the top position of the European market over Germany with 2,4 GW installed in 2014. Germany otherwise represents the most developed PV market in Europe, but "only" installed 1,9 GW in 2014[50].

Table 1 – Solar Power installed capacity, electricity production and share of European electricity production[51]

Solar power	
Installed capacity	82,8 GW (year 2014)
Electricity production	92 TWh (year 2014)
Share of European electricity production	2.8 % (year 2014)

Over the last two decades PV system prices have decreased all over the world, significantly driven by technology and market developments; the cost of PV modules decreased by three times in two years[52]. The technology is very flexible and can be adapted to many different applications[53].

One issue of concern for the European Commission has been the majority of the top global PV module suppliers are Chinese (49 % market share in 2014) and has accused the Chinese manufacturers of price dumping, forcing restrictions and duties on Chinese solar imports since December 2013.[54,55]

[48] *Entso-E, Yearly Statistics & Adequacy Retrospect 2014, 2015*
[49] *Ibid.*
[50] *EPIA, global market outlook*
[51] *Entso-E, Yearly Statistics & Adequacy Retrospect 2014, 2015*
[52] *European Commission, 2013a*
[53] *Palmblad, 2014*
[54] *IHS Webpage*
[55] *European Commission, 2016b*

CSP

CSP produces electricity by converting solar energy into high temperature heat using diverse mirror configurations. The heat is then used to produce electricity through a conventional generator system using turbine.

Spain has by far the largest installed CSP capacity in Europe. As of 2014, 49 plants were in operation and most of them had a gross capacity of 50 MW. In total Spain has an installed capacity of 2,2 GW of CSP. France has two small plants (below 10 MW) under construction and one in operation. Germany and Italy each have one CSP plant in operation with capacities below 5 MW[56].

CPV

CPV is, as mentioned, a combination of PV and CSP where lenses or curved mirrors are used to concentrate a large amount of sunlight onto a small area of PV cells to generate electricity.

3.1.1.1 Future development

The solar potential is large. The PV technology is likely to become increasingly cost effective. No fundamental technological breakthroughs are needed, combining learning and economies of scale will bring the cost of modules down[57]. The next generation solar PV is multilayer PV cells which is likely to come into full force after 2030. These units use multiple layers of PV cells in order to optimize the sunlight transformation throughout the course of the day.

Scenarios point at 0.8-3 TW of PV capacity installed worldwide in 2030. With current market trends, and without major changes of policy, a share between 7 and 11 % of PV in European electricity demand 2030 appears realistic according to EPIA (European Photovoltaic Industry Association).[58]

Investment costs of utility scale and rooftop PV systems in the IEA Energy Technology Perspectives 2014 - 2DS and the 2DS hi-Ren scenarios can be seen in the figure below.

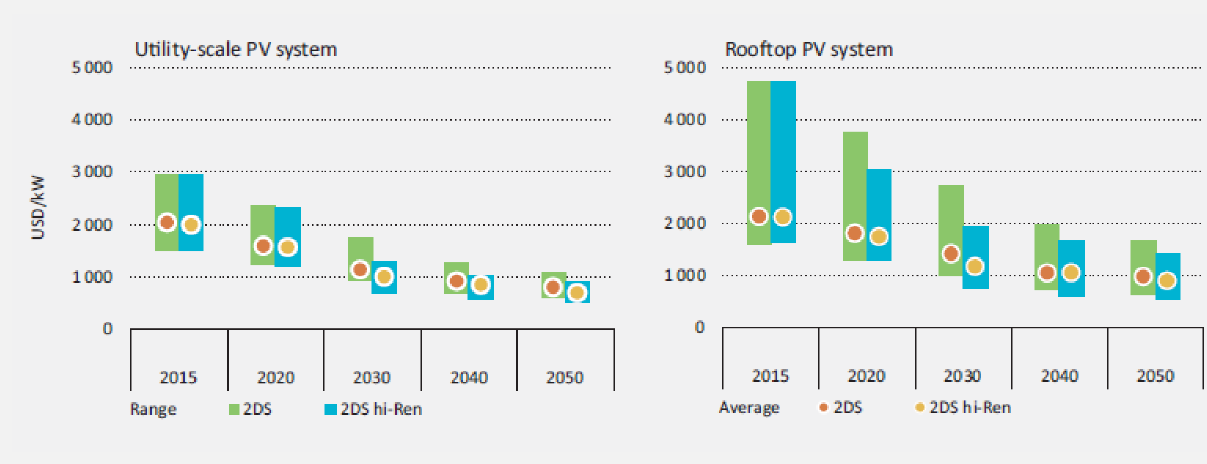

Figure 6 – Investment cost development of PV systems[59]

C-Si will continue to be the dominate PV technology, most likely also in the 2030 perspective and maybe even further. C-Si has several strengths, it is abundant and non-harmful and it is an established industry but one that still has potential for cost reductions enough to make PV interesting for the big energy picture[60].

[56] NREL Webpage
[57] Palmblad, 2014
[58] EPIA Webpage
[59] Energy Technology Perspective, 2014
[60] Palmblad, 2014

There are other technologies that will grow in specific market segments, like thin film and high efficiency PV/CPV, but C-Si is predicted to grow at least as fast in the near term future[61].

The graph below show the PV modules production capacity until 2017 (MW; %)

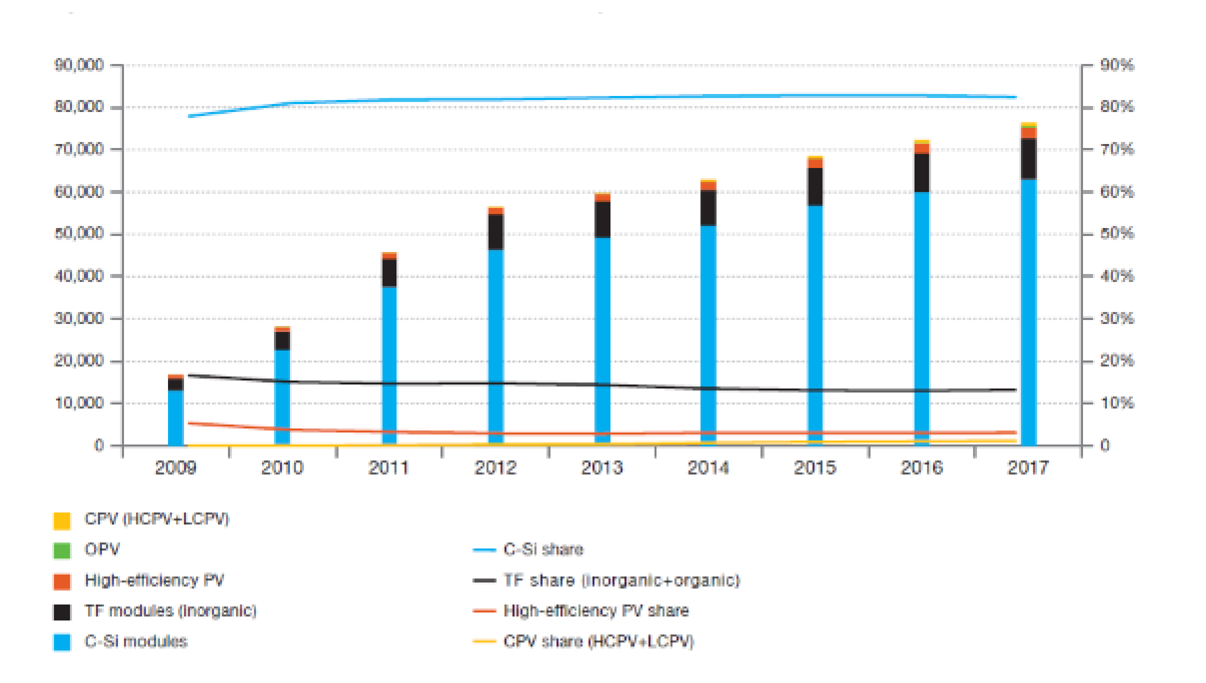

Figure 7 – PV modules production capacity until 2017 (MW; %)[62]

In the IEA Energy Technology Perspective the 2DS scenario prediction of solar PV share and the 2DS Hi-Ren (the same scenario but with a higher share of renewables) share in the power sector can be seen in the graphs below.

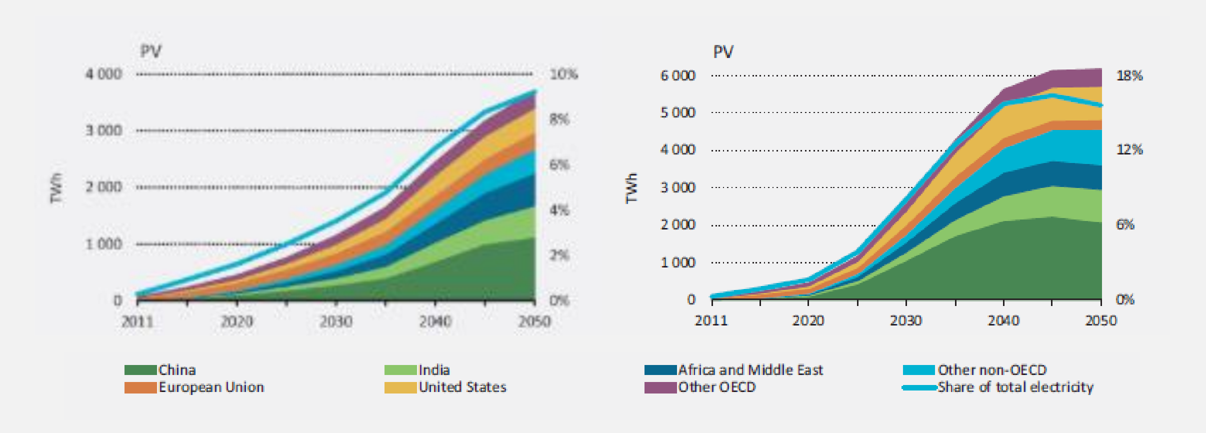

Figure 8 – PV development in the 2DS scenario (left) and 2DS Hi-Ren (right) until 2050 [63]

As can be seen solar is becoming a main source by 2050 although the majority of the increase is taking place after 2030. Current scenarios point at 0,8 TW to over 3 TW of PV capacity installed worldwide in 2030, it should however be noted that future energy scenarios have tended to underestimate solar PV potential in the past.[64]

[61] *Ibid.*
[62] *EPIA*
[63] *IEA, 2014a*
[64] *Palmblad, 2014*

3.1.1.2 Critical success factors

Solar energy is renewable and there are no direct emissions associated with the operation of a PV system. The PV market has moved from a subsidy driven market to a phase today where it is starting to become competitive without subsidies as a result of dramatic cost reductions.[65]

Handling the intermittent production of solar energy is a critical success factor for solar power production. Indeed, the electrical system should be developed in a matter that assures security of supply (so that the peak load can always be met) even when the sun is not shining, this means that sufficient storage capacity is installed to bridge the cloudy hours or other dispatchable production that produces independent of the climate.

Table 2 – Energy triangle analysis solar PV

Security of supply	Due to its intermittent nature, PV requires balancing power to be fully exploited in the energy system. PV can reduce peak load since peak production might coincide with peak consumption. The benefit of solar however is that it is not reliant on foreign fuel and therefore contributes to security of supply. Reinstating the production of solar PVs in Europe should be considered in order to lessen the dependency on import.
Competitiveness	PV is not generally cost competitive against the grid mix average price across Europe today. In some markets e.g. Italy and South Germany grid parity has been achieved and costs are continuing to go down. Large scale plants have reached market parity in Italy but generally needs support to become competitive. Feed-in-tariffs and investment support increases the speed of implementation. Net metering gives significant support and local batteries can increase self-consumption. As the price for PV cells is decreasing the technology is rapidly becoming competitive. However, a predictable and stable electricity price is necessary to facilitate large investments in PVs.
Sustainability	In the usage phase, PVs are very sustainable and generate no GHG emissions. However, as the production phase is energy and material intensive, the overall carbon footprint is low but relevant.

3.1.2 Hydro Power

Hydropower is the major renewable generation technology in Europe today. It delivers storage capacity and stabilising services for the power system which are crucial for a high security of supply of electricity[66].

There are two different types of hydro power depending on their size and characteristics. Large scale hydropower often utilize large reservoirs of water, allowing it to meet sudden demand fluctuations but also controversial since it affect water availability and the ecosystem. Small Hydro Power Plants (SHPs, usually below 10 MW) on the other hand are not only smaller but generally use the flowing water or run-of-the-river where there is a significant fall. SHPs generally don´t require reservoirs and therefore have less effect on water availability and the ecosystem. The lack of reservoirs also means that they lack storage capacity and bigger stabilising services making it more vulnerable for seasonal characteristics. Hydro power accounts for more than half of the renewable electricity production in Europe today.[67]

About 608 TWh net electricity was generated from hydropower in Europe in 2014. This corresponds to 18,6 % of the European net electricity generation. [68]

[65] *Ibid.*
[66] *Eurelectric, hydropower*
[67] *European Commission webpage, Hydropower*
[68] *Entso-E, Yearly Statistics & Adequacy Retrospect 2014, 2015*

Table 3 – Hydro Power installed capacity, electricity production and share of European electricity production[69]

Hydro power	
Installed capacity	202 GW (year 2014)
Electricity production	608 TWh (year 2014)
Share of European electricity production	18.6 % (year 2014)

There were in 2010 more than 21 800 small hydropower stations in EU (with capacity up to 10 MW).[70] The installed capacity from small hydropower plants in Europe (with capacity from 1 MW to 10 MW) corresponds to more than 15,8 GW in 2014. The large hydropower (more than 2900 plants) stations (with capacity larger than 10 MW) correspond to about 185 GW. Norway produces about 22 % of the total electricity being produced from hydro power in Europe. [71]

Table 4 – Small Hydro Power installed capacity, electricity production and share of European electricity production[72]

Small Hydro power	
Installed capacity	15,8 GW (year 2014)
Electricity production[73]	61,5 TWh (year 2013)
Share of European electricity production[74]	11,2 % (year 2013)

The map followed illustrates how hydropower can be used as a form of centralized storage. Hydropower can be generated when needed to meet rapid or unexpected fluctuations in demand due to the storage reservoir of water. There are however limited possibilities for sites and environmental impacts through land use and conversion[75]. 77% of the total storage capacity in hydro is located in the Nordic countries.

[69] *Ibid.*
[70] *Small Hydro World webpage*
[71] *Entso-E, Yearly Statistics & Adequacy Retrospect 2014, 2015*
[72] *Ibid.*
[73] *Small Hydro World webpage*
[74] *Small Hydro World webpage, same countries chosen as ENTSO-E*
[75] *Eurostat*

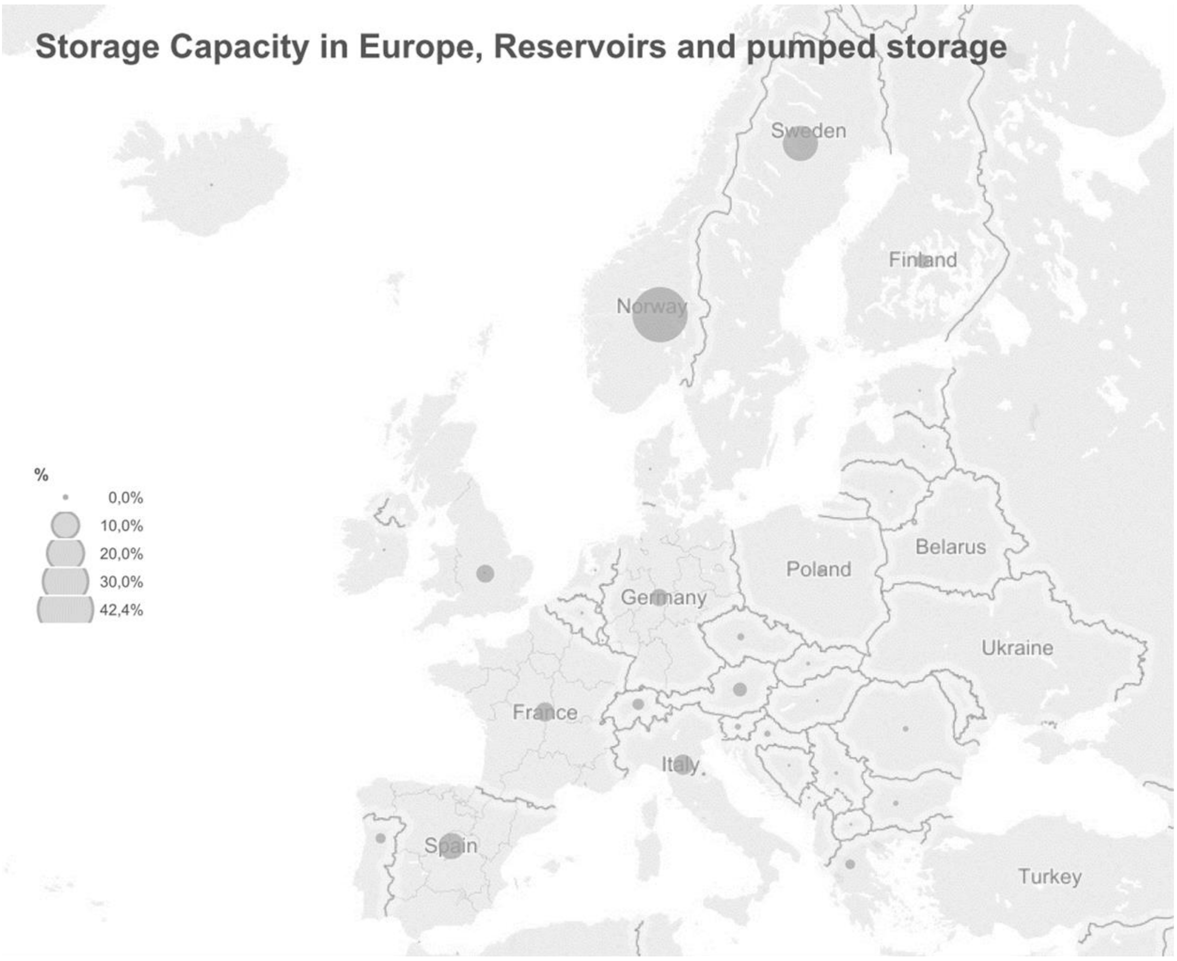

Figure 9 - Hydropower can be used as a form of centralized storage, the figure show % of total European storage capacity (EU 28). [76]

More about electricity storage can be found in chapter 6 – electricity storage.

