

The Changing Role of Nuclear Power in the European Union: Reflections from Official Scenarios Released before and after the Fukushima Daiichi Accident

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SUMMARY

Nuclear energy plays an important role in the global and European energy sectors. The nuclear disaster of Fukushima Daiichi has amplified the debate on the potential future roles of nuclear energy in the EU and has had impacts on the European Member States' energy policies; however, the reactions of the member states were vary. Concerns about common legislation, waste management, safety and risk management have also strengthened. Initiatives were taken at national, regional and international levels. The goal of this study is to highlight the main advantages and disadvantages of nuclear energy utilisation in the light of the official forecasts released before and after the Japanese accident.

Keywords: nuclear energy, energy forecasts, European Union

Journal of Economic Literature (JEL) codes: Q47, N70, P48

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INTRODUCTION

Regarding the current role of nuclear power globally, it should be noted that in 2017 449 commercial nuclear power reactors are operating in 31 countries, with over 392,116 MWe (megawatt electrical) of total capacity (WEC 2017). Recently, the average age of the world's nuclear reactors is 29.53 years; 64.81% of the global nuclear reactors have operated for at least 30 years while 90 reactors have run for 40 years or more. The largest number of reactors can be found in the USA (99), which is followed by France (58) and Japan (42), while the distribution of the installed gross capacity by world region indicates that Europe has the largest nuclear power plant capacities. In 2015 nuclear reactors generated 2,441 TWh (terawatt-hours) of electricity globally, which means that worldwide 10.7% of total electricity generation came from nuclear energy and the "big five" nuclear generating countries, i.e. the USA, France, Russia, South Korea and China (before 2012 Germany was one of the biggest nuclear energy generating countries) produced 70% of the total nuclear-based electricity in the world (Schneider et al. 2016).

After the nuclear accident in Fukushima in March 2011, the continued use of nuclear energy in the European Union (EU) gained vast political and public attention. In the EU it is up to each member state to decide whether to produce nuclear power. Debate on nuclear energy utilisation among European member states is not a new phenomenon. As Nuttall stressed in 2009, in the EU the national opinions on nuclear energy generation differ significantly due to the diverse national experiences. Nuttall classified the member states based on their opinions using key criteria reflecting the formal government policies, the extent to which policy is a consensus across major political parties, the level of acquiescence and public acceptance of policy, and the scale of operating infrastructures in 2006 (Nuttall 2009). According to this classification (see Table 1), member states were almost exactly balanced in their opinion of nuclear energy. Analysing the impact of the Fukushima disaster, Thomas (2012) distinguishes between four types of European reactions:

1. Reject the option of new reactors and force the closure of existing plants,
2. Accelerate the closure of existing plants in countries with previously long-term nuclear phase-out policies; enhanced public pressure against nuclear power plants,
3. Not proceed with plans for new plants,
4. Proceed with plans for new plants as if the accident in Fukushima had little or no relevance at all.

Table 1
EU member states' opinions concerning nuclear energy before and after the Fukushima Daiichi Accident

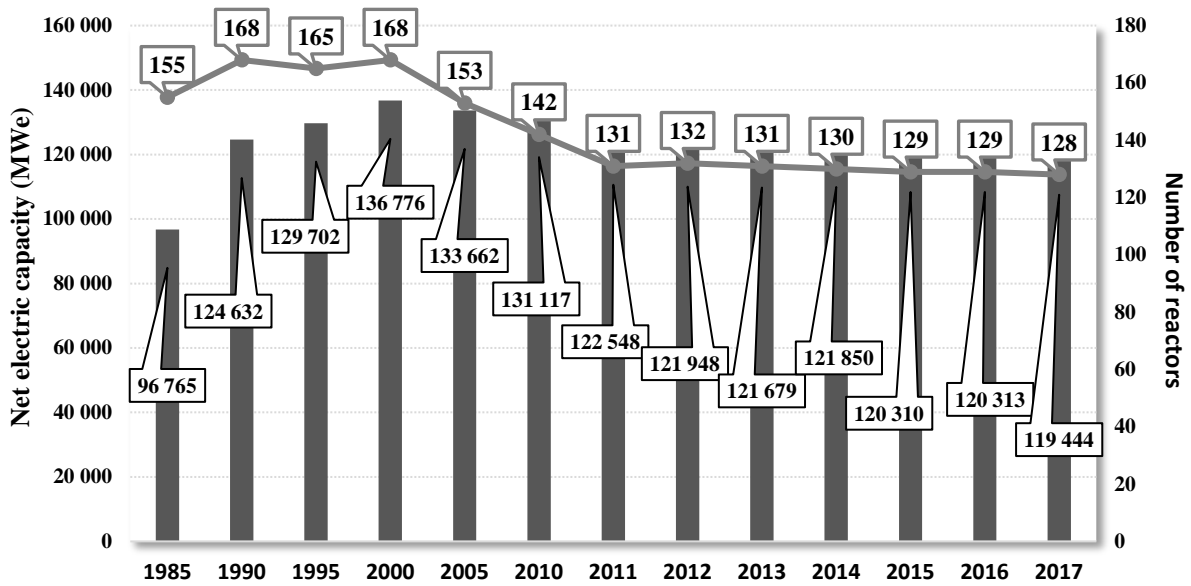
EU member states' opinion concerning nuclear energy in 2006				
Strongly Positive	Weakly Positive	Neutral	Weakly Negative	Strongly Negative
Finland; France; Romania; Lithuania; Bulgaria; Czech Republic; Hungary; Slovakia	UK; Netherlands; Spain; Portugal; Poland; Latvia; Estonia; Slovenia	Luxembourg; Denmark; Malta; Cyprus	Italy; Germany; Sweden; Belgium; Greece	Ireland; Austria
EU member states' opinion concerning nuclear energy after the Fukushima accident				
Positive (Strongly or weakly)		Divided	Negative (Strongly or weakly)	
UK; Poland; Finland; Romania; Czech Republic; Hungary; Slovakia		Bulgaria; France; Lithuania; Netherlands; Slovenia; Spain; Sweden	Austria; Italy; Denmark; Germany; Belgium	

Source: own summary based on Nuttall (2009, pp. 7-8) and Holmberg (2013)