3.1.2.1 Future development

There is a significant amount of pumped storage potential remaining in Europe today. Several countries with already existing pumped storage capacities are planning to build new plants, but so are also countries with no or a small experience in pumped storage. These countries are for example Cyprus, Estonia and Hungary.[77] Some countries are also not utilizing the potential they possess.

There are still technical and environmental challenges for hydropower that should be addressed in order to improve the technology and to exploit its remaining potential. The efficiency and dependability need to be improved, and the costs and environmental impact reduced.

The small hydropower plants can normally only compete with conventional power generation where allowances are made for the external costs associated with fossil fuels why cheaper technologies should be developed to enable the exploitation of smaller rivers and shallows reservoirs.[78]

[76] *Entso-E, Yearly Statistics & Adequacy Retrospect 2014, 2015*
[77] *Eurelectric, 2011*
[78] *European Commission webpage, hydropower*

There is a need to further improve equipment design such as for example turbines with less impact on fish populations. There is also a need to investigate different materials, to improve control systems and optimize generation as a part of integrated water management systems.[79]

"Although most of the best sites for hydropower plants have already been developed in Europe, at present only about half of its technically feasible potential has been developed for EURELECTRIC Europe and only about one third in the non-EU member states. There is thus additional potential of 600 TWh a year in EURELECTRIC Europe (of which 276 TWh a year in the EU-27), and of about 60 additional TWh a year in the non-EU member states – more than 650 TWh a year in total"[80]

The graph below shows developed and still available technically feasible hydropower potential per country in TWh. Denmark, Estonia and the Netherlands have very small hydropower generation today and with comparatively little development potential. Malta has neither hydropower generation, nor any potential. In total, the four countries make up only 0.178 TWh of hydropower generation a year and represent 0.6 TWh of hydropower potential that could still be developed. They are therefore not included in the figure.

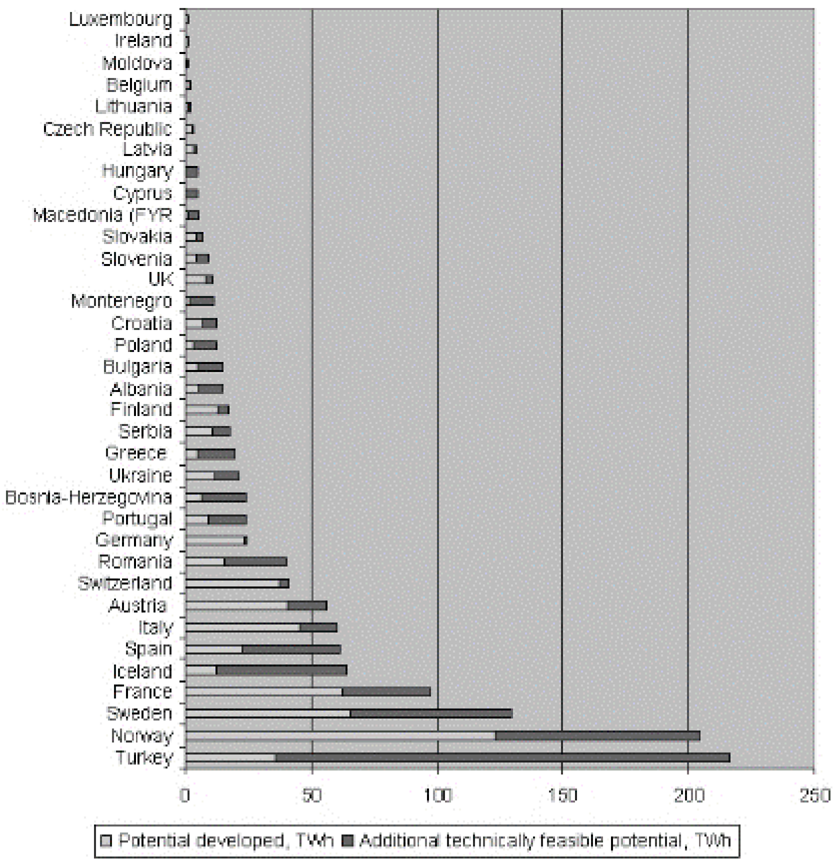

Figure 10 – Remaining hydropower potential[81]

3.1.2.2 Critical Success factor

The EOM does not provide incentive for making large investments in hydropower plants which will only be used a few hours per year. Capacity mechanisms is needed in order to attract investment.

To utilize the remaining potential of hydropower, the numerous barriers hindering the development of small hydropower should be addressed and research efforts carried out. These hinders are the issue of standardization,

[79] *European Commission webpage, hydropower*
[80] *Eurelectric, hydropower*
[81] *Eurelectric, 2011*

the regulatory and environmental constraints and the emerging issue of climate change, which could have a strong impact on hydropower production.

Table 5 – Energy triangle analysis hydro power

Security of supply	Hydro power, with its excellent ability to balance intermittent power, is greatly increasing the security of supply. Increased interconnection capacity is needed to fully exploit the balancing capacity of the hydro power.
Competitiveness	The EOM (energy only market) does not provide incentive for making large investments in hydropower plants which will only be used a few hours per year. Capacity mechanisms might be needed. Harmonization of market rules is important to fully exploit the balancing capability of hydro power. Integration of the European electricity system generally improves the business case for interconnections but different market rules e.g. capacity market connected to energy only markets is not as good business case as connecting similar markets.
Sustainability	Environmental impact from hydropower is mainly concentrated to the impact during the construction phase and the effect on the production site environment.

3.1.3 Wind

The share of net electricity generation in Europe in 2014 was 249 TWh for wind power, which corresponds to 7.6 %. The proportion of net electricity generated from wind power increased from 1.2 percent in 2002. [82]

Wind power (mainly onshore) contributes with a significant share of electricity generation in Europe. In 2014, there were about 123 GW of installed wind energy capacity in Europe, 94 % of which was installed onshore. The offshore installations represents 12,6 % of the annual wind market in the EU. The wind energy market as a whole has increased, with annual wind power installations rising from 5,84 GW in 2004 to 11,8 GW in 2014.[83]

The figure below show installed wind power capacity in Europe.

[82] *Entso-E, Yearly Statistics & Adequacy Retrospect 2014, 2015*
[83] *EWEA, 2015*

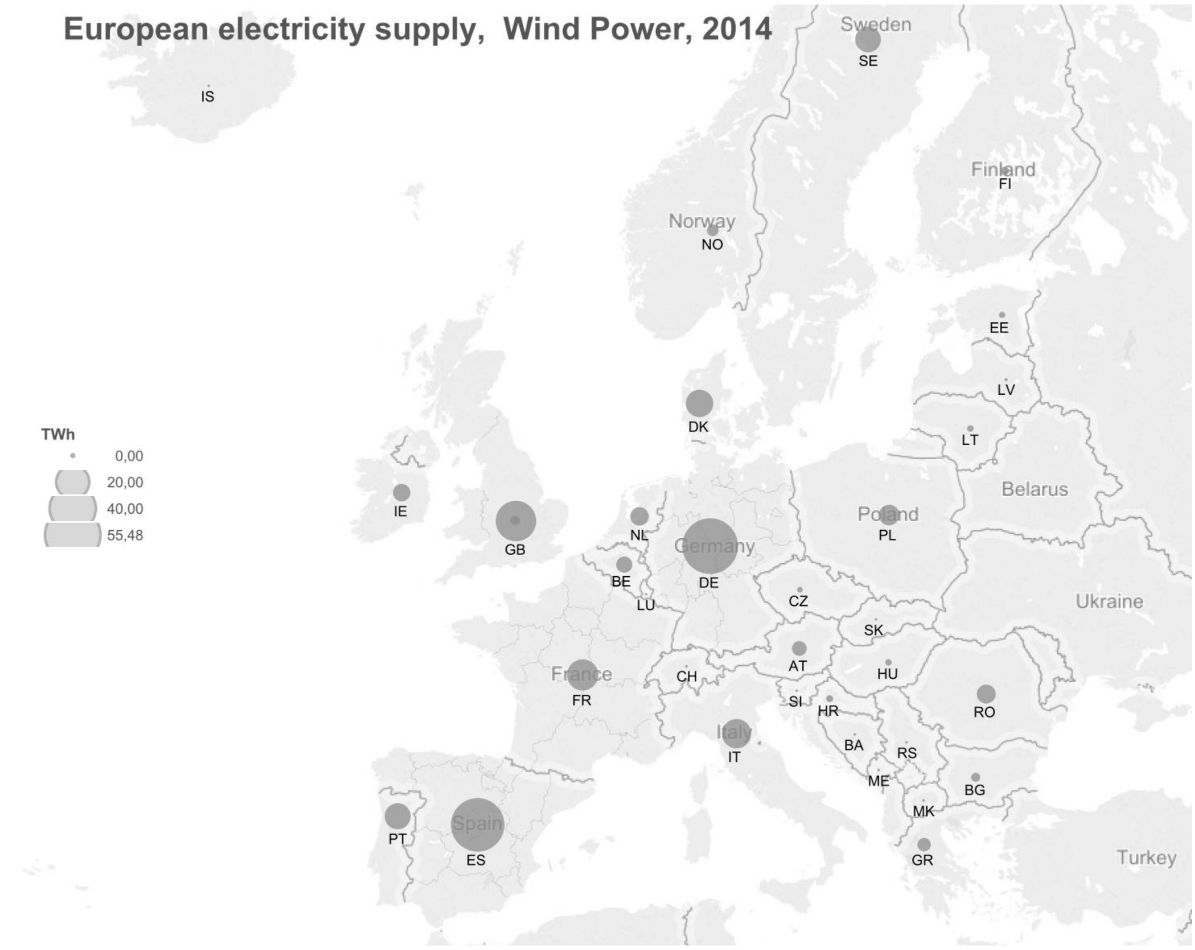

Figure 11 - Electricity from wind power in Europe [84]

In Europe, Germany was the largest market in 2014 in terms of annual installations; about 5,3 GW was newly-installed. The UK came in second place with 1,7 GW followed by Sweden, France and Norway. Of all new EU installations in 2014, 59 % were in Germany and the UK. This is a significant concentration of new-installations, since 2007 the installations were spread across Europe. Interesting to note is that at the previous large markets for wind power in Spain and Italy the decrease to current level of installations is significant with 27 GW and 107 GW installed in 2014 respectively.[85] The annual offshore and onshore wind power installations are illustrated in the diagram below. [86]

[84] *Entso-E, Yearly Statistics & Adequacy Retrospect 2014, 2015*
[85] *EWEA, wind in power*
[86] *EWEA, 2015*

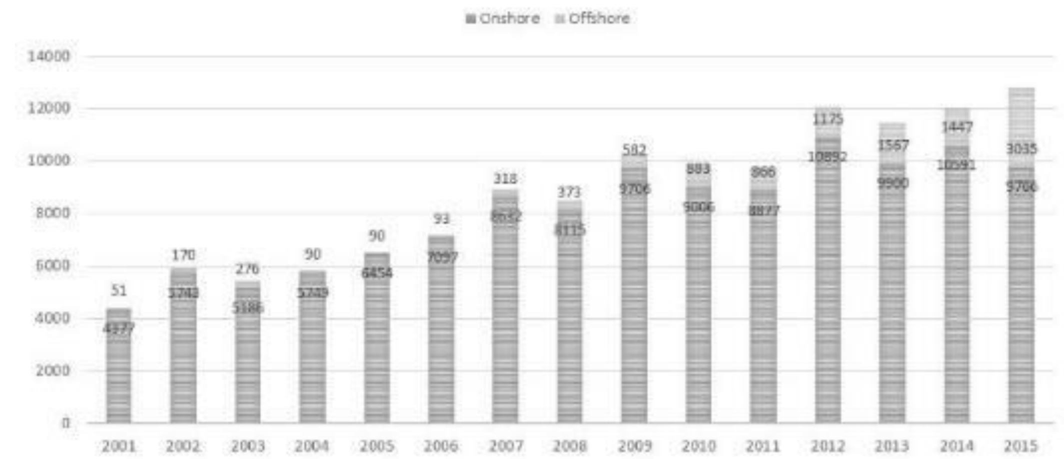

Figure 12 – Annual wind installations (MW), onshore and offshore in the EU (EU 28)[87]

Table 6 – Wind Power installed capacity, electricity production and share of European electricity production[88]

Wind power	
Installed capacity	123 GW (year 2014)
Electricity production	249 TWh (year 2014)
Share of European electricity production	7,6 % (year 2014)

3.1.3.1 Future development

A comparison of LCOE (Levelized Cost Of Energy) for different technologies however show that by 2030 onshore wind is predicted to be the second cheapest[89]. Offshore wind power is still much more expensive than onshore. Offshore wind cost of electricity production can however be reduced through up-scaling of turbines and industrialization of other parts of the plant. The industry is on track to achieve its target of cutting costs by approximately 40% by 2020[90]. EWEA predicts that wind could meet 28.5% of Europe's electricity demand by 2030 and 50% by 2050[91]. The expected development can be seen in the figure below. The European Technology Platform for Wind Energy (TPWind) sees wind energy as the leading renewable energy technology and given the right support, TPWind expects that wind energy could provide up to 34% of EU electricity by 2030. However, according to TPWind this target will not be achieved if the sector and policy makers only think in the short term, long-term strategic action in technology and policy research is fundamental[92].

[87] *EWEA, 2015*
[88] *Entso-E, Yearly Statistics & Adequacy Retrospect 2014, 2015*
[89] *EIA, 2014*
[90] *Larsen & Petersen, 2014*
[91] *Clean Technica webpage*
[92] *Larsen & Petersen, 2014*

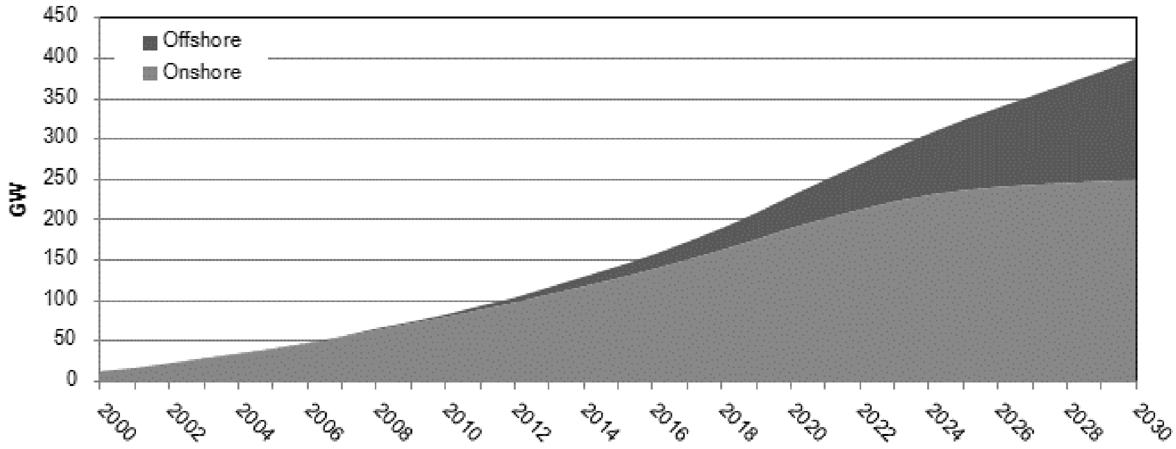

Figure 13 – Cumulative onshore and offshore wind in Europe[93]

3.1.3.2 Critical success factors

EU efforts continue with offshore wind applications where the technology is still improving and cost are decreasing.[94] Turbine manufacturer's worldwide market share depends strongly on how their home market performs.[95]

Because of the intermittent nature of wind power generation, and the fact that there is no way of storing excess energy generation, grids in Eastern Europe are stretched to their limits and face potential blackouts when output surges from wind turbines in northern Germany or along the Baltic Sea. This is a situation that highlights the difficulty many countries are facing as they try to integrate turbines in the existing limited infrastructure.[96]

Table 7 – Energy triangle analysis wind power

Security of supply	Wind power is only to a limited degree dispatchable (e.g. in Sweden 6 % of installed capacity is calculated as firm capacity). Prediction models are however continuously improved. Variability of wind can be managed by interconnectors and storage. Wind Power production does not necessarily coincides with peak consumption due to the variability of wind and can thus increase the need for balancing power. Balancing can be done with dispatchable power, interconnectors or energy storage. Wind power is not reliant on foreign fuel and therefore contributes to security of supply. There is also a strong industrial base for wind power in Europe
Competitiveness	Wind power is generally not cost competitive and requires support schemes today. The cost development is positive particularly for land based wind power but there is also potential for offshore wind to reduce its costs. A large scale European wind power expansion requires integrated European electricity system as well as cross boarder collaboration in order to function properly. "Shift focus from high economic incentives to long-term policies that provide predictable and reliable market and regulatory framework" (IEA)
Sustainability	In the usage phase, wind power is very sustainable and generates no GHG emissions. Visual, sound and vibration disturbance is however making many people reluctant to the development of wind power near communities. Also the effect on the close by bird flora is significant.

[93] *EWEA,2009*
[94] *Martinez, 2014*
[95] *European Commission, 2013a*
[96] *Governors' Wind Energy Coalition webpage*

3.1.4 Nuclear Power

Nuclear power plants can be based on either fission or fusion reactors. Fission reactors are the type of reactors used today while fusion reactors are still at research stage. Nuclear power in this report refers to fission reactors.

In Europe in 2014, more than one quarter of the net electricity generated came from nuclear power plants, and a share of the total of 26,2 %. Between 2002 and 2014, the share of electricity generated from nuclear power plants decreased from 31.6 to 26.2 percent. [97] This is primarily due to the increased renewables production in Europe but also to a modest fall of 12 % for nuclear energy in EUR-28 (compared to e.g. – 54 % for crude oil)

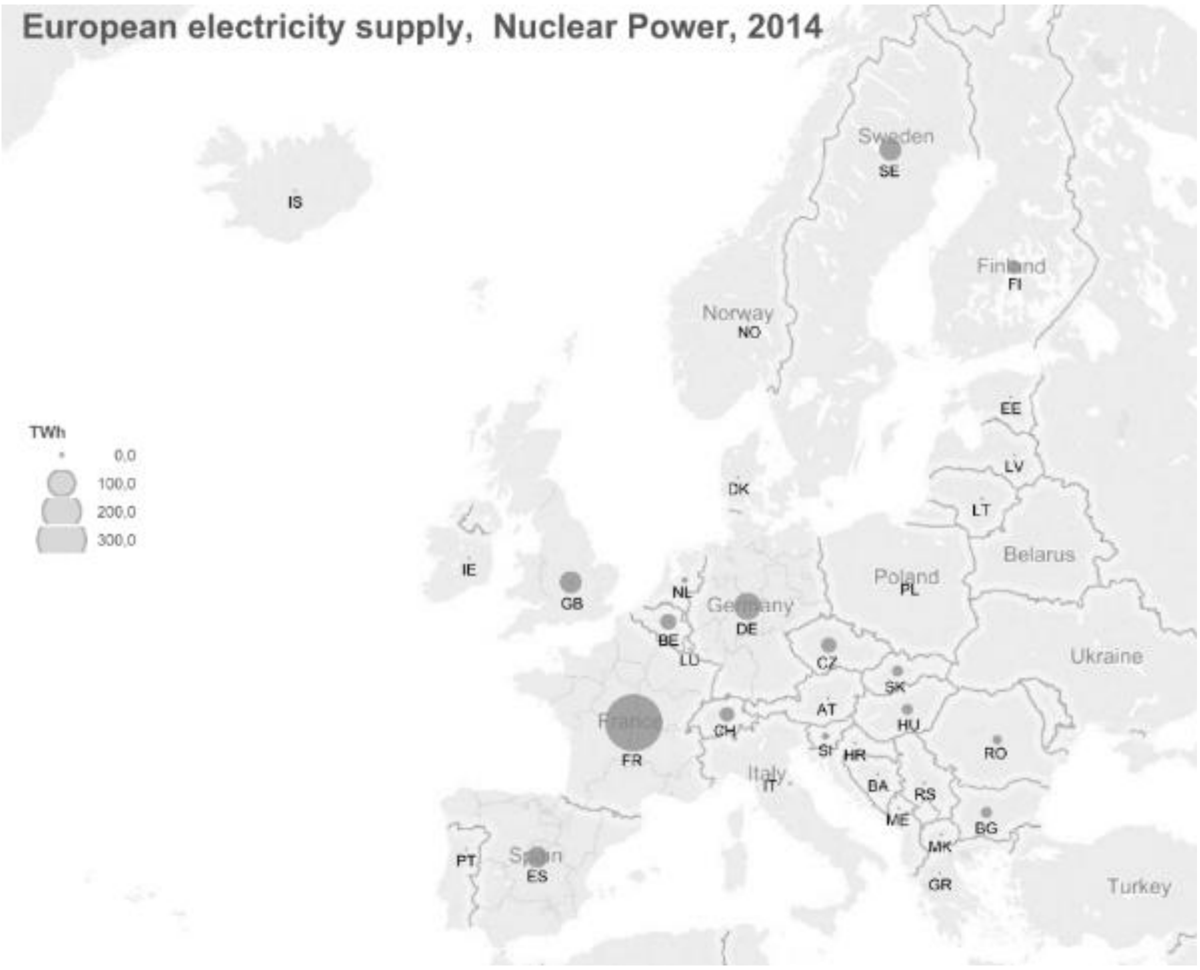

Figure 14 – Nuclear power in Europe[98]

The situation of nuclear power has changed following the earthquake in Japan in 2011. Instead of being regarded as an acceptable technology option for the future, nuclear has faced early shut down and been questioned in some countries. Germany have permanently shut down eight of its reactors and pledged to close the rest by 2022 as a consequence of the Fukushima nuclear disaster. In France, the new energy bill fix a limit to the nuclear installed power at 63,2 GW, which is almost the present figure. Other countries which have, following the Fukushima, reacted with actions are the Italians which have voted overwhelmingly to keep their country non-nuclear, Switzerland and Spain which have banned the construction of new reactors and Belgium which is considering phasing out its nuclear plants although other countries such as Bulgaria, Czech Republic, Finland, France, Hungary, Lithuania, Poland and the United Kingdom are planning to build new reactors

[97] *Entso-E, Yearly Statistics & Adequacy Retrospect 2014, 2015*
[98] *Ibid.*

Table 8 – Nuclear Power installed capacity, electricity production and share of European electricity production[99]

Nuclear power	
Installed capacity	126 GW (year 2014)
Electricity production	859 TWh (year 2014)
Share of European electricity production	26.2 % (year 2014)

3.1.4.1 Future development

There are currently four nuclear reactors under construction in Finland, France and Slovakia and additionally 23 being planned in the EU. By 2050, all of the current nuclear power plants, with the exception of the ones currently under construction/being planned will be taken out of operation.[100] If by 2050 the same amount of nuclear power is to be expected in the energy mix as today more countries need to follow suit and start building new nuclear power plants.

The German nuclear power phase-out will, according to NEPP calculations, make Germany a net importer of electricity.[101] With nuclear power kept in operation, Germany would rather have been an exporter of electricity during the full period up to 2050.[102]

Before 2030, the technology with water reactors generation 3/3+ will be the once commercially available. [103] The figure below shows the nuclear technology evolution to date and the projections for the future. The generation IV reactors are however still on the drawing board.

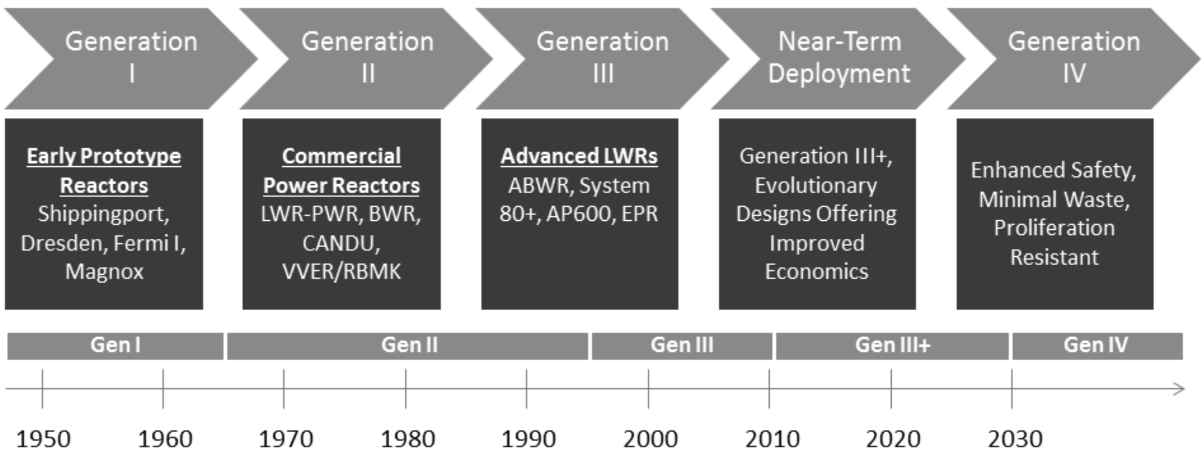

Figure 15 – Nuclear development

In order to include nuclear in the future energy mix there is a need for a decisions on building new nuclear plants. A stable political landscape is critically needed in order for investors to support nuclear. It is also critical that the long term storage of the nuclear fuel waste be developed and accepted by the public. The development of new nuclear plants may need long term electricity supply contracts which should be allowed in the European system.

[99] *Ibid.*
[100] *European Nuclear Society Webpage*
[101] *NEPP 20 conclusions, 2013*
[102] *Ibid.*
[103] *Johansson, 2014*

Depending on the type of nuclear technology used in the various countries, nuclear power produces more or less dispatchable power. In France, the flexibility of nuclear power is similar to the flexibility of coal generation (quick decrease, increase by 2% to 5% of plant power/minute). However, the economic value produced is proportional to the electricity produced when the operational cost is flat. The support to the intermittent electricity production reduces the total electricity produced and thereby reduces the profitability of the plant, as is also the situation for coal or gas generation

Fusion Nuclear Power

EUROfusion, the European programme for fusion energy, is aiming to have a demonstration fusion reactor operational before 2050 but commercial readiness of the technology is still far in the future.

The figure below shows the status of nuclear power in Europe.As can be seen, five EU countries have new units during construction and additional countries are open for discussions around new nuclear power.

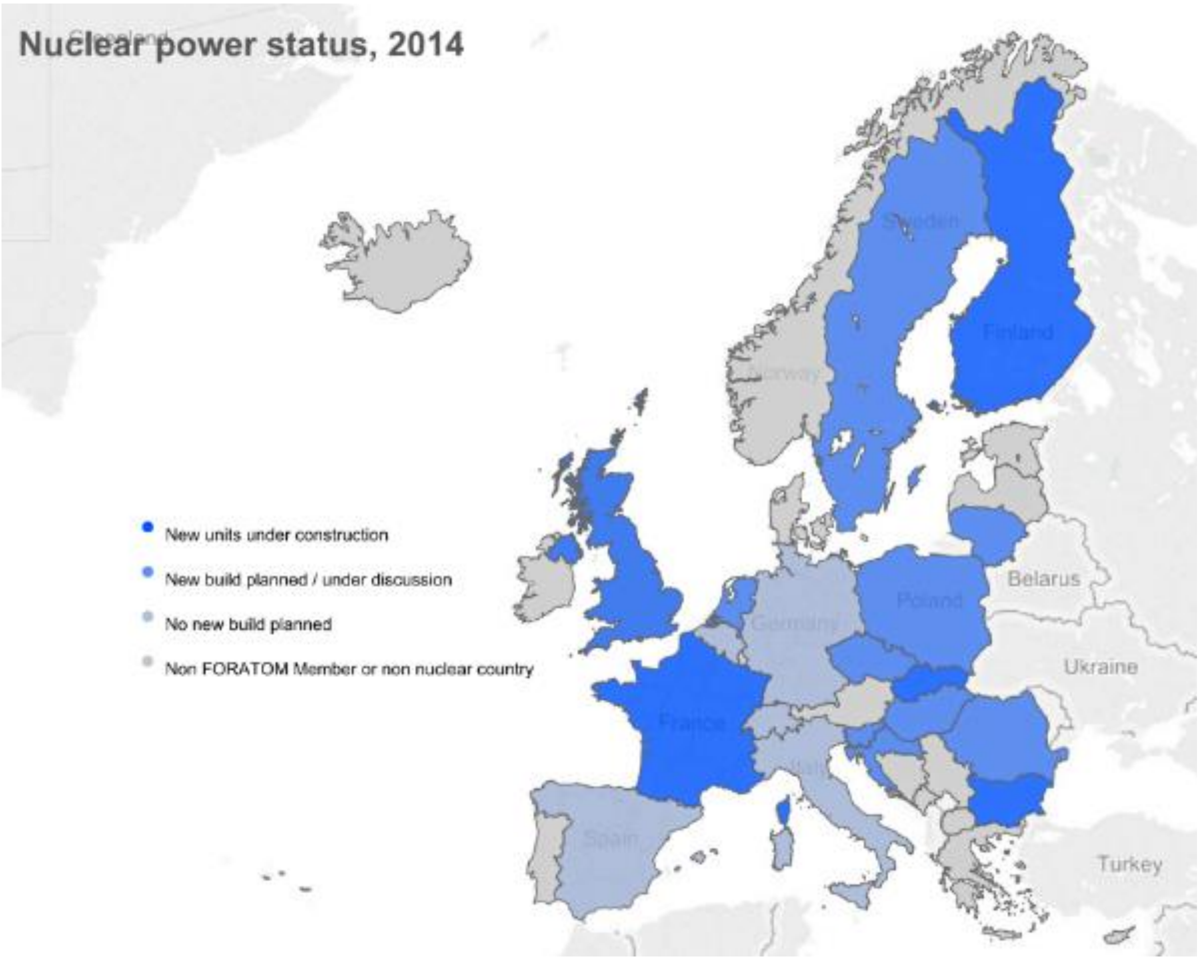

Figure 16 - Nuclear power status[104]

3.1.4.2 Critical success factors

In order to include nuclear in the future energy mix there is a need for a decisions on building new nuclear plants. A stable political landscape is critically needed in order for investors to support nuclear. It is also critical that the long term storage of the nuclear waste be developed and accepted by the public.

Table 9 – Energy triangle analysis nuclear

[104] *Johansson, 2014*

Security of supply	Uranium is readily available around the world on open markets. It is easy to store and the delivery of supply is secured. Uranium however has to be imported from outside Europe. Nuclear need to be operated at a high capacity factor in order to be cost effective. It cannot function as a balancing power in the same way that hydropower can be used.
Competitiveness	Due to the lack of public acceptance of nuclear power it will be very difficult to attract investment to this sector. If development of nuclear in Europe is desired risk mitigation for investors need to take place. One option would be for the states to take the risk. The nuclear power plants in operation is getting old and needs to be replaced in order to maintain current capacity, therefore swift action is necessary.
Sustainability	The carbon footprint for nuclear power is low, comparable to wind and solar. The spent fuel poses an environmental issue which is solved by long term storage. The spent fuel will stay radioactive for 100,000 years after the plant has been shut down and innovation is needed for the fuel to be usable again. The cost for storing additional spent fuel caused by life extension of existing reactors is marginal compared to the total storage cost. If storage is being built, the most cost efficient is to store as much fuel as possible at the storage site.

3.1.5 Coal

Europe has a large share of electricity production coming from coal, 200 GW of installed capacity and 23,6 % of all electricity produced in Europe. [105]

The graph below show the electricity produced from coal in the different European countries.

[105] *Entso-E, Yearly Statistics & Adequacy Retrospect 2014, 2015, Coal and Lignite*

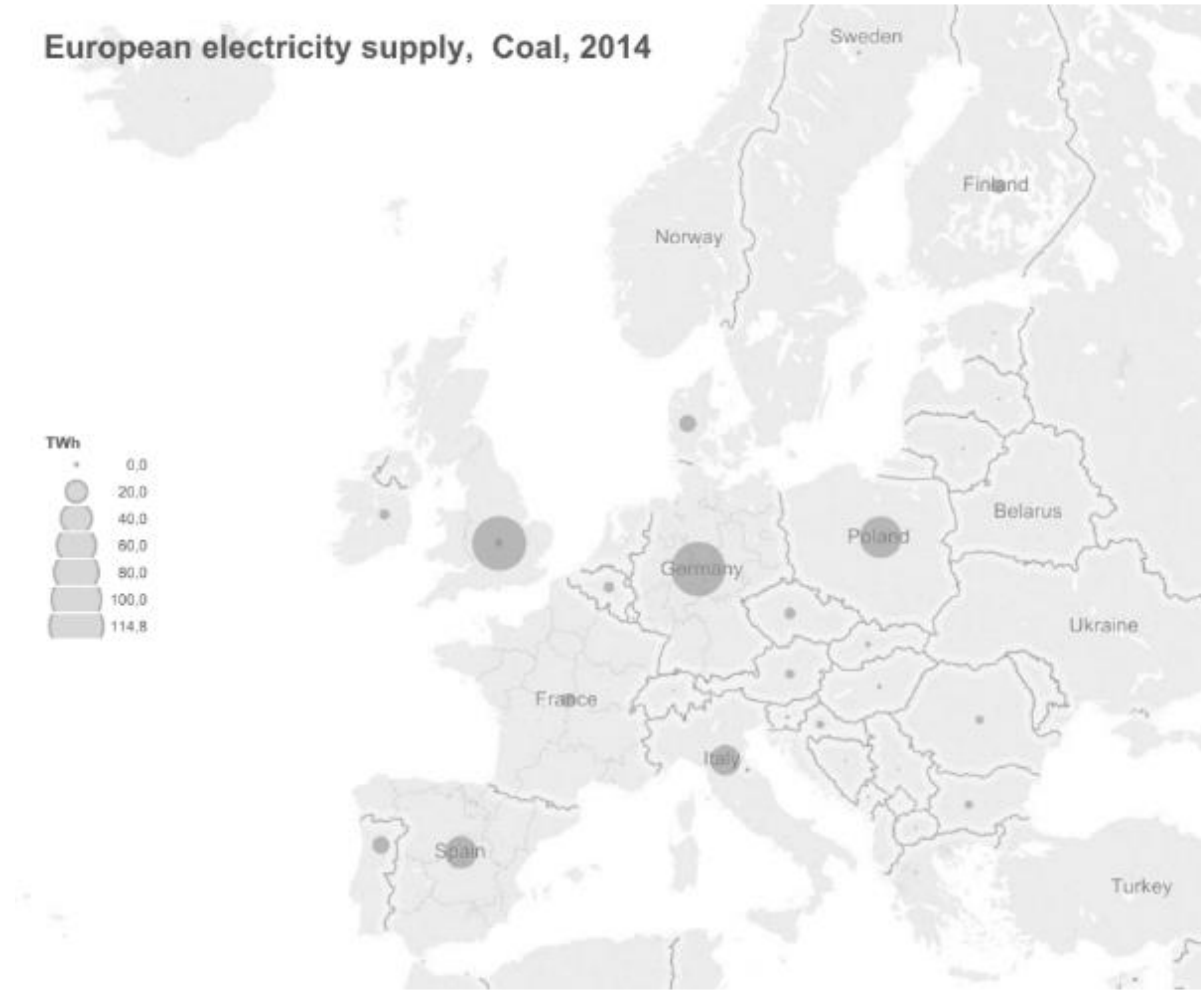

Figure 17 – Electricity production from coal in Europe[106]

Table 10 – Coal Power installed capacity, electricity production and share of European electricity production[107]

Coal	
Installed capacity	200 GW (year 2014)
Electricity production	774 TWh (year 2014)
Share of the European electricity production	23,6 % (year 2014)

3.1.5.1 Future development

The European coal power plants that are currently in use are old and will have to be shut down or refurbished in the next few decades. Regardless of how the rest of the system develops, large investments will have to be made in new thermal plants. The size of the investment will depend largely on the size of the investments in nuclear power as other thermal (solid and gaseous fuels) and nuclear are substitutes with regards to the base load.

[106] *Ibid.*
[107] *Ibid.*

An additional total amount of 1 000 TWh of new thermal power will probably be added until 2030[108]. The thermal power plants in 2030 will consist of old base load plants, new gas combined cycles, some converted and new biomass units and the previous described new peak load plants.

Many of today's coal-fired power plants can be fired with a part or fully with biomass. It is not the technical or logistical limitations which are most serious, but the much higher fuel cost.

3.1.5.2 Critical success factors

In order for coal to be part of a future energy system, CCS and Carbon use/recycling (CCSU) needs to be developed. CCSU as mentioned needs more support from institutions and the future of CCSU crucially depends on public acceptance and adequate carbon prices.