Classification in table 1 can be confirmed by the facts presented in ESA (2013), Södersten (2012), Febowitz (2013), and IEA (2013). According to these sources, following the 2011 nuclear catastrophe at Fukushima, Germany announced that it had decided to replace atomic reactors with more fossil fuel-fired plants and a growing share of clean-energy sources, and eight reactors were shut down immediately. The German Chancellor also stated that by 2022 all nuclear reactors in the country would be closed down. Italy decided not to restart its nuclear power programme, which was abandoned in the 1980s, and Switzerland also decided to abandon plans to build new nuclear reactors and will phase out its existing plants. In other countries, the Fukushima accident seems to have had limited political impact. Bulgaria, the Czech Republic, Romania, Slovakia, Finland and the United Kingdom continued their ongoing projects to expand nuclear power. A strategy plan for new construction has been approved in Poland and political support for future new construction was confirmed in the UK. After the 2012 French elections, France expressed its intention to reduce the share of nuclear in its future energy mix. The French government has scheduled closure of the country's oldest plant in 2016; however, the government continues to support the construction of the first European Pressurised Reactor at Flamanville (IEA, 2013, p. 34). The Flamanville-3 project is six years late and now expected to start up until the fourth trimester 2018 (Schneider et al. 2016, p. 180). As Holmberg (2013) highlighted, in spite of these limited changes and movements in national approaches, opinions

concerning the role of nuclear energy remained diverse among the member states (see also Table 1).

In 2017 there is a total of 128 nuclear reactors in 14 of the 28 countries of the EU, with an installed net electric capacity of 110,561 MWe in operation. In addition to nuclear reactors and power plants a sum of 140 research reactors can also be found in the EU (46 in Germany, 26 in France, 19 in the UK and 14 in Italy), moreover 26 nuclear fabrication, 10 fuel processing, and 45 fuel storage facilities are situated across the member states (EC 2013; WEC 2016). Regarding the geographical distribution of reactors, around 45% of the European Union's nuclear park is located in France, and only 14% can be found in the Eastern European Countries with nuclear plants. From technological point of view the 128 nuclear reactors in operation in the European Union are based on different technologies and types, but are mainly pressurised water reactors (101), although boiling water reactors (11) gas cooled reactors (14) and pressurised heavy-water reactors (2) can also be found. Figure 1 shows the number and the net operating capacity of nuclear reactors in the European Union between 1985 and 2017.



Source: own summary based on PRIS database

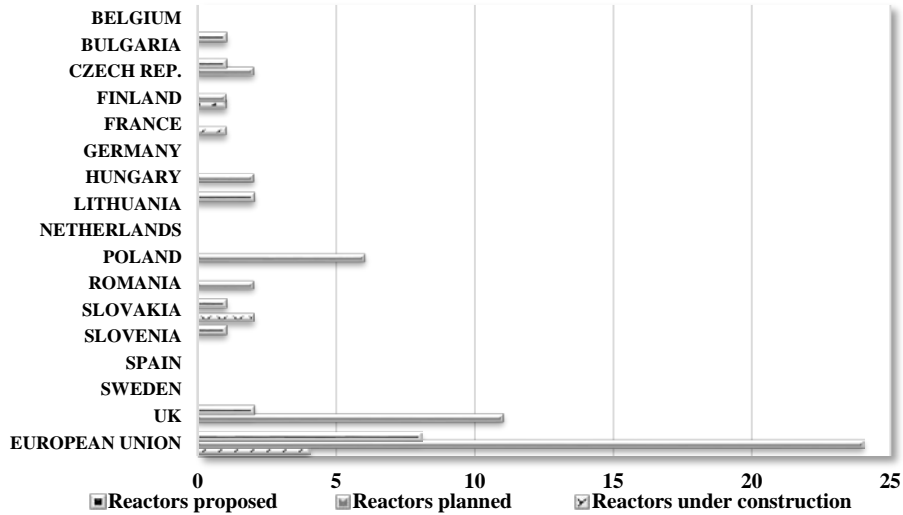
Figure 1. Number of nuclear reactors and net operating capacity (in GWe) in the European Union (including the UK)

Between 2009-2010 nuclear power capacities increased about 1% and 2 GW were removed from the system. The net operating capacity in the EU achieved its historical maximum in 1998, and in 2013 the number of reactors was 12 fewer than before the Fukushima events (8 reactors in Germany and 1 in the UK exited from service). It should be noted that in the European Union the so-called “Nuclear Renaissance”¹ was suppressed by the economic crisis and market uncertainties induced by deregulation, liberalisation and privatisation tendencies. Since 2000 only two new nuclear reactors (in the Czech Republic and Romania) have been connected to the grid (WEC 2016, p. 21); therefore, in the absence of newly constructed plants, nuclear reactors in the European Union are ageing.

Figure 2 illustrates the number of grid-connected European nuclear reactors by years of operation. According to this figure, 14 reactors from the total capacity have reached or exceeded the age of 40 years, and the large majority of installed reactors have been operating for at least 30 years. In 2017, the average age of European nuclear reactors is 32.53 years. In addition to this, while nuclear reactors are designed for 30-40 years of operation, there is a tendency that the operators of the reactors try to

extend the reactor’s lifetime to 50-60 years. According to its forecast, the EC (2013) also suggests that between 2010 and 2025, 38 nuclear reactors will have to be decommissioned in the EU and the decommissioning time of 104 reactors will be apposite after 2025, or is still unknown. While Foratom (2015) proposed a target of commissioning 100 new nuclear reactors between 2025 and 2045 (WNA 2017a), as Figure 3 shows, as of March 2017 two reactors – Olkiluoto-3 in Finland and Flamanville-3 in France – are under construction in the western part of the EU, while in June 2009 the construction of Mochovce-3&4 in Slovakia restarted and the General Assembly of Slovenské Elektrárne (SE) shareholders approved SE's strategic plan for 2017-2021, including the release of funds (€5.4 billion) for the Mochovce nuclear power plant expansion (Enerdata 2017). According to the latest available information Mochovce-3&4 are expected to start commercial operation in 2017. Besides these, delayed construction projects representing a total of 4,392GWe nuclear capacity and 32 new units (sum of 38,645GWe) are planned or proposed in the European Union.

¹ As WNA titled the phenomenon in which several countries around the world decided to invest or reinvest in nuclear generation in the beginning of the 21st century.