Table 11 – Energy triangle analysis coal

Security of supply	Coal power contributes to security of supply with regards to balancing the electricity system as it is dispatchable. The fact that a large part of the coal used in Europe has to be imported however reduces the security of supply.
Competitiveness	The low coal price makes coal quite competitive in Europe today. Especially since shale gas development has increased rapidly in US and pushed the coal prices down, coal is replacing other more expensive power producing alternatives in Europe.
Sustainability	Coal fired electricity has the major disadvantage of emitting carbon dioxide and particulates when combusted. If combined with CCSU however coal could potentially be included also in the future renewable energy system.

3.1.6 Gas

Gas is widely used for electricity production in Europe. Gas for electricity production can be one of the following:

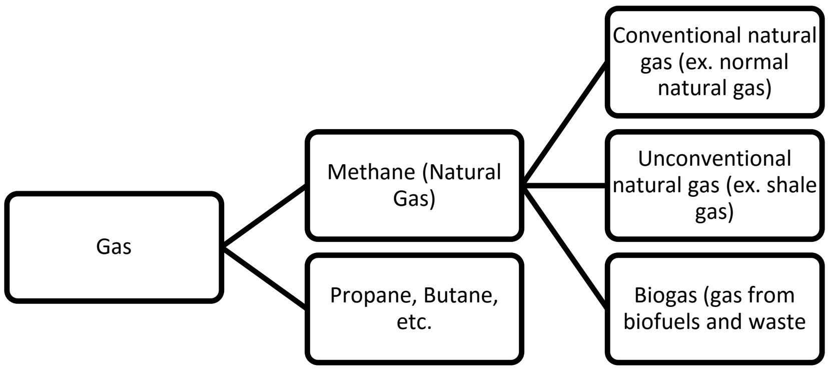

Figure 18 – Different uses of gas in the electricity production

Conventional natural gas is gas that is extracted from the bedrock with conventional drilling technologies. The chemical composition of natural gas is methane. Conventional gas can be liquefied by lowering its temperature and is then called LNG (liquid natural gas).

Natural gas can also be extracted from the bed rock using un-conventional extraction methods. This type of natural gas can for example be shale gas which is deeply integrated in the bed rock and needs to be extracted using hydraulic fracturing and horizontal drilling. The gas that is extracted from shale formations and conventional natural gas is however the same.

[108] *Strömberg,L. 2014*

The difference between conventional natural gas and shale gas can be seen below.

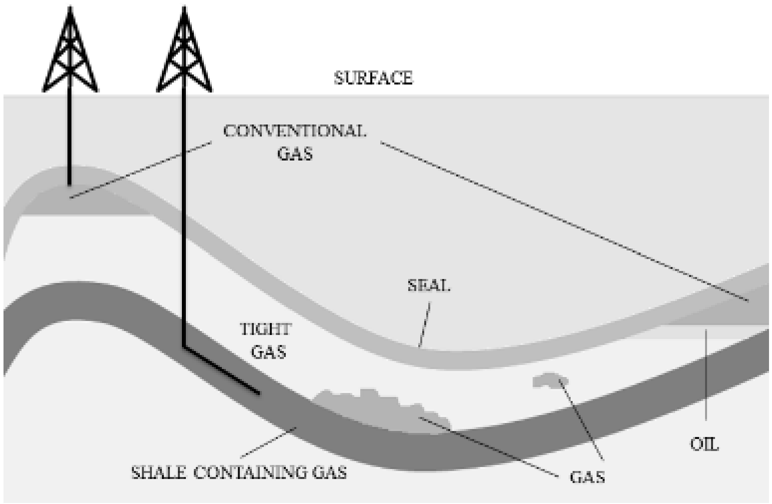

Figure 19 – Gas in the bedrock[109]

A third variant of natural gas is biogas. This gas is produced from biofuel or municipal waste. This gas, although the exact same compound as conventional and un-conventional natural gas, is considered renewable because of the way it is produced.

The majority of gas used for electricity production comes from conventional natural gas. The distribution of natural gas produced electricity in Europe can be seen in the figure below.

[109] *Nordling et. al. 2014*

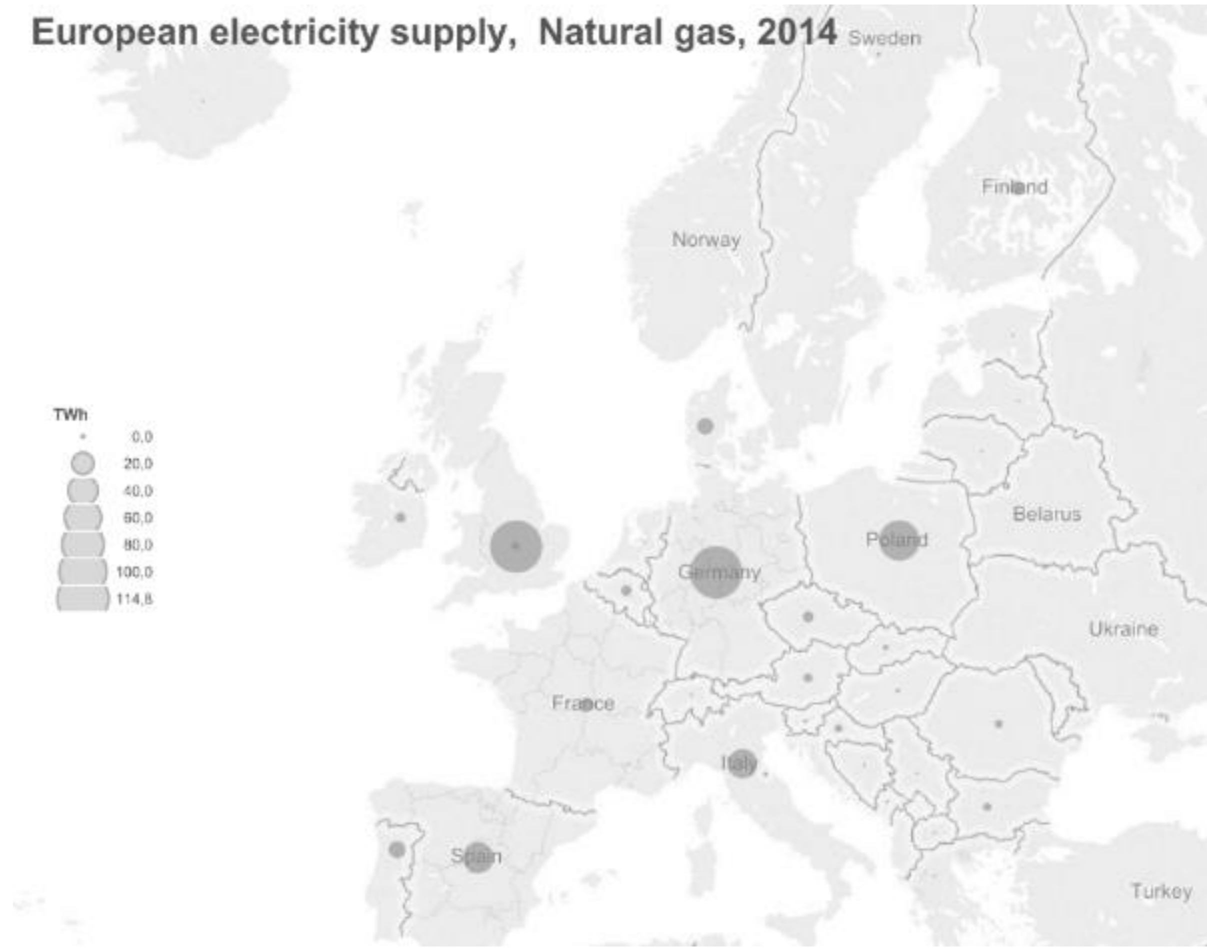

Figure 20 – Electricity production from natural gas in Europe [110]

The status of conventional natural gas in Europe can be seen below.

Table 12 – Conventional Natural Gas installed capacity, electricity production and share of European electricity production[111]

Conventional Natural Gas	
Installed capacity	215 GW (year 2014)
Electricity production	375 TWh (year 2014)
Share of the European electricity production	11,4 % (year 2014)

3.1.6.1 Future development

Gas utilization will probably increase considerably in the future. Shale gas is one possible source of gas that is explored in parts of Europe. USA is at present the only country with large scale shale gas production. The main success factor in USA has been the large gas resources as well as land to explore. Other important success factors are the great experience in oil and gas extraction, and the authority's acceptance for prospecting without stringent environmental requirements on this work. Further, the companies have had an access to the land for exploration; this is because American land owners have the right to be compensated when extraction takes place. The political

[110] *Entso-E, Yearly Statistics & Adequacy Retrospect 2014, 2015*
[111] *Ibid.*

situation in Europe is somewhat different and the public across many countries is opposed to this technology. More research is required to map the viable resources in Europe and on calculating the costs and benefits of using shale gas on a large scale.

In the following table figures on the estimated technically viable resources of shale gas are shown. As can be seen, the figures show a very large potential for shale gas if to be extracted and utilized in the European energy system, especially for Poland, France and Ukraine.

Table 13 – The market for natural gas in Europe 2012, and the estimated technically viable resources of shale gas in selected European countries where there is a potential for shale gas[112]

	Natural gas market 2012			*Shale gas*
	Production *TWh*	**Consumption** *TWh*	**Import/(Export)** *% of consumption*	**Estimated** *TWh*
Poland	64	187	127	42 700
France	6	457	442	40 000
Ukraine	205	669	464	37 500
Romania	110	143	33	14 900
Denmark	66	40	(28)	9 400
Great Britain	388	774	384	7 600
Netherlands	832	476	(355)	7 600
Turkey	7	468	469	7 000
Germany	127	903	715	5 000
Bulgaria	4	30	26	5 000
Sweden	0	12	12	2 900
Spain	1	336	334	2 300
Total				**182 100**

The thermal power plants portfolio in 2030 will consist of old base load plants still in use, new gas combined cycles, some converted and new biomass units, and new peak load plants. It is assumed that between 500 and 1000 TWh will be produced with gas[113].

Due to the low load factor of these, (they will stand for the major part of load-following power) the number of plants and the installed power in MW will be huge, maybe up to 2000 plants with a capacity up to 500 GW.[114]

Biogas for electricity generation is rising rapidly in Europe. By the end of 2014, more than 17,240 biogas power plants, with a total installed capacity of 8,3 GW, were in operation which represents a 18% growth from previous year. The share of total EU electricity generation is still very low. Germany has seen rapid growth, particularly during 2009–2011, and still dominates the market with 10 786 plants. Sweden also has growing bio-power shares from gaseous fuels. Limited but growing quantities of gaseous biofuels (mainly biomethane, which is purified biogas) are fueling cars, buses, and other vehicles in several EU countries. By the end of 2014 there were 367 biomethane plants in EU most notably in Germany and in Sweden with 178 and 59 plants respectively. [115]

Production of biogas is expanding rapidly in a number of countries, although the actual volume of biogas produced is not known. In the United Kingdom, the number of plants producing biogas rose from 54 in 2011 to 813 in 2014.

[112] *Nordling et al, 2012*
[113] *Strömberg, L. 2014*
[114] *Ibid.*
[115] *European Biogas Association webpage*

Elsewhere in Europe, rapid expansion has also been driven by policy changes. For example, Italy alone saw its number of operational biogas plants increase from 521 to 1,391 within two years, driven primarily by a high feed-in tariff and support focused on small-scale plants. The Czech Republic and Slovakia also have seen significant expansion in the number of plants. [116]

3.1.6.2 Critical success factors

Shale gas reserves could play an important role for a country's energy independence. The technical potential for shale gas is high in Europe, especially in Poland and France. France however has imposed A prohibition on hydraulic fracturing because of its potential impact on the environment. The EU has deferred the decision to explore shale gas to each member state and a moratorium on hydraulic fracturing has been imposed by several countries. The production levels of shale gas are also expected to be lower in Europe than in USA. This is for example because of the fact that shale gas reservoirs in Europe are deeper located than the ones in USA, which complicates the extraction. Another reason is the more stringent system of rules when it comes to industrial law, environment and security issues. The industry for gas extraction is significantly smaller in Europe, and the lack of market competition will bring up the costs.[117]

The future for CCSU plays a crucial role for the environmental friendliness for future thermal power plants. Additionally large investments in peak load power plants need to be secured which is difficult in an energy-only market (EOM) where there will be few incentives for long-term investments.

[116] *Ibid.*
[117] *Nordling et al, 2014*

Table 14 – Energy triangle analysis gas.

Security of supply	**Conventional natural gas:** Since conventional natural gas is mainly imported to Europe it does not contribute to security of supply. **Shale gas:** Shale gas that could be extracted within Europe contribute greatly to European security of supply. **Biogas:** Also biogas that can be produced domestically increase the European security of supply.
Competitiveness	**Conventional natural gas:** Conventional natural gas is not cost competitive at low utilization rates and has recently been pushed away by cheap imported coal. **Shale gas:** European shale gas is not cost competitive today due to the very expensive extraction techniques required. Cost reduction is however expected as the technology matures. **Biogas:** Biogas is not cost competitive without subsidies.
Sustainability	**Conventional natural gas:** Conventional natural gas emits greenhouse gas emissions however at a lower rate than coal when combusted. **Shale gas:** Shale gas has a higher impact on environment than conventional natural gas in terms of greenhouse gas emission. This is because of leakage in the extraction process. It is also debated as to the effects of the extraction process on ground water supply. **Biogas:** Biogas is considered sustainable since it is combusted during the same time frame it is created.

3.1.7 Biomass and waste

In 2014, 187 TWh of electricity was produced from biomass and waste in Europe.[118] Biomass is biological material derived from living, or recently living organisms. In the context of biomass for energy this is often used to mean plant based material, but biomass can equally apply to both animal and vegetable derived material. Biomass is carbon based and is composed of a mixture of organic molecules containing hydrogen, usually including atoms of oxygen, often nitrogen and also small quantities of other atoms, including alkali, alkaline earth and heavy metals.[119].

The range of biomass and waste feedstocks available for use is very wide. A general categorisation is described:

- Energy crops - biomass fuels grown specifically for use as a fuel for energy production. These include woods (e.g. willow, popular, eucalyptus) and perennial grasses such as miscanthus, sweet sorghum, and phalaris.

- Forestry Residues - wood fuels produced from existing lumbering and coppicing operations in established forestry (e.g. wood chips, forestry trimmings, sawdust, bark)

- Agricultural Wastes- biomass wastes produced by agricultural farming practises for food production (e.g. straw, bagasse, poultry litter)

- Municipal Waste - wastes generated from household, industrial and commercial sources. This waste can be raw, i.e. unsegregated or segregated (glass, metal paper etc., removed). It can also be in its “as produced” form or densified to form a pellet, commonly known as dRDF (densified Refuse Derived Fuel)

[118] *Gross electricity generation, Eurostat Database*
[119] *Biomass Energy Centre webpage*

- Specialized Industrial Wastes- there are a range of waste materials generated by industry that have the potential to be used for energy production. Examples include tyres, clinical waste, waste solvents and other chemicals, car fragmentation waste, meat processing wastes and waste wood-derived products[120].

Biomass and waste provided around 5,9 % of the EUR-28's electricity generation in 2014. Biomass is used primarily in countries with extensive forest industries, where residues such as branches, wood chips and sawdust can be used to produce electricity and heat. Countries with large agricultural industries and industries that produce waste products that can be used as biofuels also have potential to increase their use of biomass[121].

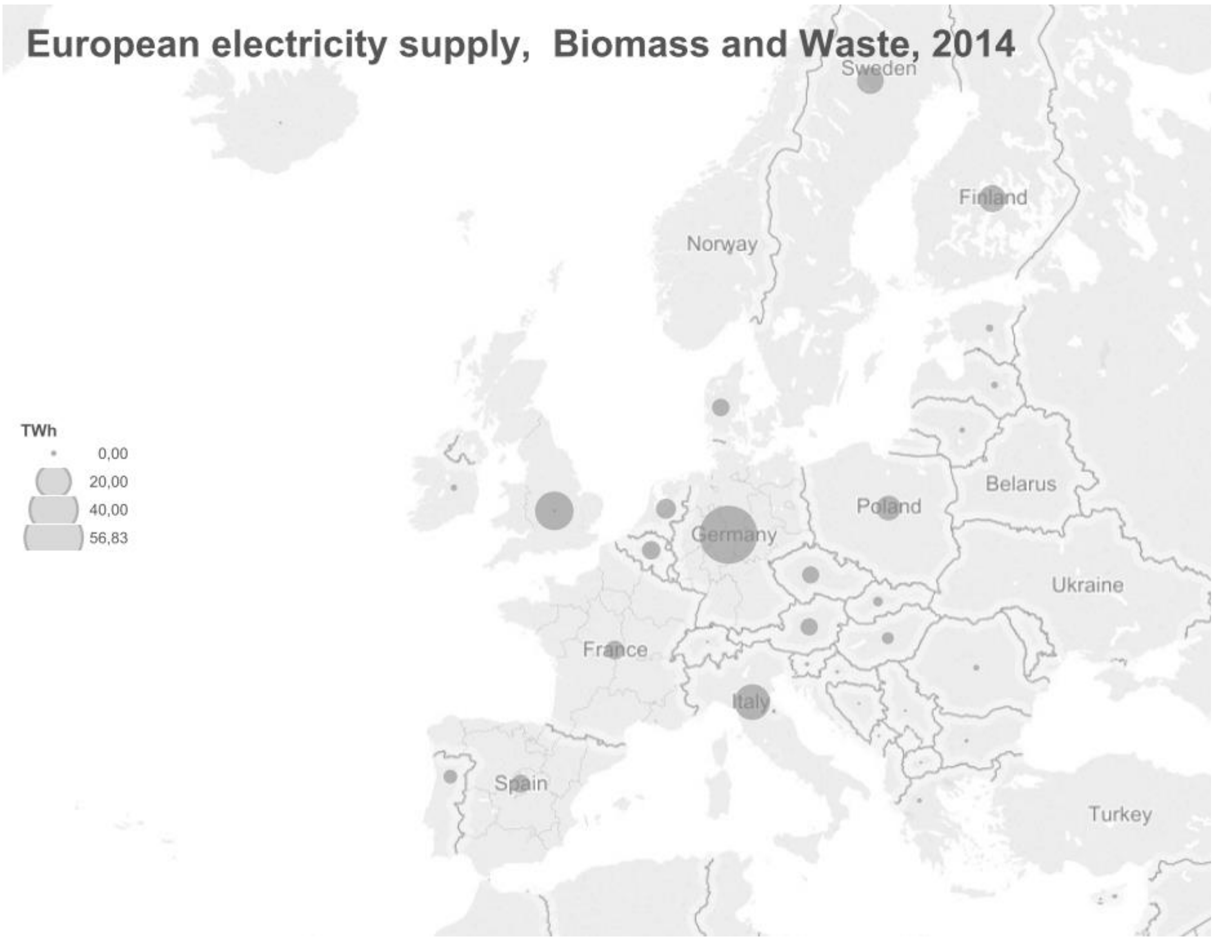

Figure 21 – European electricity supply from biomass and waste[122]

The specifics of EU's biomass and waste electricity production are detailed below.