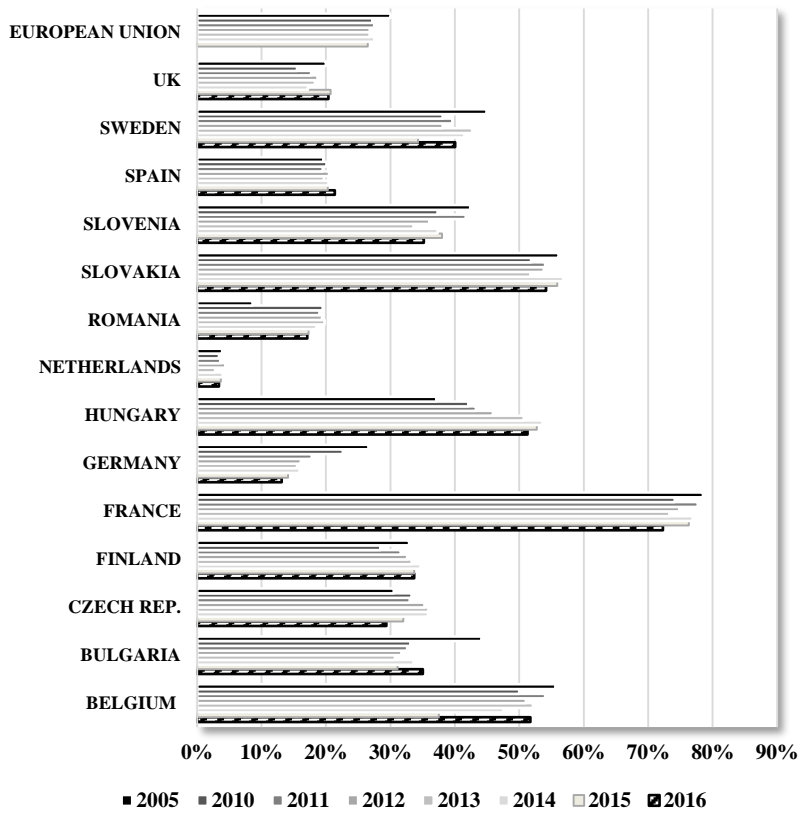


Source: own summary based on PRIS database

Figure 2. Number of nuclear reactors proposed, planned or under construction in the EU-28 (as of March 2017)

In 2011 primary production of nuclear energy in the EU-27 counted for 234,010 Mtoe, which represents a 1% reduction between 2005 and 2011, while during the period between 2011 and 2015 primary production of nuclear energy reduced by 5.47% to 221,202 Mtoe. Nuclear

energy was the most important source of electricity production in 2012, when nuclear power produced 26.8% of the commercial electricity in the European Union.



Source: own model, based on PRIS and EUROSTAT databases

Figure 3. Shares of nuclear energy in electricity production – EU-28

Figure 3 illustrates the changes in the share of nuclear power in electricity production by the European member states. As the figure shows, between 2011 and 2012 the contribution of nuclear energy to electricity generation stagnated or decreased in most of the member states; a significant increase was observed only in the Netherlands (+22.22 percentage points), Czech Republic (+6.97%p) and Hungary (+6.00%p). In France 74.8% of electricity was generated by nuclear reactors, and nearly half of nuclear electricity generated in the EU came from French nuclear power plants in 2012. Between 2012 and 2016 the contribution of nuclear energy to electricity generation slightly increased in most of the member states, while a significant reduction can be observed three countries, namely in the Netherlands (23%p), Czech Republic (17%p) and Germany (19%p). Although electricity production is by far the principal function of today's operating reactors, in the EU member states a number of them are also currently used for district heating (in

Hungary, Bulgaria, Romania, Czech Republic, Slovakia) and for process heating (in Slovakia) as well (IAEA 2013, 2017).

In order to better understand the debate on nuclear power and the fragmented nature of national policies, in the following section pros and cons of nuclear energy generation will be summarised in the light of the effects of Fukushima and the future role of nuclear energy presented in the European energy scenarios published before and after the accident.

DATA AND METHODS

In order to examine the main impacts of the Fukushima Daiichi accident and the future role of nuclear power use in the European Union, scenarios released before and after the Japanese disaster are analysed.

Table 2
Overview of the EU-28 scenarios released before March 2011

Study	Scenario name	Main targets
IEA (2009): World Energy Outlook	WEO ref	No specific targets
	WEO 450 ppm	Stabilising worldwide greenhouse gas (GHG) concentration below 450 ppm
IEA (2010): Energy Technology Perspectives	ETP Baseline	No specific targets
	ETP Blue Map	Stabilising worldwide GHG-concentration below 450ppm
EU DG ENER (2010): Trends to 2030 update 2009	EU DG TREN Reference	20-20-20 targets achieved by 2030
	EU DG – ENV Baseline	
	EU DG – ENV NSAT	
	EU DG – ENV NSAT- CDM	
ECF (2010): Roadmap 2050	ECF Baseline	No specific targets
	ECF 80% RES	-80% GHG of 1990 levels by 2050
	ECF 60% RES	-60% GHG of 1990 levels by 2050
	ECF 40% RES	-40% GHG of 1990 levels by 2050
Greenpeace&E REC (2010): Energy [R]evolution	Reference Scenario E[R] Ref.	No specific targets
	Revolution Scenario E [R] basic	-80% GHG of 1990 levels by 2050
	Advanced Scenario E[R] Adv	100% Renewable energy sources (RES) share of primary energy demand and -95% GHG of 1990 levels by 2050
Eurelectric (2009): Power Choices	Eurelectric Power Choices	-40% GHG of 1990 levels by 2030 and -75% by 2050

Source: Prognos (2011)

Studies published before 2011 were summarised by Prognos (2011), commissioned by the European Commission. This paper investigates eight governmental, non-governmental and academic or university studies with 26 mid- and long-term future energy scenarios for the

European Union, particularly with regard to the role of nuclear power. Table 2 summarises the main targets of the 13 EU-28 scenarios analysed by Prognos (2011) and selected for further investigation in this paper.