Table 15 – Biomass and Waste installed capacity, electricity production and share of European electricity production

Biomass and waste	
Installed capacity[123]	37 GW (year 2014)

[120] European Commission webpage, bioenergy
[121] Strömberg,L. 2014
[122] Gross electricity production, Eurostat database,
[123] Gross electricity production, Eurostat database

Electricity production[124]	187 TWh (year 2014)
Share of European electricity production	5,2 % (year 2014)

3.1.7.1 Future development

Biomass plants will take a relatively small but distinct part of the supply system.[125] The number of power plants in Europe that run solely on biomass is expected to increase dramatically in the coming years. After wind power, biomass is the fastest growing energy source in Europe[126].

Many of the coal fired boilers can be fired with a part or fully with biomass. It is easy to burn wooden biomass in a coal fired boiler if it is milled down to typical sawdust size. Moisture content does not matter[127].

3.1.7.2 Critical success factors

The main advantage with biomass, environmental considerations, depends on if it is produced in a sustainable way, where each step from the growing to the energy conversion need to be monitored. The effects of direct and in-direct land use during growing is one such factor when there is a conflict with some types of biomass such as corn that otherwise could be used as food and might therefore not be suitable for energy production. The European union has therefore adopted a set a of recommendations to ensure sustainable biomass, such as ensuring at least 35 % less greenhouse gases over their lifetime, preserving biodiverse areas, forbidding biomass from land converted from forests etc.[128]

The limitations for biomass, apart from the complicated competition with feed stock, stem from the fact that biomass cost three times more than coal, the volume of the biomass is very large and shall be transported, the fuel feed system have to be adjusted or rebuilt and only coal boilers with relatively low efficiency can be used due to the problem with fouling and corrosion. In Europe, up to half the production cost stems from fuel, remaining is divided between operation, maintenance and capital costs.[129]

Europe has a very large production of electricity with coal. Many of these boilers can be fired with a part or fully with biomass. It is easy to burn wooden biomass in a coal fired boiler if it is milled down to typical sawdust size, moisture content does not matter.

Table 16 – Energy triangle analysis Bioenergy

Security of supply	Biomass can be converted into a stable and reliable supply of electricity and heat. Biomass can be securely sourced on small scales, but supply of larger volumes is currently difficult to secure. One important step is to establish a global trade and certification system. Biomass resources are geographically diversified and political risk is limited.
Competitiveness	Biomass can only compete with coal if environmental considerations are included, and if fuel can be produced effectively. It is not technical or logistical limitations which are serious, but the much higher fuel cost. Using biomass to produce electricity is currently more expensive than using energy sources such as coal, gas or nuclear power. The global biomass supply chain is developing and, over time, technological and logistical improvements will bring down prices. An increased CO2 price will also improve the economic competitiveness of biomass.
Sustainability	By using biomass in power production instead of fossil fuels, CO2 emissions can be significantly reduced. Carbon dioxide is emitted into the atmosphere when biomass is

[124] Gross electricity production, Eurostat database
[125] Strömberg,L. 2014.
[126] Ibid.
[127] Ibid.
[128] European Commission, biomass
[129] Strömberg, L. 2014

	burned, but when biomass grows it binds carbon dioxide through photosynthesis. Properly managed biomass is therefore carbon neutral over time.

3.1.8 Carbon capture and storage (CCS)

A future electricity system including energy from fossil fuels requires other mitigating factors to lower CO_2 emissions. CCS technologies are the main possibility to accomplish this. So far CCS has contributed to a global storage of about 50 Mton CO_2. 7000 km of CO_2 pipelines are in operation in the world today. Storage of CO_2 is controversial for onshore storage where the perceived risks are the main issue.[130]

CCS has a potential to substantially decarbonize Europe's electricity system. According to EASAC policy report 20, several factors will however constrain the rate of deployment of CCS; a substantial transport and storage infrastructure will need to be created, the public perception will play into the permitting of developments and there is a need to develop confidence in the geological processes that will determine the long-term security of the stored carbon dioxide. EASAC policy report 20 further argues that although the costs of CCS technologies will reduce, CCS will continue to add to the costs of fossil-fired power stations and industrial processes.

Before 2020 there is a need for small set of demonstration projects of the CCS technologies, post 2020 there is a need for widen deployment to power and industry and 2030-2050 there could be a possible commercial deployment of CCS with a power plant capacity with CCS of 40 GW.[131]

In order to succeed, CCS needs more support from governmental institutions. The future of CCS crucially depends on public acceptance and adequate carbon prices. Field tests and demonstrations of safe CO_2 storage could possibly change people's perception of risk.[132] One conclusion of the EASAC policy report 20 is that since CCS will continue to add to the costs of fossil-fired power plants, the value of avoiding the emission of a tonne of CO_2 needs to be sufficient, and sufficiently predictable, if the private sector is to make the major investments in CCS that are required.

CCS is one example of "clean coal technologies" that is being developed to reduce the emissions from coal and other fossil fuels, another example is integrated gasification combined cycle (IGCC) that uses high pressure gasifier to turn carbon based fuels to synthesis gas in order to remove impurities such as particles, mercury and sulphur dioxide an could be used in combination with CCS. At this stage more research is needed. [133]

Associated to CCS, the reuse or recycling of carbon is very promising issue, while consumption of carbon is industrial or all day life via fabrication of platform molecules of interest in biology, medicine, agribusiness, chemical industry, …

3.2 Future European Electricity System

Whichever scenario the future European energy system will follow it will consist of mixture of intermittent power and dispatchable power. Fossil fuels and nuclear power will dominate the European electricity system for the next 20-30 years. Even with the renewable proportion expanding massively, a large part of the power generation in Europe will be based on fossil fuels in 2050. There are four possible transformation paths to a carbon free energy system;

- Gen3 and/or Gen4 generation nuclear
- More cost efficient renewable energy production and substantial support of balancing power and storage facilities
- Coal or gas in combination with carbon capture and storage (CCS)[134]
- Power-to-gas in combination with hydrogen storage, making use of excess renewable electricity production

[130] *Aam, 2014*
[131] *Aam, 2014.*
[132] *Aam, 2014.*
[133] *Wang, 2016*
[134] *NEPP, 2014*

The future energy system will most likely be a mixture of the four paths. Gas will play an important role in all possible scenarios of the future. Considering security of supply, development of European shale gas resources seems inevitable.

4 Transmission and Distribution

The following chapter will briefly describe the European interconnectivity as well as smart grids, which might be a way to increase the flexibility of the transmission and distribution system. The chapter ends with a short text about district heating, underling the increasing interconnectivity between the electricity and heating as well as one possible way forward to more flexibility in the transmission and distribution system.

The European energy system of 2030 has to address the problem of solar and wind power's intermittency. This can be done in a number of ways and an effective solution might combine several methods. A different frame of the electricity system may also be important in order to create incentives for investors to make necessary investments in the future energy system. Instead of an energy only market (EOM), a capacity market might be needed.

In the future electricity system, both the transmission system (high voltage) and the distribution systems (low voltage) need to be optimized. Transmission refers to the electricity transferred from the generating power plants to the electric substations while the distribution system carries electricity from the transmission grid to the end user.

On the other hand, a future system might also have developed new cutting edge technologies as well as more cost efficient electrical storage alternatives. These technological leaps are hard to predict and although the following analysis is based on current knowledge and the current system a future system might have a decreased need for thorough changes of the transmission and distribution system and offering new possibilities and solutions.

4.1 Interconnections

When increasing the renewable electricity production in Europe, interconnections between countries will be more important. Large wind power capacities in countries like Germany and Denmark need to be balanced with storage capacities in for example hydro power in countries like Norway.

The importance of interconnections between countries has been recognized by the European Commission that has in recent draft guidelines for Climate and Energy policy Framework 2030 suggested to:

"Advancing, and where appropriate, identifying new projects of common interest (PCI:s) necessary to reach the existing interconnection target of 10 % (mentioned above) and to increase the target to 15 % by 2030."

The interconnection target is set to be equal for all EU countries although the need and factual implementation varies greatly across Europe.

The interconnection capacity for the different EU countries shows that there is currently a spread between "below 5%" to ">15%", some countries already have more than 30% interconnection capacity.

Mapping the share of renewables also shows significant differences between countries with below 5 % renewables to over 60 % renewable (including non intermittent such as hydro). Import capacity as a % of net generation capacity in 2011 can be seen in the figure below.

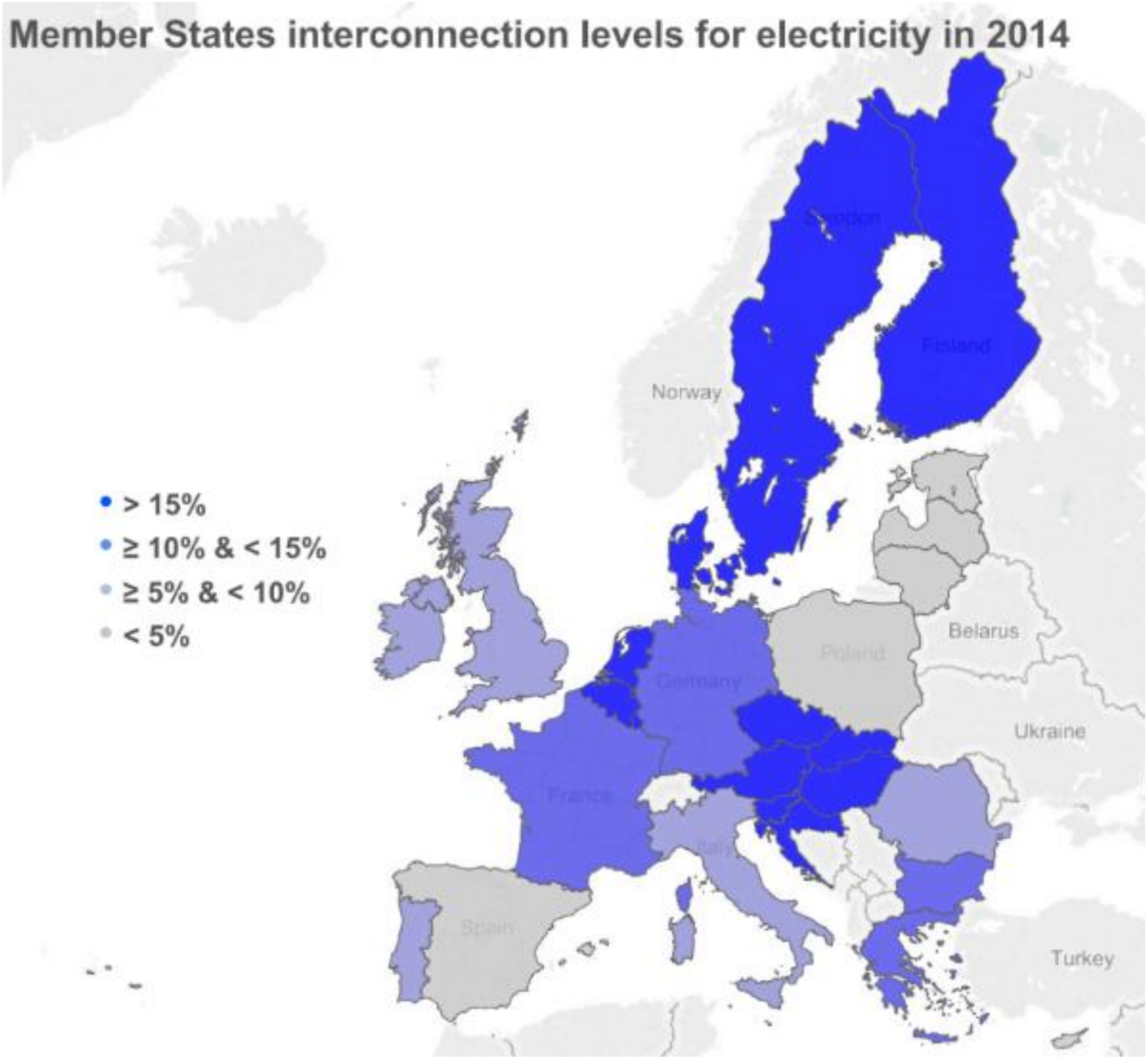

Figure 22 – European interconnection capacity map [135]

[135] *National Grid, 2014*

Figure 23 – European countries renewable share % in 2014[136](renewable includes hydro)

The transmission grid has an instrumental significance to allow sharing of resources particularly in systems with high degree of intermittent renewables. As stated above, the European demand of 10 % interconnection capacity of total installed capacity is currently not related to the intermittent renewable production capacity. An interconnection target that is related to the national intermittent renewable share on the other hand would incentivize a better cooperation between countries and increase European security of supply. This would serve the European electricity system much better than the current fixed target program.

4.2 Smart Grids

Since an increased portion of intermittent renewable power will be introduced to the electricity system, demand on the regulation and flexibility of the transmission and distribution system will increase. The future grid needs to better match supply and demand of electricity. Smart grid technology such as home energy controllers, virtual power plants and storage capabilities are solutions that will transform the system to a smarter electrical grid. The fact that also the transport system is being increasingly electrified emphasizes the need for an electricity system transformation. To build a more efficient grid, Smart grid technologies are increasingly applied.

Smart grids are defined by IEA as:

"Smart grids are networks that monitor and manage the transport of electricity from all generation sources to meet the varying electricity demands of end users. They are, and will continue to be, deployed at different rates in a variety of settings around the world, depending on local commercial attractiveness, compatibility with existing technologies, regulatory developments and investment frameworks."

[136] https://www.entsoe.eu/Documents/Publications/Statistics/electricity_in_europe/entsoe_electricity_in_europe_2014.pdf

Smart grid technologies are applied on all levels in the electrical grid from the high voltage grid to distribution of electricity to individual consumers.

Transmission

On the high voltage grid the key smart grid technologies are:

- HVDC (High Voltage Direct Current),
- FACTS (Flexible AC Transmission) and
- WAMS (Wide Area Monitoring Systems).

HVDC and FACTS uses power semiconductors to control the power flow in the transmission lines and increases the transmission capacity, WAMS detects potential instabilities in the grid and can give information to operators or automatic systems to avoid network collapse. With smart grid technologies it is possible to:

- Build a stronger grid and still limit how disturbances are spread.
- Minimize the visible infrastructure and thereby increase acceptance

HVDC is commonly used for interconnections between countries and regions due to the technical capability to construct long subsea or underground cable transmission systems. FACTS and WAMS technologies can increase the safe operating range of transmission lines.

Interconnectors, particularly built with smart grid technologies play an important role in the electricity system particularly when renewable generation is increasingly used.

Distribution

The electricity consumer’s involvement in shifting electricity consumption will be vital. In a smart grid solution, the consumers can be flexible and use less electricity at the time when it´s favorable for the electricity system and when favorable off-peak prices are provided. Service providers from the competitive, deregulated market might create offerings by which system services can be provided as they are required. This requires an infrastructure which ensures cost-efficient access to these resources for actors within the Smart Market and processes to resolve congestions on distribution level.[137]

4.2.1 Current status

Transmission

Smart grid technologies are well established in the transmission area in Europe. All major smart grid technologies are established and used in Europe and most of the leading global companies in this field are based in Europe.

Distribution

In the distribution area the main focus in the smart grids has historically been on smart meters that already are rolled out fully in some countries whereas other countries still use conventional metering. There are very clear links between the need for “smart regulation” and smart grid technologies. Unless regulation is adopted the benefits from smart grid technologies cannot fully be captured One example is that hourly billing and reading significantly increases the value of smart grid technologies used by end users of electricity. Incentives and services that align the interests of the end user and that of the power company is one important factor but it is also important to support innovation as a transition to valuable grid services using i.e. test areas. Addressing issues distort participation in the transition, such as support schemes. Overall a ”smart regulation” is a framework addressing services, technology, innovation and user participation of the grid transformation

4.2.2 Future development

Transmission

[137] *Kreusel, 2014*

Although smart grid technologies are widely used in Europe there is also a tendency that Europe is losing ground internationally in the application of smart grid technologies. One example is HVDC technology where internationally there a many projects in service and under construction with 800 kV and transmission capacities up to 8.000 MW per overhead transmission line. In Europe the highest voltage and capacity used is 500 kV and 2.000 MW. There is also a strong development in HVDC Cable technology allowing more power to be transmitted in subsea and underground cables. State-of-the-art for transmission capacity in one cable system has recently been increased from 1000 MW to 2600 MW.

Distribution

Smart grid solutions on the distribution level generally imply collection of information, making educated decisions and finally create actions. This gives a strong correlation to the development of IT Technology, sensors and power electronics. In all these technology fields there is a very strong development, not primarily driven by the Smart grid market, but where this market can benefit from the development. The cost performance will improve significantly and allow much more sophisticated solutions in the distribution grid at moderate cost. The result is that more intelligence will be found in the low voltage distribution and there will be a merger between smart grids and "intelligent homes". End consumers are not only participating in the electricity market and making investments in local solutions (not only limited to local generation), but also act as an integral part of smart grid solutions, as contributing to peak cut-off. Consumers could then be presented with more detailed information, allowing educated decisions and creating incentives such as attractive off-peak rates to even peak loads.

4.2.3 Critical success factors

On the transmission level, one of the key critical success factors is to overcome the acceptance problem for new transmission infrastructure. Here smart grid solutions can play an important role to minimize the need for new physical transmission infrastructure and offer solutions for subsea and underground transmission. But there will still be a need of significant investments in new transmission infrastructure and the acceptance problem needs to be addressed with a combination of information and regulation.

The transmission and distribution business is highly regulated. The smart grid development in general is thus strongly driven by regulation. Here the work to develop "smart regulation" is very important. Another critical success factor is the ability to adopt technology development is other areas for use in smart grid applications. As mentioned the key technologies are here IT Technology, sensors and power electronics.

Successful coupling between vectors (electricity, gas, and heat) is a key challenge of smart grid operation. Moreover thermal storage and transport will be a key issue in smart cites, smart building and isolated zones.

4.3 District Heating

The European electricity system is increasingly interconnected with large areas of the energy system, with the increased electrification in the heating and transport sector. The growth in electricity demand and capability has the potential of transforming both energy supply and end use. One area where electricity generation has an indirect effect on the heating sector is district heating. The basic idea behind district heating is to recycle the surplus heat, from electricity generation, industrial processes, from fuel and biofuel-refining or when waste is burned, and to supply it to a number of customers through a distribution network. [138]

District heating is available throughout Europe with over 5000 district heating systems and a market share of 10 % of the heating market. Especially countries in the northern and eastern part of Europe uses district heating and cooling i.e. in the Swedish city of Gothenburg, 90 % of all the apartment blocks are heated, using this method. There are also plants, i.e. in Denmark that combine renewable energy sources with heating and allow electricity to be stored as heat during peak production periods. [139]

[138] *Cogen webpage*
[139] *IEA, 2014b*

The district heating and cooling example shows the complexity and the increasingly interconnectivity of the European electric system but also one potential solutions with i.e. transmission and distribution flexibility as well as storage capacity.

4.4 Transport sector

The transport sector has in recent years seen a rapid development of a wide range of electric vehicles. With promises to reduce carbon intensity, local pollutants and increase energy efficiency, battery electrical vehicles (BEVs), Fuel-cell electric vehicles (FCEVs) and Plug-in Hybrid Electrical Vehicles (PHEVs) have made the transport sector more and more interconnected with the electrical system. This transformation is possibly a way of integrating variable renewable energy in the power generation mix but the transport sector will also inheriting the cons of the current system, such as emissions occurring in the power generation.

In 2015 over 1 million electric cars on the roads were exceeded, with additionally 200 million two-wheelers and 170 000 busses accompanying them. In Europe, the market share of electrical vehicles exceeded 1 % in Denmark, France, Sweden and 10 % in the Netherlands with Norway as the European champion with a market share of 23 %. These developments have been encouraged by public policies such as investments and public-private partnerships, increased battery capacities and electrical car pricing. The Paris Declaration on Electro-Mobility and Climate Change and Call to Action, also sets a 2030-goal of 100 million electric cars and 400 million 2 and 3 wheelers. [140]

The electrification of the transport sector is another example of the increasing interconnectivity of the European electrical system, with both opportunities and challenges.

5 Electrical storage

The electrical storage chapter showcase the current status, future development and critical success factors for different sorts of storages of electricity, ending with how the transport system might be influenced or influence the electrical system.

Storage of electricity (both small and large scale) will play an increasingly important role in the future. The need for shifting electricity supply in time, although the electricity system also has an inherent capability to deal with mismatches increases substantially when the share of intermittent power is brought into the system. The storages that will be in demand are diverse in terms of storage volume capability, discharge rate and type. Thermal storage is not covered in this report but a good overview can be found in DTU International Energy Report 2013. There is a multitude of different storage options, the figure below show the most common storage technologies.

[140] IEA, 2016

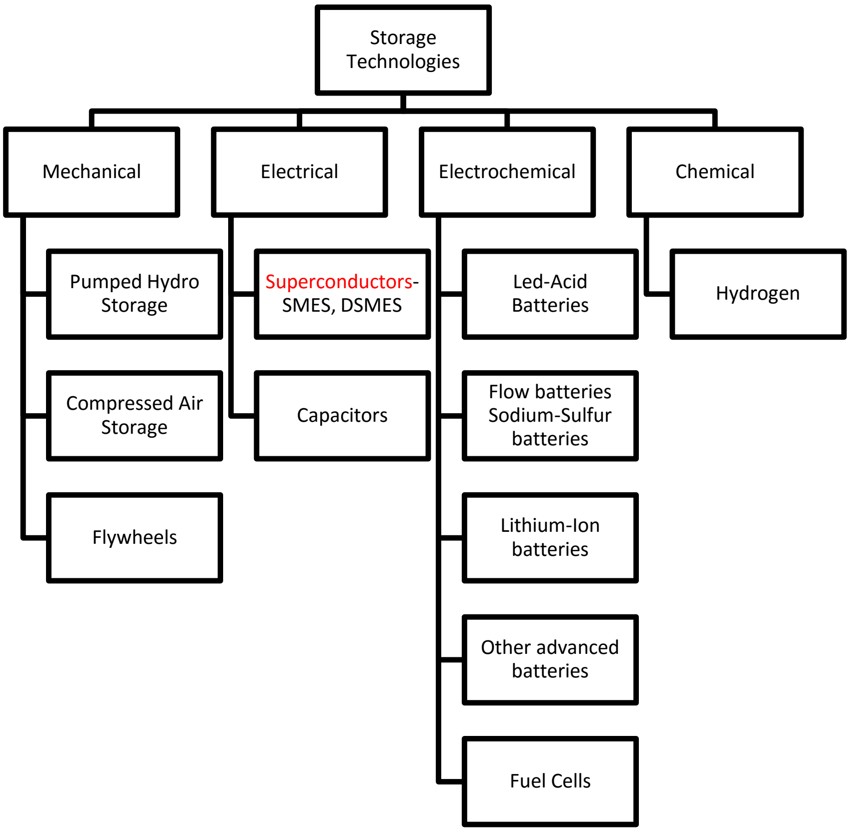

Figure 24 – Energy storage technologies

The purpose of the storage function differ, the most common ones are presented below:

- Price arbitrage
- Balancing energy
- Provision of black-start services
- Stabilizing conventional generation
- Island and off-grid storage
- T&D deferral
- Industrial peak shaving
- Residential storage

The table below shows different functions in different parts of the energy system.

Table 17 – Parts of the energy system

	Part of the energy system		
Function	Transmission system and central storage (national and European level)	Distribution system and regional storage (city/area level)	End-user (building, household level)
Balance between supply and demand	- Seasonal / weekly variations - Large geographical unbalances - Large variations from wind and solar *(electrical and heat storages can be integrated)*	Daily / hourly variations *(electricity and heat/cooling storages can be integrated)*	Daily variations *(electricity and heat/cooling storages should be integrated)*
Distribution demand (transport of energy)	- Voltage and frequency regulation (electricity) - Addition to normal peak load production - Participate in balance and regulation markets (electricity) - International trading (electricity)	Voltage and frequency regulation (electricity) Participate in balance and regulation markets (electricity)	Aggregation of small storages in order to support distribution needs (take care of capacity problems, reduce losses)
Energy efficiency	Better efficiency in the global energy mix	Load control/Storage control for increased efficiency in the distribution system	Local production and consumption, change in behaviour, increased value of local production, energy efficiency buildings integrated with district heating and cooling

5.1.1 Electricity storage in the transport system

It is likely that in the future the transport sector will come to rely increasingly on electricity, and this will create a possibility as well as a challenge to use the small distributed and mobile storages in a controlled and strategic manner in order to benefit the whole electrical system. This development is very dependent on the development of batteries. The coupling of electrical mobility to the grid will be an important issue of peak cut-off.

The development of an electricity based transport infrastructure is however still quite far in the future and is not expected to play a major part until 2030. *"Based on announcements of public authorities, the current network of private and public charging points is expected to increase significantly only in France with 4,400,000 points by 2020. In the rest of EU, only 600,000 points are expected to be deployed by 2020, further aggravating the already existing imbalance among Member States"*[141].

5.1.2 Current status

Thermo-mechanical electricity storages are the type used most extensively today. Pumped hydro storage (PHS), with an installed capacity of more than 100 GW, accounts for more than 99 % of current global electricity storage capacity.

Hydro reservoirs provide a storage function without pumping, just by keeping the water until the need occurs. Hydro reservoirs are mainly located in Northern Europe. As much as 70 % of the total European storage capacity in reservoirs is located in the Nordic countries. Interconnectors make this storage accessible for continental Europe.

[141] *European Commission, 2013*

5.1.2.1 Batteries

“Battery storage of electricity has a history as long as that of pumped hydro storage, but batteries has still not yet found widespread applications in larger electricity grids. Pilot-scale trials of grid-scale systems are now under way, however, based on a large variety of battery chemistries. Battery storage is of special interest in regions with weak grids and high renewable penetration, such as the French territories of the Caribbean, Corsica, Sardinia and the Canaries. Battery systems are also being tested in continental Europe at locations where the grid is weak, as in some places in Italy.

Other pilot projects include batteries in distribution grids very close to final consumers, in areas where local solar generation is installed, to prevent grid congestion and control voltage variations. Finally, wind and solar equipment manufacturers are experimenting with large battery installations to stabilize the output of wind farms and large PV installations. One example is the Sol-Ion project, where Li-ion batteries (5–15 kWh, 170–350 V) are used to level out mismatches between power demand and solar production.”[142]

Battery storage finds increasing use together with PV panels to increase self-consumption. Typically self-consumption can be increased from 30% to 60% by installing local batteries. Germany has introduced an incentive scheme for local batteries that has created a significant market for local storage. In 2013 more than 6000 systems were installed and the market is expected to grow to 100.000 systems per year.

Table 18 – Comparison of Electrochemical Storage Technologies (MW, Discharge, Cycles, Function)[143]

Technology	Capacity Range (MW)	Discharge Duration	Cycles at 80% depth of discharge	Storage Function
Lead-acid	0.1-1 MW scalable (largest 40 MW)	1 min-5 h	1000-2100	Power quality / Bridging
Nickel Based	0.1-1 MW scalable	1 min-10 h	500-1500	Power quality
Lithium Based	0.1-1 MW scalable (largest 32 MW)	1 min-10 h	2000-9000	Power quality / Bridging
Sodium sulphur	1-34+ MW	10 min-8 h	2500-3500	Bridging
Zink Bromo	0.1-10 MW	10 min-10 h	1400-3500	Bridging
Vadium redox	0.1-10MW	10 min-6 h	10000-14000	Bridging
Metal Air	0.1-10 MW	1 min-6 h	1-100	Power quality / Bridging

[142] *Larsen & Petersen, 2013*
[143] *The Energy Storage Technologies (EST) Market 2011-2021, 2010.*

Table 19 – Comparison of Chemical Energy Storage Technologies (EST) (Round-trip %, Cycles, discharge hours, USD/kWh, Wh/kg, W/kg)[144]

Technology	Round-trip Efficiency	Life Span (Cycles)	Discharge Speed (hours)	Cost (USD/kWh)	Specific Energy (Wh/kg)	Specific Power (W/kg)
Lead-acid	70-90%	600-2100	1-5	75-210	30-50	75-150
Nickel-alkaline	72-80%	3000	1-10	280-850	35-75	150-800
Lithium-ion	85-95%	7000	1-10	700-1000	35-250	150-2200
Sodium-sulphur	89-93%	2500	1-8	400-500	100-225	385-600
Zink bromide	75%	3500	1-10	500-1400	70-85	42-200
Vadium redox flow	85%	10000	1-6	500-1400	30-50	110-300
Metal-air	50%	<100	1-6	75-280	450-650	200-600

5.1.2.2 Power-to-Gas

There are about 40 research projects under way in Europe which has a pressing need of handling the situation of large amounts of intermittent production.[145] "Power-to-gas stores energy by converting electricity to gas– most often hydrogen or methane – via electrolysis (for hydrogen), optionally followed by methanation (for methane). The chemical fuel produced in this way is versatile, energy dense and can be stored indefinitely without losses. Methane can be used directly as fuels for cars, trucks and ships it can possibly also be used in aircraft in a liquefied form. Hydrogen still needs a lot of research and development in order to be commercially used. The established gas distribution infrastructure can handle synthetic methane and low hydrogen concentrations. It is also possible to convert the chemical energy in the stored gas back into electricity, but the round-trip conversion efficiency is relatively low, at around 35%. Many European resources are being put into improving the economics of electrolysis by reducing equipment costs, increasing life time and conversion efficiency. Germany in particular is carrying out a great deal of hydrogen research funded by the government and the car industry"[146]

The general principle of the power to gas technology can be seen below:

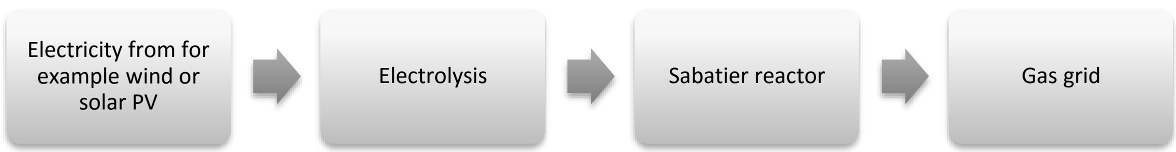

Figure 25 – Power to gas technology, general principle

The following two tables provide summarizing information about power to gas, with H2 and CH4 production.

[144] *Visiongain, 2010.*
[145] *Byman, Haraldsson, & Jernelius, 2013*
[146] *Larsen & Petersen, November 2013*

Table 20 – Power to gas, with H2 and CH4 production[147]

Power to gas, H2 production	
Used for	Long term storage, grid balancing
Length of use	Seconds to months
Capacity	kW-GW
Energy density	3 kWh per Nm³ (+/- 3 kWh)
Energy efficiency	62-82%
Losses	0-1% per day
Start-up time	AEC in minutes, PEM in seconds
Service Life	AEC depreciates to 75% in 10 years. PEM has short membrane lifetime, 5-10 years.
Production phase	Commercially available (AEC) and prototype (PEM)
Investment cost	700 -1100 EUR per kW (ex. overhead construction costs)
Geographic requirement	None
Power to gas, CH4 production	
Used for	Long term storage, grid balancing
Length of use	Seconds to months
Capacity	kW-GW
Energy density	9.81 kWh per Nm3
Energy efficiency	49-56%
Losses	0-1% per day
Start-up time	Minutes to hours
Service Life	Assumed to last over 20 years. Catalysts 72000-144000 Nm³ gas.
Production phase	Commercially available
Investment cost	2400 EUR per kW (ex. overhead construction costs)
Geographic requirement	None

Storage of H2 can also be used in other applications than power to gas such as mobility and stationary applications using fuel cells. Hybrids of H2 production and storage with other systems like batteries, supercapacitor, flywheel, renewable energies are also promising both for small scale distributed or isolated stationary applications, for example.

5.1.2.3 Pumped Hydro Storage

Pumped Hydro Storage is a form of mechanical energy storage where water is pumped from a reservoir at a low height to a reservoir at a higher height. The difference between a pumped hydro storage system and a hydro-electricity generation system is the presence of the pump in a hydro storage system. This pump uses electricity to increase the energy potential of water, a form of energy which can be stored. When electricity is needed the hydro storage plant works like a hydro-electricity generation plant: the water is released from the most elevated reservoir into a pipe which leads it to a turbine connected to a generator. The water's energy potential is first transformed into kinetic energy in the pipe, then into rotational energy in the turbine and ends up as electrical energy after the generator.

In many pumped hydro storage plants, the generator is simply reversed into motor-mode to drive the pump when electricity/water needs to be stored. A typical layout of a pumped storage plant can be seen below:

[147] *INTIS GmbH. Power to Gas. 2013.*

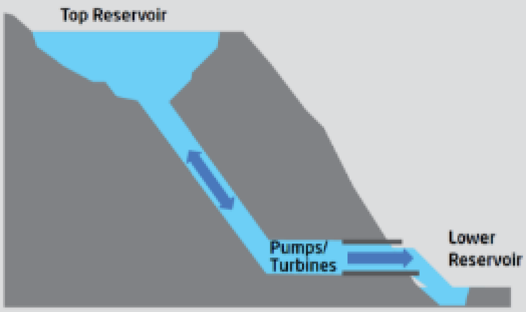

Figure 26 – Pumped hydro storage

Pumped hydro storage uses reversible pump-turbines to move water to a high reservoir for energy storage. When power is required, the water is allowed to flow back down to the reservoir.

Pumped storage is a mature technology, very well suited for centralized applications - not yet implemented on a small scale; Europe has a limited number of potential sites left. There are environmental concerns, given the profound impact on landscapes.[148]

The following table shows the technical details of pumped storage.

Table 21 – Technical details of pumped storage[149]

Pumped Storage	
Used for	Peak mitigation, minute reserve
Length of use	1 to 24 hours
Capacity	Up to 5000 MW depending on size, height, difference and generator capacity
Energy density	0.35 – 1.12 kWh/m³
Energy efficiency	65-85%
Losses	0-0.5% capacity per day
Start-up time	Seconds to minutes
Service Life	50-100 years
Production phase	Commercial available
Investment cost	500-3600 EUR/kW depending on the location
Geographic requirement	Height difference

5.1.2.4 Compressed Air Energy Storage (CAES)

CAES systems use electricity to compress air and store it in a reservoir, either an underground cavern or aboveground pipes or vessels. When electricity is needed, the compressed air is heated, expanded, and directed through an expander or conventional turbine-generator to produce electricity.

CAES is the only commercial bulk energy storage plant available today, other than pumped hydro. There are two operating first-generation systems: one in Germany (290 MW Huntorf) and one in Alabama, US (110 MW). Other projects are under development. CAES will be most prominent in the US, where a number of sites have already been singled out for compressed air schemes. The EU will also see CAES projects, especially if the first adiabatic CAES

[148] *Boston Consulting Group, 2010.*
[149] *INTIS GmbH. Power to Gas. 2013.*

project, ADELE, proves successful.[150] ADELE is an advanced adiabatic compressed air energy storage (AA-CAES). It is a demonstration plant that probably will be operational in 2016.[151]

In the past few years, improved second-generation CAES system cycles have been defined and are being designed. Second-generation CAES hold the potential for lower installed costs, higher efficiency, and faster construction time than the first-generation systems. In one type of advanced second-generation CAES plant, a natural-gas-fired combustion turbine (CT) is used to generate heat during the expansion process. In such a plant, about two-thirds of the electricity generated is produced from the expansion turbine and about one-third from the CT. New compressor designs and advanced turbo-machinery are also leading to improved non-CT-based CAES systems.