Studies released after the Fukushima Daiichi fallout are the available publications of IEA (2012a) *World Energy Outlook*; European Commission (2011) *Energy Roadmap 2050*; and IEA (2012b) *Energy Technology Perspectives*,

representing in sum 11 scenarios, while IEA (2016) *World Energy Outlook* consists the latest available official energy scenarios. The main goals of the 14 scenarios examined are reflected in Table 3.

Table 3
Main targets and details of scenarios released after 11 March 2011

Study	Scenario Short name	Main targets
IEA (2012a) World Energy Outlook	Current policy scenario WEO_2012_current_EU	Government policies adopted by mid-2012 continue unchanged
	New policy scenario WEO_2012_new_EU	To provide a benchmark to assess the potential achievements of recent developments in energy and climate policy. Existing policies are maintained and recently announced commitments and plans are implemented in a cautious manner.
	450 ppm scenario WEO_450_EU	To demonstrate a plausible path to achieve the climate target. Policies are adopted that put the world on a pathway consistent with having around a 50% chance of limiting the global increase in average temperature to 2°C in the long term, compared with pre-industrial levels.
IEA (2016) World Energy Outlook	Current policy scenario WEO_current_2016	Implementation of any new policies or measures beyond those already supported by specific implementing measures in place as of mid-2016.
	New policy scenario WEO_new_2016	Current measures are specifically time-bound and expire, they are not normally assumed to lapse on expiry, but are continued at a similar level of intensity through to 2040.
	450ppm scenario WEO_450_2016	Limiting the average global temperature increase in 2100 to 2°C above pre-industrial levels.
IEA (2012b) Energy Technology Perspectives	6°C scenario (6DS) ETP_2012_6Ds	Largely an extension of current trends. By 2050, energy use almost doubles (compared with 2009) and GHG-emissions rise even more. The average global temperature rise is projected to be at least 6°C in the long term.
	4°C scenario (4DS) ETP_2012_4Ds	Takes into account recent pledges made by countries to limit emissions and step up efforts to improve energy efficiency. In many respects this is an ambitious scenario that requires significant changes in policy and technologies. Moreover, capping the temperature increase at 4°C requires significant additional cuts in emissions in the period after 2050.
	2°C scenario (2DS) ETP_2012_2Ds.	Energy system consistent with the 450ppm emissions trajectory. The 2DS acknowledges that transforming the energy sector is vital, but not the sole solution: the goal can only be achieved if CO ₂ and greenhouse gas emissions in non-energy sectors are also reduced.
EC (2011) Energy Roadmap 2050	Reference scenario EU_2011_ref	40% emission reduction by 2050 Includes current trends and long-term projections on economic development, policies adopted by March 2010, i.e. 2020 targets for RES share and GHG reductions as well as the Emissions Trading Scheme (ETS) Directive.
	Current policy initiatives EU_2011_cpi	40% emission reduction by 2050 Updated measures adopted, e.g. after the Fukushima events following the natural disasters in Japan, and being proposed as in the Energy 2020 strategy; the scenario also includes proposed actions concerning the "Energy Efficiency Plan" and the new "Energy Taxation Directive"
	High energy efficiency EU_2011_high_ee	85% emission reduction by 2050 Political commitment to very high energy savings; including e.g. more stringent minimum requirements for appliances and new buildings; high renovation rates of existing buildings; establishment of energy savings obligations on energy utilities. This leads to a decrease in energy demand of 41% by 2050 as compared to the peaks in 2005-2006.
	High renewable energy sources EU_2011_high_res	85% emission reduction by 2050 No technology is preferred; all energy sources can compete on a market basis with no specific support measures. Decarbonisation is driven by carbon pricing, assuming public acceptance of both nuclear power and Carbon Capture & Storage (CCS).
	Diversified supply technologies EU_2011_div_tech	85% emission reduction by 2050 Strong support measures for RES leading to a very high share of RES in gross final energy consumption (75% in 2050) and a share of RES in electricity consumption reaching 97%.
	Delayed CCS. EU_2011_d_ccs	85% of GHG emission reduction by 2050 Assuming that CCS is delayed, leading to higher shares for nuclear energy with decarbonisation driven by carbon prices rather than technology push.
	Low nuclear EU_2011_low nuclear	85% emission reduction by 2050 Similar to diversified supply technologies scenario but assuming that no new nuclear capacity (besides reactors currently under construction) is being built, resulting in a higher penetration of CCS (around 32% in power generation).

Source: own summary, based on EC (2011) and IEA (2012a, 2012b, 2013)

Besides the aforementioned studies and scenarios, statistics of nuclear reactors used in this paper are provided by the EUROSTAT database and the PRIS database of the International Atomic Energy Agency (IAEA). MS Excel was used for the calculations and for the creation of figures.

RESULTS

Strengths and Weaknesses of Nuclear Energy

The future role of nuclear power plants in the European Union depends on the main supporting and adverse factors associated with the use of nuclear energy. Based on the relevant literature and reports, these factors are summarised in Table 4. Promoters of nuclear energy often stress that nuclear power meets the main goals of the European Energy Policy and criteria for a sustainable energy mix, i.e. use of nuclear power can contribute to energy independence, security of supply, while it is affordable and has low emission potential (Bernard 2013). There is broad international acceptance that stabilising the atmospheric concentration of greenhouse gases at below 450 parts per million (ppm) of carbon-dioxide equivalent would help avoid the worst impacts of climate change. In

the EU, the energy sector is by far the largest source of greenhouse-gas (GHG) emissions, accounting for 29% of the total in 2015. Nuclear energy is seen to offer a major contribution to action against climate change, due to its low emissions of CO₂. Compared to fossil-fuel based energy generation technologies, nuclear power at the point of electricity generation does not produce any GHG emissions that damage local air quality (e.g. WEC 2007a; 2007b; Bauer et al. 2008; NEEDS 2008). If nuclear energy were expanded 10 fold, it could help in reducing total annual CO₂ emissions in the second half of the 21st century by about 30% (van der Zwaan 2006; IEA 2013). It is also estimated that nuclear power plants have nearly zero regional environmental impact regarding their acidification and eutrophication potentials. The major environmental and health issues of nuclear energy utilisation are considered to be radioactive waste generation and management and ionizing radiation. However, there is a controversy at European level as to whether nuclear energy should be classified as renewable. On 4 February 2011 the European Council recognised its status as carbon-neutral energy, alongside renewables. Concepts rejecting the renewable status of nuclear power plants are based on the fact that natural uranium and other types of fuel are not renewable energy resources.

Table 4
The nuclear debate

PROS	CONS
<ol style="list-style-type: none"> 1. Supports the goal of European energy policy by meeting the 4 criteria for a sustainable mix: <ol style="list-style-type: none"> a. low carbon energy source b. competitive costs c. reduce fossil fuel dependency d. reduce GHG emissions 2. Stable output 3. High efficiency 4. Ready-to-use technology 5. Existing supply chain available 6. Wastes and risks can be managed 7. Nuclear safety can be ensured by appropriate measures 	<ol style="list-style-type: none"> 1. Public pressure against the use of nuclear energy 2. Waste and safety concepts and costs (as well as health, environmental effects) 3. Need for further RD&D activities 4. Problems associated with financing new nuclear projects, state aid needed 5. Need for ageing management 6. Need for risk and hazard management 7. Long construction time 8. Risk of exposure to radiation 9. Problems with fuel and waste transportation 10. Uranium is not a renewable source 11. Strong dependence on external sources of uranium 12. Non-proliferation issues

Source: own summary, based on WEC (2007a), IEA & NAE (2010), Andoura et al. (2011), Keppler & Marcantonini (2011), Euroconfluences (2011), OECD&NEA (2012), Thadani et al. (2012), Fisher (2013), Keppler et al. (2013), Bernard (2013), ENEF (2013), Poncelet (2013)

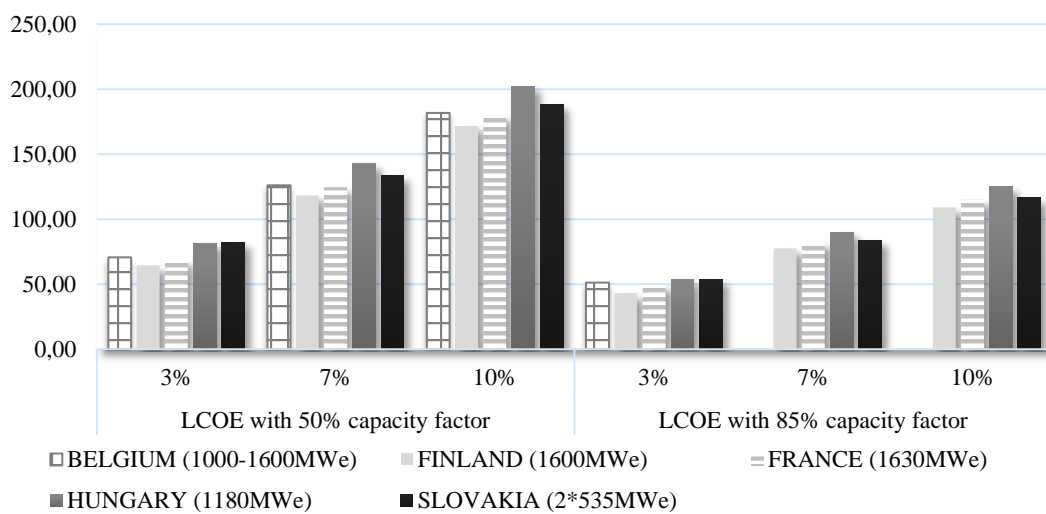
Uranium is a main source of fuel for nuclear reactors, and according to the WEC (2016) worldwide output of total identified uranium resources has grown by 70% since 2005, and identified resources of uranium are considered sufficient for over 100 years of supply based on current requirements. In 2012, demand for natural uranium in the EU represented approximately one third of global uranium requirements. Regarding energy independence, Europe is strongly dependent on external sources of uranium. Uranium is mined in 20 countries, although about 80% of

world production comes from just ten mines in five countries: Australia, Canada, Kazakhstan, Namibia and Niger in 2016 (WNA 2016). European uranium delivered to EU utilities originated in the Czech Republic and Romania and covered only 2.6% of the EU's total requirements in 2015 (ESA 2015). However, uranium reserves are distributed more evenly and available in large quantities in several politically stable countries (including Canada and Australia) by comparison with hydrocarbons. According to ESA (2015) in 2015 the enrichment services

supplied to EU utilities totalled 12,493 tSW (1 tonne of separative work equals to 1000 separative work unit, which measures the effort made in order to separate the fissile, and hence valuable, U-235 isotopes from the non-fissile U-238 isotopes, both of which are present in natural uranium), delivered in 1,989 tonnes of low-enriched uranium, which contained the equivalent of 16,090 tonnes of uranium (tU). Of this, 60% of the requirements were delivered by European providers, while the quantity of mixed-oxide fuel loaded into nuclear power plants in the EU totalled 10,780 kg of plutonium, which represents a 15% increase over the amount of plutonium used in 2011. ESA (2015) suggest that gross average reactor requirements for natural uranium will grow to 16,745 tU/year for 2016-2025 and then decrease to

14,588 tU/year for the 2026-2035 period. For 2016-2025 gross average reactor requirements for separative work will reach 13,657tSW/year and 11,890 tSW/year for the period between 2026 and 2035 (ESA 2015).

One of the biggest advantages of nuclear energy is seen in its stability. Nuclear power plants have high availability and load factors, while their dispatchable nature and load-following capability ensure that the energy produced is not dependent on weather conditions. According to the PRIS database, for the period 2014-2016 the EU-wide average energy availability of nuclear plants was 83.86%, and the highest availability was experienced in Romania, Finland and Slovenia, while in 2016 unit capability factors exceeded 90% in Finland, Hungary, Romania and Spain.



Source: IEA & NAE (2015, p. 59)

Figure 4. Levelised costs (LCOE) of electricity of European nuclear plants (USD/MWh)

Nuclear energy is said to be one of the most competitive energy generation technologies due to its cost structure and limited impacts of fuel price volatility. According to the joint report of the International Energy Agency and the Nuclear Energy Agency (2015) the levelised cost of electricity (LCOE) - i.e. the per-kilowatt-hour cost building and operating a generating plant over an assumed financial life and duty cycle (EIA 2017, p. 1) - of new nuclear plants in 2030 will be competitive with other generating options; however the more investment intensive the option, the more sensitive the LCOE is to the value of the discount rate (see Figure 4). Investment costs represent by far the largest share (around 60% on average) of LCOE, as construction costs of nuclear energy generation are significantly higher in comparison to those for fossil fuel technologies. In 2016 nuclear production costs in the European Union were around 1eurocent/kWh, which is much lower than for coal and gas plants (WNA 2017b). Since fuel costs represent only 10-15% of total generation costs, fuel price volatility has little influence on

production costs compared to fossil based energy generation.