CAES plants employing aboveground air storage would typically be smaller than plants with underground storage, with capacities on the order of 3 to 50 MW and discharge times of 2 to 6 hours.[152]

Aboveground CAES plants are easier to site but more expensive to build (on a USD/kW basis) than CAES plants using underground air storage systems, primarily due to the incremental additional cost associated with aboveground storage. CAES systems using improved first generation designs also continue to be evaluated and are being proposed.

Underground CAES storage systems are most cost-effective with storage capacities up to 400 MW and discharge times of 8 to 26 hours. Siting such plants involves finding and verifying the air storage integrity of a geologic formation appropriate for CAES in a given utility's service territory.[153]

Adiabatic CAES:

The adiabatic CAES technology is partially mature; mainly for large-scale centralized applications; most developed countries have the necessary potential storage caverns; Japan and Spain have very few sites, however; little public concern expected.

By 2025 storage costs (Levelized cost of energy (LCOE)) for 180 cycle per year expected to be 0.088 EUR/kWh and for 360 cycles per year the LCOE is expected to be 0.073 EUR/kWh. This is significantly lower than the LCOE´s of batteries and of hydrogen for both cases. It is lower or equal to the LCOE of gas turbine and combined-cycle gas turbine for both cases.[154]

The following table presents summarizing information about CAES.[155]

Table 22 – Compressed air storage

Compressed air storage	
Used for	Peak mitigation, minute reserve
Length of use	1 to 24 hours
Capacity	Depends on storage cavern size
Energy density	0.5-0.8 kWh/m³ (at 60 bar, pressure dependent)
Energy efficiency	CAES 42-54%, AA (advanced adiabatic)-CAES up to 70%
Losses	0-10% per day
Start-up time	Minutes, after 3 min already 50% of the capacity is available, after 10-14 minutes 100%
Service Life	25-40 years
Production phase	CAES: Commercial Availability, AA CAES: Development phase
Investment cost	750 (CAES)-1200 (AA-CAES) USD per kW (580-925 EUR)
Geographic requirement	Nearby salt cavern, empty gas field or aquifer

[150] *Visiongain, 2010.*
[151] *RWE webpage*
[152] *DOE/EPRI, 2013*
[153] *DOE/EPRI, 2013*
[154] *Boston Consulting Group, 2010.*
[155] *INTIS GmbH. Power to Gas. 2013.*

5.1.2.5 Flywheel

Flywheels store energy in the form of the angular momentum of a spinning mass, called a rotor. The work done to spin the mass is stored in the form of kinetic energy. A flywheel system transfers kinetic energy into AC power through the use of controls and power conversion systems. Most modern flywheel systems have some type of containment for safety and performance enhancement purposes. This containment is usually a thick steel vessel surrounding the rotor, motor-generator, and other rotational components of the flywheel. If the wheel fractures while spinning, the containment vessel would stop or slow parts and fragments, preventing injury to bystanders and damage to surrounding equipment. Containment systems are also used to enhance the performance of the flywheel. The containment vessel is often placed under vacuum or filled with a low-friction gas such as helium to reduce the effect of friction on the rotor. A flywheel can be seen below:

Figure 27 – Flywheel

Flywheels have excellent efficiency and long life spans, but their very high energy density limits their use primarily to Uninterrupted Power Supply solutions. However, Beacon Power has developed large scale flywheels with a 20MW capacity (200, 100kW units) for frequency regulation services in New York, and is already earning revenues from this project. Flywheel projects for power quality applications are expected to strongly increase over the ten year forecast.[156]

Although sales of flywheels are predicted to increase rapidly in Europe and Asia, the US is likely to remain the largest market until 2021.[157]

Shorter energy duration storage systems that are not generally attractive for large-scale grid support applications, which require many kWh of MWh of energy storage.

They have a fast response time of 4 milliseconds or less, can be sized between 100 kW and 1650 kW, and may be used for short durations up to 1 hour. They also have very high efficiencies of about 93 %, with lifetimes estimated at 20 years.[158]

Levelized total cost of flywheel compared to combustion turbine: 410-440 USD/kW-year.

5.1.2.6 Superconducting Magnetic Energy Storage (SMES)

SMES have high efficiencies of over 90 % and instantaneous charge/discharge cycles make SMES ideally suited to power quality support. SMES are generally small in size due with a current maximum of around 10MW of storage capacity. The physical size of the coil will be a limiting factor for this technology; the magnet systems are incredibly heavy and when scaling up design dimensional and weight factors make SMES unfeasible. Increasing the thickness of the superconducting wire creates more heat and reduces efficiency. The effects of the magnetic field on surrounding areas have also not been thoroughly studied.

[156] *Visiongain, 2010.*
[157] *Visiongain, 2010.*
[158] *EPRI, 2010*

SMES is the most established of the high power technologies with installations connected to grids in Europe, Japan, and the US. Hitachi built their first 1.4 kWh SMES facility in 1986 to study transmission line stability. American Superconductor installed SMES for the Wisconsin Public Service grid to improve voltage stability.

The US will be an important market for the SMES as will Germany and Japan although sales will not reflect the faster growing flywheels and ultra-capacitors market.[159]

5.1.2.7 Ultra-capacitors

The main advantage of ultra-capacitors is their high power density, efficiency and life cycle, being able to charge and discharge rapidly for over 1 million cycles.

Ultra-capacitors are only just breaking through into the grid storage market but boosted by nanotechnology and driven by developments in regenerative braking in transport, they will play a more significant role. The US, Korea and Japan will be the biggest markets for ultra-capacitors.[160]

5.1.2.8 Comparison SMES, flywheels and ultra-capacitors

Table 23 – Comparison SMES, flywheels and ultra-capacitors

Technology	Round-trip efficiency	Life Span	Discharge Speed	$/kWh	Energy Density (Wh/kg)
SMES	90%	30-50000 cycles	1-8 seconds	3000	40-60
Flywheel	93%	20 years	0.004- seconds	410-440	200
Ultra capacitors	95%	1000000+ cycles	0.001-3 seconds	10000	1-30

5.1.3 Future development

Energy storage is closely aligned with the technologies for wind and solar due to the potential role of energy storage in the integration of variable renewable resources. The further development of electricity storage technologies will be important for all applications, from large-scale generation and grid ancillary services all the way down to customer and end-user sites[161].

Larsen & Petersen, 2013 argues that energy storage needs to be a field of its own right, not just an add-on renewable. Further *Larsen & Petersen, 2013* means that it is important to work on the market-terms; there should be incentives for storing energy and building these systems. Each storage technology has advantages and disadvantages and in the future several of these carriers will be used.

A future energy sector relying heavily on power production from renewable resources will most likely require substantial energy storage in the form of chemicals. The figure below illustrates the concept of such an energy infrastructure[162].

[159] *Visiongain, 2010.*
[160] *Visiongain, 2010.*
[161] *The Centre for Low Carbon Futures, 2012*
[162] *Larsen & Petersen, 2013*

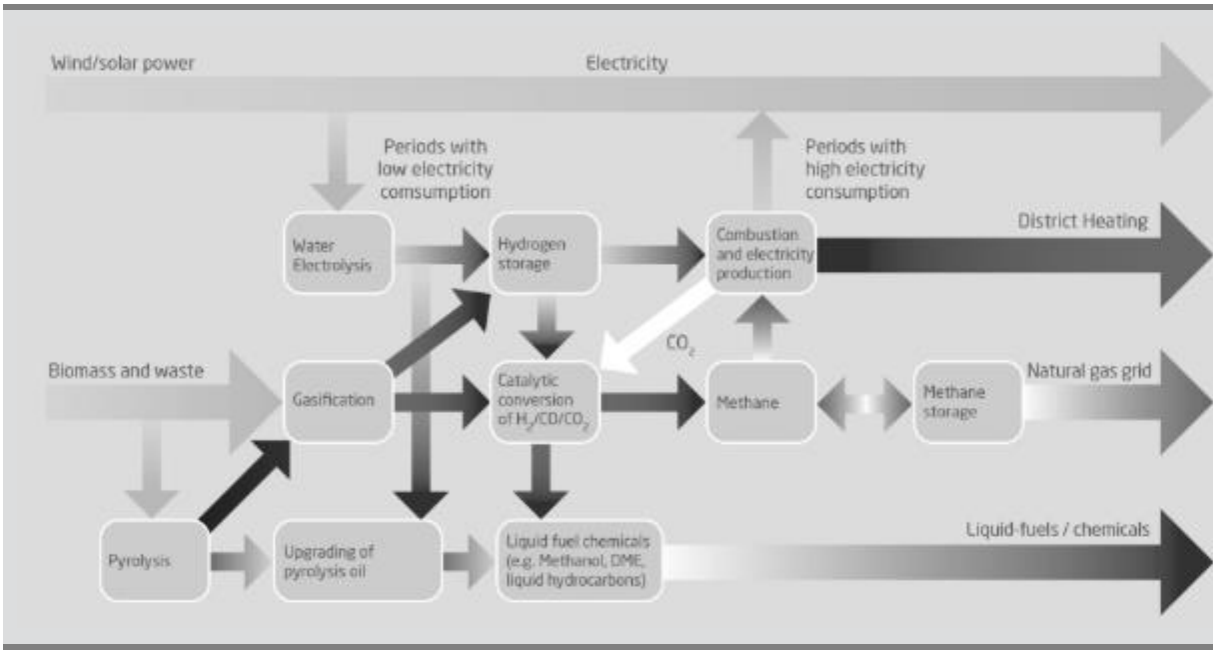

Figure 28 – Energy Infrastructure[163]

A future energy infrastructure could easily involve several of the energy carriers in the figure, and local opportunities and requirements may determine the energy carrier that is preferred in a given situation. It is clear that catalysis and electrolysis will play pivotal roles in all of the described storage routes[164].

The main hurdle for batteries is high investment costs, though these are expected to decrease over the next decade, driven by scale benefits and technology innovations.

"The largest potential for electrochemical storage in a future sustainable energy infrastructure is probably for frequency and voltage stabilisation in connection with sustainable energy sources as well as in dealing with hourly and daily fluctuations caused by variations in production from wind and solar power. This requires very fast and reversible energy storage with low energy losses and high durability, which in turn means that batteries used for large-scale storage face quite different challenges compared to those in portable and mobile applications."[165]

Costs are decreasing rapidly particularly for lithium-ion batteries driven by sharp increase in volumes in electronics, power tools and electric vehicles. The current rate of decrease is 20% per year and the downward trend is expected to continue for a long time.

Electricity for plug-in hybrid vehicles (PHEV) and all-electric vehicles (EVs) is one important future demand for electricity. The possible impact of these vehicles on the market for energy storage is though complex. (UK-report)

There are a large number of possible fuels for fuel cells. When looking at the fuel cell market, it has the largest spread in the transportation sector. Cost decrease with growing production volumes.

The storage revenues for different technologies can be seen in the graph below. As can be noted, the deferral of transmission and distribution investment and demand charges are the two most profitable.

[163] *Larsen & Petersen, 2013*
[164] *Larsen & Petersen, 2013*
[165] *Larsen & Petersen, 2013*

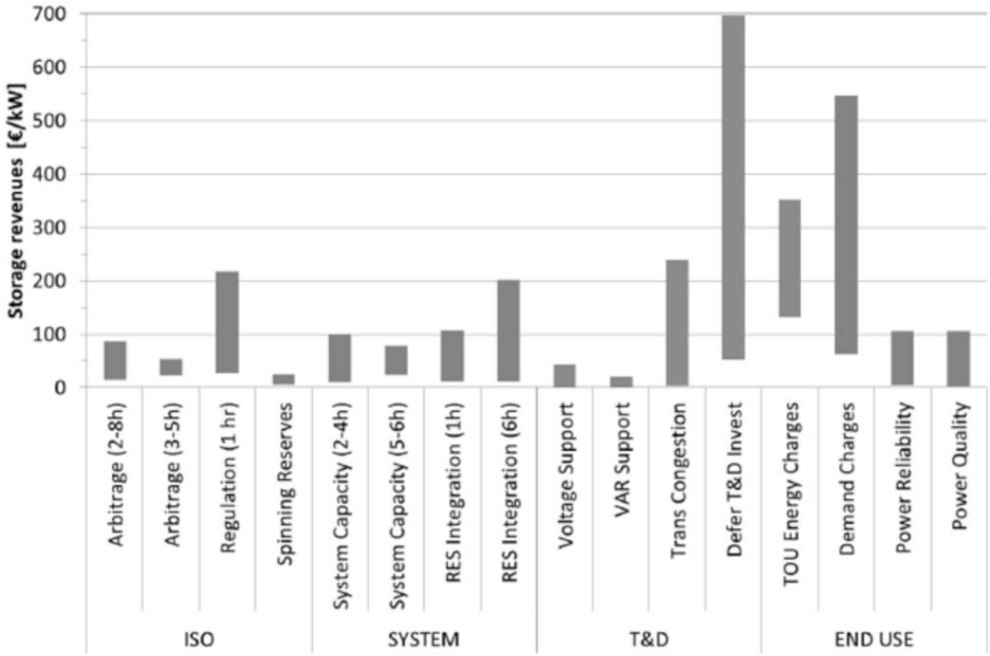

Figure 29 – Storage revenues[166]

5.1.4 Critical success factors

To stimulate development in energy storage technologies and their integration in energy systems, *Larsen & Petersen, 2013* recommends a series of initiatives to be taken over the next two decades:

- Energy storage should be supported as a separate field of research
- Demonstration of connections between grids, such as the power-to-gas concept
- Design of market terms for integrating energy storage in the electricity system
- Regulatory settings should be developed to favour the effective coupling of the power, heat and gas infrastructures

Success factors for Power-to-Gas[167] are summarized to be the following:

- The price of methane relative the electricity price
- The number of hours a power-to-gas operates per year which corresponds to the number of hours the electricity price is low enough
- The possibility for using the heat produced
- Whether the produced gas can be distributed in a gas pipes or through trucks

[166] *xxx*
[167] *Byman, Haraldsson, & Jernelius, 2013*

6 Challenges for the European Energy system

The European energy system faces a number of challenges and this chapter takes a closer look at the economic challenges such as the system costs as well as the regulatory and research needs for the different production technologies, transmission and distribution as well as energy storage.

6.1 Economic challenges: The system costs

After this overview over the state of the art of different technologies and the energy triangle analysis a closer look at the respective costs provides an additional dimension for the future use of different technologies. Costs and environmental issues have to be carefully balanced by policy makers. The cost of different technologies depends greatly on their capacity factor. The table below shows estimated LCOE for the European electricity production sources for the years 2019 and 2040 respectively. The future is always hard to predict with technological and economical leaps and were the following analysis is based on current knowledge and system, a future system might offer new possibilities and solutions, as well as new cost structures.

The Capacity factor refers to the total number of full load hours that the production technology has during a year, hence 75 represent 6570 hours.

LCOE represent the levelized cost of electricity for the production technology and is one way to summarize overall competiveness of different technologies. It represents the cost per MWh based on the total expected life time of the technology and the capacity factor and key inputs are capital costs, fuel costs, fixed and variable operations and maintenance (O&M) costs, financing costs, and an assumed utilization rate for each plant type. The importance of key inputs varies with the technology but could also be affected by availability of various incentives, fuel prices, existing resource mix and regional differences.

The picture clearly shows the comparatively high system costs for offshore wind and coal. For offshore wind there are challenges in terms of installation and especially maintanence of already operating offshore turbines.

As can be seen in the table, the fossil fuels have considerably higher operation and maintenance costs but lower installation costs, especially natural gas.

Table 24 – Levelized cost of electricity[168]

Plant Type	Year	Levelized Capital Cost	Fixed O&M	Variable O&M including fuel	Transmission investment	Total System LCOE
Solar PV	2020	99	10	0	4	113
	2040	92	10	0	4	106
Hydroelectric	2020	64	4	6	2	75
	2040	69	4	7	2	81
Onshore	2020	52	12	0	3	66
	2040	53	12	0	3	68
Offshore	2020	152	20	0	5	177
	2040	133	20	0	5	158
Advanced Nuclear	2020	63	11	11	1	86
	2040	56	11	12	1	80
Biomass	2020	42	13	34	1	90
	2040	39	13	31	1	84
Conventional Coal	2020	54	4	30	1	90
	2040	51	4	31	1	87
Advanced Coal	2020	69	6	32	1	108
	2040	62	6	29	1	99
Advanced Coal with CCS	2020	88	9	37	1	135
	2040	76	9	33	1	119
Conventional Natural Gas CC	2020	13	2	60	1	75
	2040	12	2	68	1	83
Advanced Natural Gas CC	2020	14	2	56	1	73
	2040	13	2	64	1	80
Advanced Natural 'Gas CC with CCS	2020	27	4	67	1	99
	2040	23	4	78	1	106

The levelized capital cost have been re-calculated from american to european numbers using the capacity factor of EU-27. Fixed O&M, Variable O&M including fuel and transmission investment have been calculated using the exchange rate between US-dollar to Euro, as well as differing general fuel prices such as gas prices in respective area when it is applicable.

Dong Energy however present figures for offshore wind to be below 100 €/MWh in 2020.[169] Also DTU International Energy Report 2014 expect the cost of future offshore wind energy to be a lot lower than presented by IEA in the table above.