It is worth mentioning that beside fuel cost fluctuations the range of generating costs depends on the age of the given nuclear plant and the regulatory requirements concerning safety inspections and security measures, since O&M costs represent around 24%. The IEA & NAE (2015) also estimates that decommissioning and disposal costs make up 10% and 15% of the capital costs of a plant. While nuclear investment costs are estimated to show a constant but small decline by 2035 or 2050 in scenario studies analysed by Prognos (2011), the EC (2011) estimates a slightly higher risk premiums for new nuclear investment in Current Policy Incentives and Decarbonisation scenarios, because they consider that investors might factor into their decisions the possible effects of policy reactions to the Fukushima accident, which affect nuclear plants under investment consideration. It is also estimated by the IEA (2012b) that due to the aging nuclear European capacity, serious

investments need to start around 2020, and while the third generation designs of nuclear power plants deliver superior safety they are extremely expensive. Due to cost overruns and project delays, capital needs of a nuclear project stretch the financial capability even of the largest utilities, and the very unusual risks hinder bank financing (IEA 2012b, p. 178). This also suggests that in order to be able to refinance the high capital costs, new nuclear power plants need a guaranteed long operating life and guaranteed high full-load operation. In competitive energy markets investment risks and financial challenges are dominant (van der Zwaan 2008; WEC 2013). In general, in the EU-27 between 2000 and 2004 energy investments were delayed because of the political and regulatory changes affecting energy markets. Energy scenarios for 2035 and 2050 being analysed emphasise that measures towards the creation of the integrated European energy market will continue to affect the risks associated with new energy investments. OECD & NEA (2012, p. 81) suggests that decisions to build a nuclear power plant represent a greater commercial risk than is normally associated with other electricity sources, because:

- The technical complexity of nuclear plants tends to lead to delays in construction and cost overruns;
- Changes in government policy or legislation affecting nuclear energy, or in regulatory requirements, could delay the plant in entering operation, adding to costs;
- Such changes occurring during the plant's operating lifetime could also add to costs and potentially prevent the plant from operating for its full lifetime;
- The long planning and construction timescale and long operational lifetime provide greater potential for long-term changes in the electricity market to impact revenues;
- At the same time, the high proportion of fixed costs (due largely to high investment costs) results in greater vulnerability to short-term market fluctuations;
- There may be uncertainties about the costs the plant will be required to pay for decommissioning and long-lived waste disposal.

ENEF (2010) highlighted that external financing of nuclear project is particularly challenging because of: high capital cost and long payback times; uncertainties related to planning and construction period including supply chain constraints, possible delays, cost overruns and changing regulations; the fact that the economics of nuclear power is sensitive to regulation related to safety and market conditions (volatility in the price of carbon credits); the specific nature of nuclear projects (political uncertainties, public acceptance); and the related costs of spent fuel, waste management and decommissioning. It is also stressed in the literature (e.g. van der Zwaan 2008; Fiáth & Megyes 2010; Kiyar & Wittneben 2012; Virág et al. 2012) that in the new liberalised energy markets with new types of risks (market risks, political risks, regulatory risks, price and cost risks, technological risks, etc.), private investors value rapid and high returns increasing the cost of capital. The economic crisis and the Fukushima Daiichi accident

have exacerbated the problem of financing new nuclear power plants by highlighting the need for higher safety standards and creating a more critical public attitude (Kiyar & Wittneben 2012). In order to facilitate new constructions, ENEF (2010) suggests that new and innovative financing models must be stimulated, such as power user investments, utility joint ventures and power user–power supplier agreements, and project finance.

While the nuclear industry itself is multi-faceted and supports 250,000 highly qualified direct jobs, including engineers and researchers, and around 800,000 jobs in total (Foratom 2012, p. 16), public acceptance of nuclear energy utilisation is one of the five classic problematic features of nuclear energy. However, according to Berényi (2015, p. 81) public awareness, knowledge about the possibilities, legal regulation, reliability of supply chain and cultural and religious traditions should also be considered in an investment project initiative. The 2005 Eurobarometer survey (EC 2005) showed that the EU public is not well informed on nuclear issues, including possible benefits in terms of mitigating climate change and the risks associated with the different levels of radioactive waste (EC 2007, p. 16). It found that 40% of the opponents of nuclear energy would change their mind if solutions to nuclear waste issues were found (EC 2007, p. 16). According to the report of Eurobarometer on Nuclear Safety (EC 2010), before the Fukushima accident 68% of European citizens thought that nuclear energy helped to make nations less dependent on fuel imports, 51% believed that nuclear energy ensured more competitive and more stable energy prices, and 46% considered nuclear energy as a technology that helps to limit climate change. While 51% of the respondents agreed that the risks of nuclear power as an energy source outweigh its benefits, 73% of EU citizens wanted nuclear energy to be maintained or decreased.