[168] *EIA, 2015*
[169] *Dong Energy, 2013*

6.2 Regulatory and research needs

Security of supply and Balancing the energy system	**Regulatory Needs and Market requirements**	**Research needs**
PV		
Due to its intermittent nature, PV requires balancing power to be fully exploited in the energy system. PV can reduce peak load since peak production might coincide with peak consumption.. The benefit of solar however is that it is not reliant on foreign fuel and therefore contributes to security of supply. Reinstating the production of solar PVs in Europe should be considered in order to lessen the dependency on import.	PV is not generally cost competitive against the grid mix average price across Europe today. In some markets e.g. Italy and South Germany grid parity has been achieved and costs are continuing to go down. Large scale plants have reached market parity in Italy but generally needs support to become competitive. Feed-in-tariffs and investment support increases the speed of implementation. Net metering gives significant support and local batteries can increase self-consumption.	Costs for PV have historically been falling with 20% per year and are expected to continue to fall with about the same rate. There is still a significant potential for further cost reduction and performance increase. Research is needed in all areas to become or stay competitive. Research is needed to improve existing technologies, in new technologies and production technology. Research should include the whole value chain for complete systems since the cells already today represents only about 40% of system cost. Building integration represents a potential for cost reduction and requires research. Regarding technology there is not one clear winner and several technology trails should thus be followed.
HYDROELECTRIC		
Hydroelectricity today represents a significant domestic electricity production resource and in addition a main contributor to system balancing. Significant storage capacity exists particularly in northern and hydro power is the main contributor to system balancing particularly in northern Europe. Increased interconnection capacity is needed to fully exploit the balancing capacity of the hydro power.	Harmonization of market rules is important to fully exploit the balancing capability of hydro power. Integration of the electricity system generally improves the business case for interconnections but different market rules e.g. Capacity market connected to energy only markets is not as good business case as connecting similar markets. Harmonization of markets rules is generally positive.	Hydro power is generally a mature technology but research is still needed e.g. To study minimization of environmental impact, how regulating power best can be used in an integrated system needs to be studied.
WIND		
Due to its intermittent nature, wind power requires balancing power to be fully exploited in the energy system. Wind Power production does not necessarily coincides with peak consumption due to the variability of wind and can thus increase the need for balancing power. Balancing can be done with dispatchable power, interconnectors or energy storage. Wind power is not reliant on foreign fuel and therefore contributes to security of supply. There is also a strong industrial base for wind power in Europe.	Wind power is generally not cost competitive and requires support schemes today. The cost development is positive particularly for land based wind power but there is also potential for offshore wind to reduce its costs. A large scale European wind power expansion requires integrated European electricity system as well as cross boarder collaboration in order to function properly. "Shift focus from high economic incentives to long-term policies that provide predictable and reliable market and regulatory framework" (IEA)	Research is needed into wind power in combination with other power systems such as power-to-gas. These types of integrated systems will increase the usability of wind power. Research is also needed in cost reduction in operation and maintenance of offshore wind as well as improving the capacity factor of both onshore and offshore wind. Research is also needed in site selection and better predicting future wind quality and speed.

Security of supply and Balancing the energy system	Regulatory Needs and Market requirements	Research needs
NUCLEAR		
Uranium is readily available around the world on open markets. It is easy to store and the delivery of supply is secured. Uranium however has to be imported from outside Europe. Nuclear need to be operated at a high capacity factor in order to be cost effective.	Due to the lack of public acceptance and uncertainty of the future regulatory framework of nuclear power it will be very difficult to attract investment to this sector. If development of nuclear in Europe is desired risk mitigation for investors need to take place. One option would be for the states to take the risk. The nuclear power plants in operation is getting old and needs to be replaced quite soon in order to maintain current capacity, therefore swift action is necessary.	Further research is needed into long term storage of spent fuel. Research is also needed into how to communicate complex technical issues to the public. Further research is also needed in to the next generation reactors. Fusion reactors still need much more research in order to be commercially viable and will not be an option before 2030.
GAS		
The flexibility of gas power is great to combine with the intermittency of wind and solar power. At the moment gas has to be imported as very limited conventional natural gas resources are available within Europe. Shale gas however could change this situation and substantially increase the European security if supply.	The gas power plants are not profitable on a low utilization rate and a capacity market needs to be developed in order for them to survive. Development of shale gas also needs a solid regulatory framework for extraction and environmental issues in order to be realized.	Research is needed into the environmental effects of hydraulic fracturing and horizontal drilling. The EPA (US Environmental Protection Agency) is currently conducting an investigation into the environmental effects of shale gas and is expected to be released in 2014. If proven to be a safe technology, this investigation can be used as a material to promote and increase public acceptance for shale gas.
ENERGY STORAGE		
Energy Storage in the form of batteries, pumped storage, heat storages etc. will be vital in order to balance the energy system. The energy storage will help shift the intermittent electricity production in time and smoothen both supply and demand.	Current regulatory regimes are limiting the use of storage e.g. by not allowing distributing companies to own storage. This has to be solved by reformed regulation. Energy storage on local level could be more attractive by changing regulation to allow local storage to participate e.g. in the balancing market	Energy storage, particularly battery storage is under rapid development both in terms of cost and performance. There are also many technologies under development with potential to give significant reduction of cost and increased performance. Therefor research in both basic technology and production technology is required.
SMART GRID		
Smart grid solutions in all levels of the system are instrumental for balancing the power system in Europe. Strengthening of the grid also needs to be combined with increasing the controllability of the grid, increased smartness. Thereby the grid can contribute to integrate the system further and allow sharing of balancing resources without increasing the risk to spread disturbances. But balancing can also be done on more local level e.g. by contributing to peak shaving.	To fully exploit the benefits of smart grid solutions regulation can give incentives for smart grid applications e.g. by increased return. Smart grid solutions will generally benefit from more liberalized markets rules such as hourly metering and billing.	Smart grid solutions is generally raising the technological level of the grid by combining IT technology and Power technology. Research is thus required in IT, Power Electronics and power system "promote the development metrics, national data collection and international data co-ordination" (IAE)

Security of supply and Balancing the energy system	**Regulatory Needs and Market requirements**	**Research needs**
CCS		
For all fossil fuels, CCS will have to be applied from around 2030 onwards in the power sector in order to reach the decarburization targets. CCS is also an important option for decarburization of several heavy industries. CCS may be the only option available to reduce direct emissions from industrial processes at large scale needed in the longer term. In the power sector, CCS could be a key technology for fossil fuel-based generation that can provide both base load shares of variable renewable energy and balancing capacity in an electricity system with increasing	The industry needs to adopt CCS technologies as a measure for them to reduce their CO2 footprint. "Near term policies should be supported by credible long-term climate change mitigation commitments" (IEA) The future of CCS crucially depends on public acceptance and adequate carbon prices; it needs to be sufficient demonstrated on large scale this decade. Carbon prices will need to reflect and internalize external costs.	Research is needed for clean coal technolgies such as CCS and IGCC to be used and profitable. Large-scale Pilot plants have to be built. Support R&D for more optimal CCS. A strong need to inform people about CCS in Europe drawing upon past and present experience as a basis for improving the knowledge and persception of CCS. Problems and opportunities with geological storage have to be studied. CO2 reuse should be investigated as a complement to CCS.
HEAT PUMPS		
Using heat pumps for heat generation is an effective way of electrifying the energy system. The heat pumps will also make the energy system more energy efficient. Heat pumps are often combined with heat storage that can play an important role for system balancing.	Heat pumps are contributing to renewable energy production and this contribution should be measured and documented to give full recognition to the value creation by heat pumps.	Research is needed into increasing the COP of heat pumps and how to integrate them in PV and storage systems.
ENERGY EFFICIENCY		
A prerequisite for reaching high energy efficiency is moving towards an electrified energy system. Electrification of processes generally increases the efficiency typical example is electrification of transport. Energy efficiency will reduce the energy need and thus decrease the dependence on imported fuel.	Energy labeling is a good example of regulatory initiatives that supports energy efficiency and should be expanded.	Potential for energy efficiency is significant and research in both new system solutions, technologies and behavioral science is needed.

The matrix above clearly highlighted the importance of certain technologies for balancing the electricity system. Additionally it became apparent that in most cases regulatory needs and market requirements are as important as technological development – sometimes even more.

Research needs are most pressing in the area of storage, grid and nuclear technologies. Especially storage and grid technologies perform key functions in a European Energy system based on intermittent renewable energies and much more research is needed in these areas. Also nuclear and shale gas technologies require more research to make these technologies more acceptable. In their current state of the art there is strong opposition to them in several European countries.[170]

In terms of regulatory needs and market requirements it is worthy to note that several technologies are ready for market roll-out but inhibited by certain regulation (storage), negative market incentives (gas) or missing business models (grids). When it comes to building new pump storage facilities or expanding the grid the "not in my backyard"-phenomenon in many European countries also hinders the expansion of the energy system.

[170] *Under **Horizon 2020** - the EU Framework Programme for Research and Innovation between 2014 and 2020 - a budget of €5 931 million has been allocated to non-nuclear energy research which is built around seven specific objectives and research areas (e.g. reducing energy consumption and carbon footprint) (European Commission). The European Strategic Energy Technology Plan (**SET-Plan**), adopted by the EC in 2007, is the **technology pillar of the EU Energy and Climate policy.** It seeks to set out a long-term energy research, demonstration and innovation agenda to guide the research and development of new energy technologies and promote their uptake by the market. The plan comprises measures relating to planning, implementation, resources and international cooperation in the field of energy technology.*

7 Market observations

The following chapter describes a number of market observations to be reflected upon and ends with a sub-chapter about the electricity market and how an energy only market or capacity market might influence the system

The European electricity system is at a crossroads. The development of the electricity system might take different directions (market designs) with opportunities on the national, regional and European level. National capacity markets and support systems for renewables are pushing for more planning and nationalization of the market. At the same time, EU is promoting an integrated European electricity market, with the implementation of network codes and a European market model (target model) already by 2014. The reformation of the electricity market aims primarily at securing the future supply of electricity, in EU.

➔ *In order for the EU targets to be reached until 2030 a harmonization of the market including subsidies might be required. A developed European Internal Market might be required in the long term in order to reach the 2050 goals.*

Balancing generation and consumption will pose an ever increasing challenge for the future electricity system. Europe should have a stronger focus on the installed capacity, to safeguard the continuous supply of electricity in the European system. Renewable power often has a lower capacity credit and is more complex to implement. It is still not clear how a massive expansion of wind power and solar power will affect the need for reserve- and regulating power. Balancing generation and consumption will pose an ever increasing challenge for the future electricity system, and smart grid technologies are part of the solution. In conclusion, there are three principal challenges that the market and its actors might face:

1. Managing the continuous balancing of the system.
2. Designing the system for reliable supply even during the hours when wind and solar power give a small contribution, but demand is high.
3. Designing the system so that hours with high wind/solar generation and low electricity consumption, is not leading to locked in generation and price collapse. The challenges, as can be seen, consist of utilizing existing resources efficiently as well as of dimensioning the system optimally.

➔ *There are example solutions to the above presented challenges, to reflect on:*
- *The expansion of the European transmission grid. The expansion of renewable power requires an extensive and rapid expansion of the European transmission grid, since the grid is overloaded already. As for CCS, a huge expansion of the electricity grid is associated with great uncertainty and thereby it is a critical element in the transformation.*
- *Increased usage of both thermal and electrical storage, placed in different parts of the energy system. Local small scale storages as well as central large scale units are required to fully balance the energy system. Regulatory changes might be required in order to capitalize on the benefits of storage technologies.*
- *Demand control, where both industrial consumers as well as households and large commercial facilities are connected.*

Capacity markets influence the location of new investments and the need for new transmissions. Access to peak load capacity will partly replace transmission capacity. Properly handled, capacity markets can be implemented without any additional costs for the customers. The increased cost associated with paying for capacity will be balanced by reduced electricity prices of the same magnitude.

➔ The introduction of subsidies for renewable power generation has brought challenges to the market when it comes to conventional generation. A capacity market should be considered to secure investment in dispatchable power sources that are required for security of supply.

With a larger share of intermittent power, electricity prices will, in the long run, vary more

More variable generation results in a more volatile electricity prices. The introduction of a European Internal Market together with a capacity market will probably help stabilize and reduce the volatility.

De-carbonization of the energy system. Fossil fuels and nuclear power will dominate European electricity generation for the next 20 - 30 years. The existing electricity generation system is the starting point for the development to come and will for a long time influence the structure of the system. Even with the renewable proportion expanding massively a large part of the power generation in Europe will probably be based on fossil fuels by 2050.

➔ *There are examples of transformation paths to a carbon free energy system:*

- *Next generation nuclear*
- *More cost efficient renewable energy production*
- *Carbon Capture and Storage*

The future energy system will most likely be a mixture of the three paths. Gas will play an important role in all possible storylines of the future. Considering security of supply, development of European shale gas resources seem inevitable.

The actors in the electricity system will face different challenges in the transformation. The actors in the electricity system will face different challenges in the transformation.

The biggest challenge for the transmission system operator is to expand the network fast enough given the long lead times in combination with uncertainty regarding the location of the new power sources. Investments in storage facilities can reduce the investments in upgrading the transmission and distribution infrastructure. There is an obvious risk that renewable power will be trapped-in in some regions and cross-border collaboration is a key in mitigating this problem.

From a regulatory perspective there are three overall challenges:

- The first one is to create the economic incentives required for the necessary dispatchable power.
- The second one is to create the incentives that stimulate effective investments in the networks.
- The third challenge is to create the incentives needed for the potential flexibility of demand to be utilized. Smart grid is much about having the customers contribute to the balancing of the electricity system and thereby reduce the need of regulating power and grid extensions.

Additional, a market which rewards not only energy but also installed capacity needs to be developed in order for the new system to be competitive and provide security of supply. Key requirements for the future electricity markets are described below.

7.1 Electricity market design

On an Energy Only Market (EOM) all decisions made by electricity consumers and power providers are based on spot prices. For investments in the first place to become profitable on an EOM, shortages most occur, or high risk of such, for a minimum number of hours. The situation on an EOM is further aggravated by the introduction of large intermittent power generation such as wind and solar power. As a result of this intermittency the regulation capacity in hydropower (important in the Nordic countries) and thermal (important in the rest of Europe) is required. This complicates the investment problem.

In the next few years there is no need for new power generation as an average over a year since the expansion of renewable electricity is so strong and because of weak economic growth. However, the need to increase capacity during hours of peak consumption and low wind and solar power production may increase. This particular type of investment in power plants, utilized only during a short period of time and highly dependent on high electricity prices at the specific time they are operated, will be the most insecure investments in the power market. The question is if there will be any investors prepared to make such an insecure investment. This also needs to be reflected in the design of support systems like feed-in premiums and design of markets for ancillary services.

The issue described above and throughout the whole report may be an important reason why various forms of re-regulation of the electricity system in Europe are being discussed. An alternative is to create a capacity market (CM) in the EU, or in certain countries. On a capacity market one can procure the desired capacity, possibly up-section in different types of power and consumption flexibility. Since under capacity is much costlier than excess capacity, the procured capacity on a capacity market should be done with a certain spare margin. In practice, one should procure as much capacity as the risks of shortage are negligible.[171]

As has previously been mentioned, a large portion of intermittent power (such as wind and solar) in the European energy system will require the system to have large flexibility and fast response. Peak load plants are needed to a larger extent than before and investments in expensive plants that will only be used for a few hours per year are necessary to guarantee security of supply. However, with an energy-only market (EOM) there are few incentives for large investments in peak load power plants. The incentives to invest in high-tech, clean technology are especially low and a high power rating and low energy production tends to give plants with low investment cost and high fuel cost. If thermal power plants are to provide the peak load energy needed, open cycle turbines with natural gas, LNG or light oil will be the major choice.[172]

[171] *NEPP Progress Report Part 1, 2013*
[172] *Strömberg L., 2014*

8 Conclusions

Conclude the key finding of this reflective paper and describes some possible trajectories that the European electricity system might take.

The current European electricity system is predominantly supplied by fossil fuel, nuclear and hydro power. The European thermal power fleet (coal, nuclear and gas) is aging and 2/3 needs to be replaced within the next 30-40 years. CCS technology is failing due to non-viable costs. The instability in long term policies is halting investors into the European power sector. Nevertheless perspectives of power-to-gas could help CCS.

- ➔ Large changes might be needed and unavoidable in the near future to improve supply sustainability and safety.
- ➔ If the expansion rate of sustainable electricity production is not increased rapidly, nuclear power might be a non-avoidable option in case of failure of CCS. New nuclear power plants then need to be planned promptly if they should be ready in time to replace the current old capacity before its end of life.
- ➔ Stable and long term policies can be developed in order to attract investment to the energy sector.

The equalization of sustainability, security of supply and competitiveness (energy triangle) and the focus on non-regret options is paralyzing European development.

- ➔ Use and develop gas as one possible intermediate solution in the transformation of the energy system.
- ➔ Accept temporary tradeoffs for the long term security, competitiveness and sustainability of supply.

Solar PV is expanding rapidly and is very unevenly distributed between the European countries. Wind power is unevenly distributed in Europe and mainly located onshore. Major expansion in the wind power sector is planned to take place offshore.

- ➔ Research is needed in order to lower the costs for offshore wind
- ➔ Expansion of renewable energy in Europe can be very costly and require storage capabilities and interconnections between countries
- ➔ Regulation can to be adjusted to promote storage, the possibility of a capacity market should be investigated
- ➔ Increase the electricity share coming from hydropower in order to utilize its potential as balancing power and storage
- ➔ Transmission requirements between countries need to be correlated to the renewable electricity share in the country

This discussion paper aims to give a brief description of mainly the electricity production but also transmission and storage – challenges for the future European electricity system. Taking into account the challenges for the future European electricity system, and due to limits of time and scope, iall these areas should be further studied.

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11 Glossary information

Latest available and comparable data has been used in this paper and includes several data sources, terms, definitions and areas distinctions. Some of them are described below;

European electricity production

The European electricity production chapter includes statistics about installed capacity, electricity production and share of European electricity production. Data originates from the ENTSO-E yearly statistics & Adequacy Retrospect 2014, except in the chapter about Biomass and Waste or when it is otherwise stated. Following European countries and areas are included;

- Austria, Bosnia-Herzegovina, Belgium, Bulgaria, Switzerland, Cyprus, Czech Republic, Germany, Denmark, Estonia, Spain, Finland, France, United Kingdom, Greece, Croatia, Hungary, Ireland, Iceland, Italy, Lithuania, Luxemburg, Latvia, Montenegro, FYR of Macedonia, The Netherlands, Norway, Poland, Portugal, Romania, Serbia, Sweden, Slovenia, Slovak Republic and West Ukraine.

EUR-28/European Union

The following countries and areas are included in EUR-28;

- Austria, Belgium, Bulgaria, Cyprus, Czech Republic, Germany, Denmark, Estonia, Spain, Finland, France, United Kingdom, Greece, Croatia, Hungary, Ireland, Italy, Lithuania, Luxemburg, Latvia, Malta, The Netherlands, Poland, Portugal, Romania, Sweden, Slovenia and Slovak Republic

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EURSTAT

Eurostat is a Directorate-General of the European Commission of the European Union, responsible for providing statistical information and is used for i.e. the chapter about Biomass and Waste which and their data consist of the following comparable countries:

- Austria, Bosnia-Herzegovina, Belgium, Bulgaria, Cyprus, Czech Republic, Germany, Denmark, Estonia, Spain, Finland, France, United Kingdom, Greece, Croatia, Hungary, Ireland, Iceland, Italy, Lithuania, Luxemburg, Latvia, Montenegro, FYR of Macedonia, The Netherlands, Norway, Poland, Portugal, Romania, Serbia, Sweden, Slovenia, Slovak Republic and Ukraine.