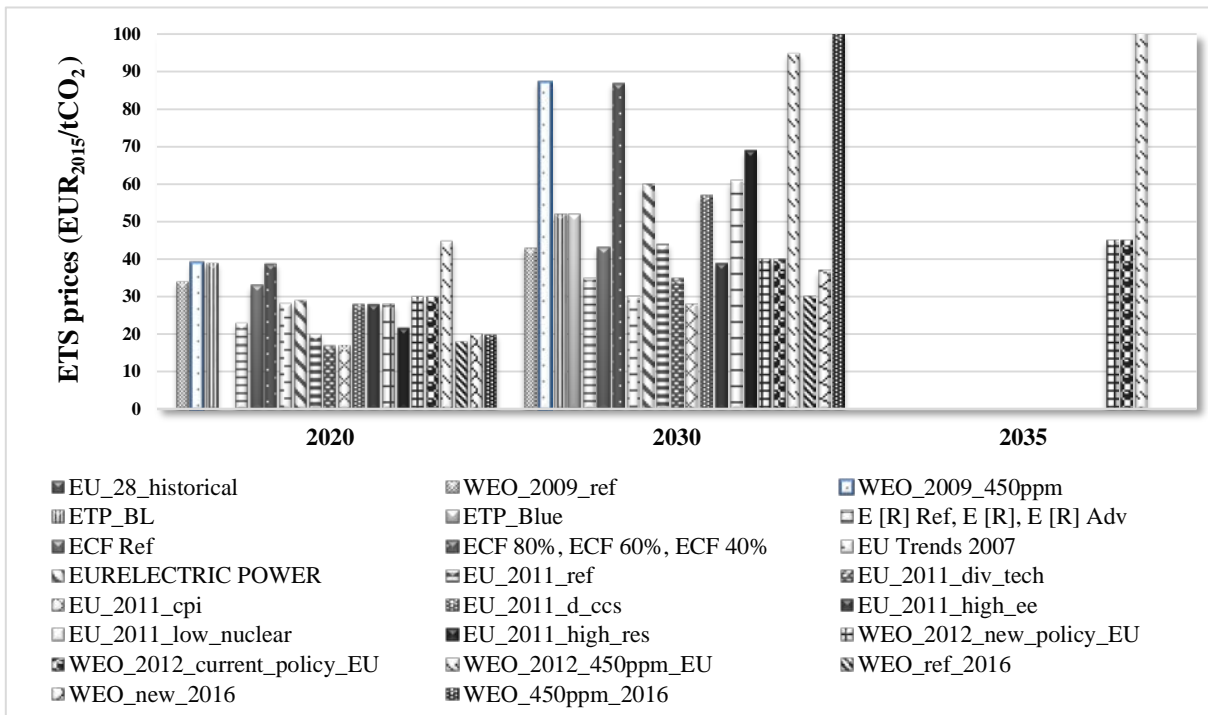
According to the survey of IPSOS MORI (2012a) held after the Fukushima Daiichi accident, only 38% of global respondents supported nuclear energy as a way to producing electricity. In the European Union the reactions of citizens were diverse: in Germany and Belgium opposition to nuclear energy increased, and in 9 of 27 EU countries (Belgium, France, Germany, UK, Hungary, Italy, Poland, Spain and Sweden) less than 1/5 of those opposed to nuclear power reported that they had been influenced by the accident (IPSOS MORI 2011). Another survey of IPSOS MORI (2012b) comparing attitudes to nuclear energy in April 2011 (at the height of the Fukushima crisis) and in September 2012 showed that worldwide the level of public support for nuclear energy had increased by around 14% to 45% during that period in most countries. However, it should be noted that since then no European-wide opinion poll has been carried out (Foratom 2017, p. 5). Public acceptance, political attitude, approaches and measures towards the use of nuclear energy are significantly influenced by proliferation, radioactive waste management and nuclear safety concerns.

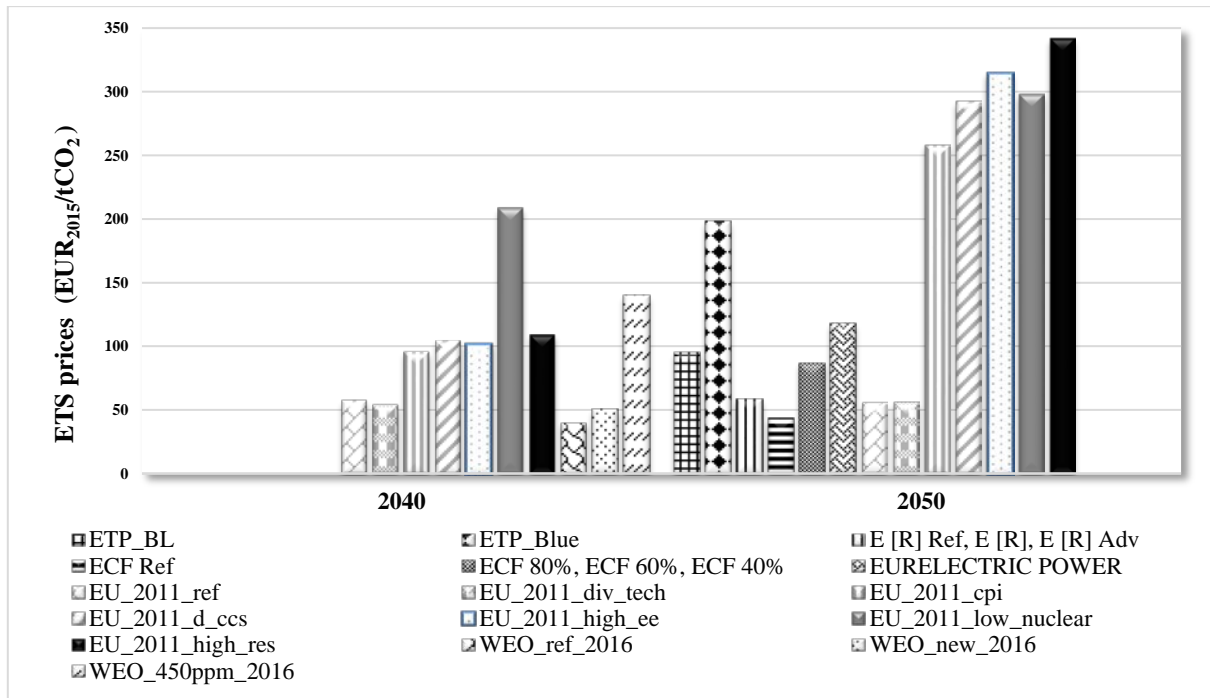
In response to the Japanese nuclear crisis, the European Union restarted discussions on the potential need for common action on the issue of nuclear crisis prevention, and the scope and modalities of stress tests as targeted reassessment of the safety margins of nuclear power plants in the light of the lessons drawn from the events in Fukushima related to extreme natural events challenging the plant's safety functions was developed (Andoura et al. 2011, p. 3; EC 2012). Additional costs of safety measures and improvements of nuclear power plants is estimated to be in the range of €30 million to €200 million per reactor unit (EC 2012).

Besides the aforementioned aspects, the future of nuclear energy utilisation in the European Union is influenced by trends in energy and electricity demand, the development of different energy generation technologies, and policy decisions regarding climate change, nuclear safety requirements and RD&D. Figure 5 shows that carbon prices are estimated to rise moderately by 2030 and 2050 respectively in all scenarios, despite the low recent EU-ETS prices and the uncertainty associated with the future system of EU-ETS. It should be noted that high carbon prices encourage the replacement of fossil-fuel based energy technologies by low carbon technologies, which is in favour of nuclear competitiveness for a base

load electricity supply relative to fossil fuel technologies (ENEF, 2012 p. 51).

Regarding fossil fuel prices, all scenarios reveal a moderate increase in coal prices by 2035 or 2050, and increasing gas and oil prices until 2030 can be expected, since, as Bartha (2015, p. 12) highlights, fuel prices are mostly influenced by the price of oil. In the medium term electricity prices are estimated to increase in almost all scenarios examined. Investment costs of renewable energy generation technologies are assumed to significantly decline (especially for concentrated solar power plants and wind) in the long term due to their learning rates, while the investment costs of coal and gas technologies are expected to increase because of necessity for carbon capture and storage (however it is also expected that Carbon Capture and Storage technologies will only be commercially available after 2030). ENEF (2012) emphasises that competition between technologies will also be influenced by national and EU-level taxation, the use of feed-in tariffs and subsidies for renewable technologies, and the stability and predictability of national and EU-level legislation, while technological progress regarding traditional and new type of grid structures (smart grids, smart metering) is also expected.





Source: own summary based on IEA (2009, 2010, 2012a; 2012b, 2016), Greenpeace & EREC (2009), Eurelectric (2009), EU DG ENER (2010), ECF (2010), and EC (2011)

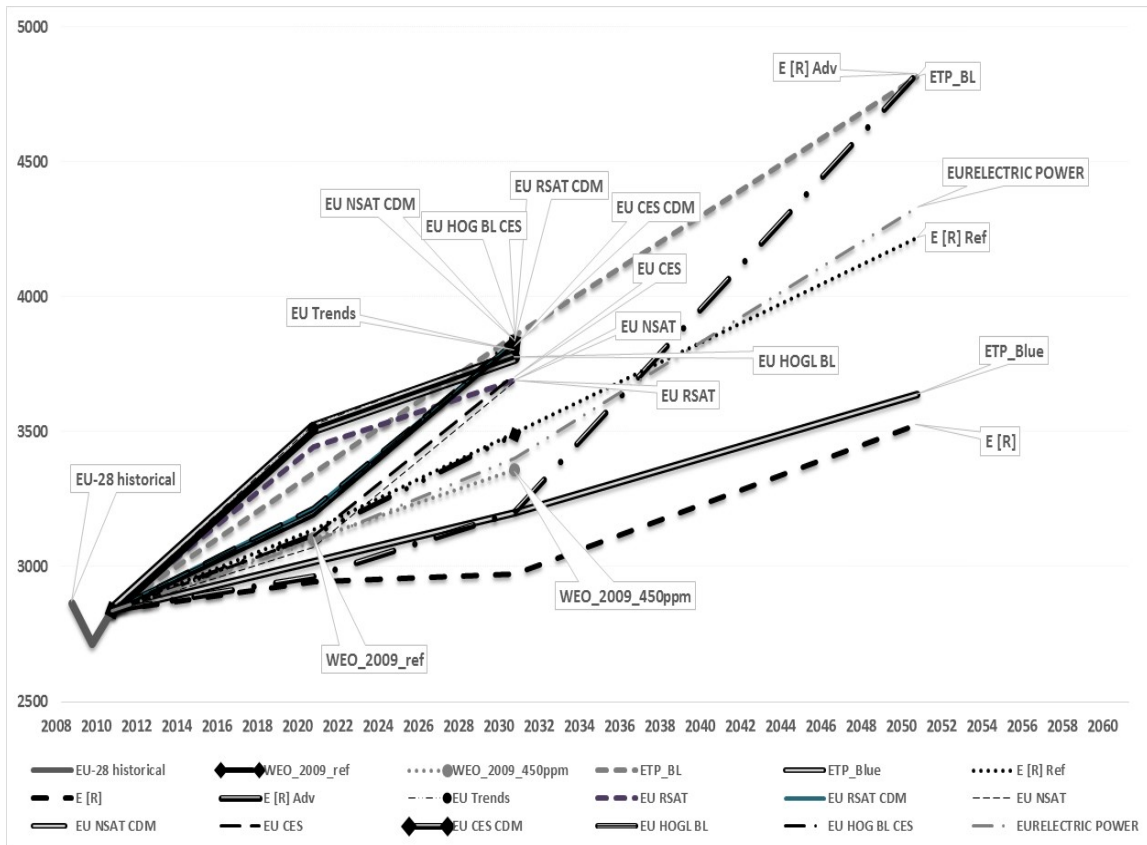
Figure 5. ETS prices in EUR₂₀₁₅/tCO₂ in all scenarios examined

Achieving the EU's energy objectives is only possible with modernisation of existing energy infrastructures. Energy R&D and innovation play an essential role in developing cheaper, more efficient and reliable energy technologies. In IEA member countries spending on low carbon energy RD&D over the last decade has shifted towards renewable sources, notably wind energy and solar PV, and as highlighted in IEA (2016), in the European Union the share of public RD&D spending on nuclear energy fell to 10% of the total budget by 2015. While the performance of existing nuclear reactors has been improving due to incremental innovations focusing on operational, safety, security, waste management, standardisation, and radiation protection issues, radical innovations in new type of nuclear designs and advanced fuels are still awaited against the fast technological innovations in renewable based technologies. Scenario studies analysed in this paper assume that the main research focus will still concentrate on Generation III/III+ reactor designs and Generation IV reactors are expected to become available for deployment beyond 2030. Besides

electricity generation, the most important opportunity for nuclear energy in the available scenarios is the potential use of nuclear energy for direct heat and transportation purposes.

Trends in Nuclear Capacities and Share in Electricity Generation

Regarding electricity demand, as can be seen in Figure 6 and Figure 7, all scenarios from the Prognos (2011) study and scenarios published directly after the Fukushima accident suggest that electricity demand could rise steadily until 2030, but by varying degrees due to the varied population growth expected by the authors. However, the decarbonisation of electricity generation and the expected rate of substitution towards electricity for fossil fuels in transportation and heating could play a significant role in the increase of total electricity demand.

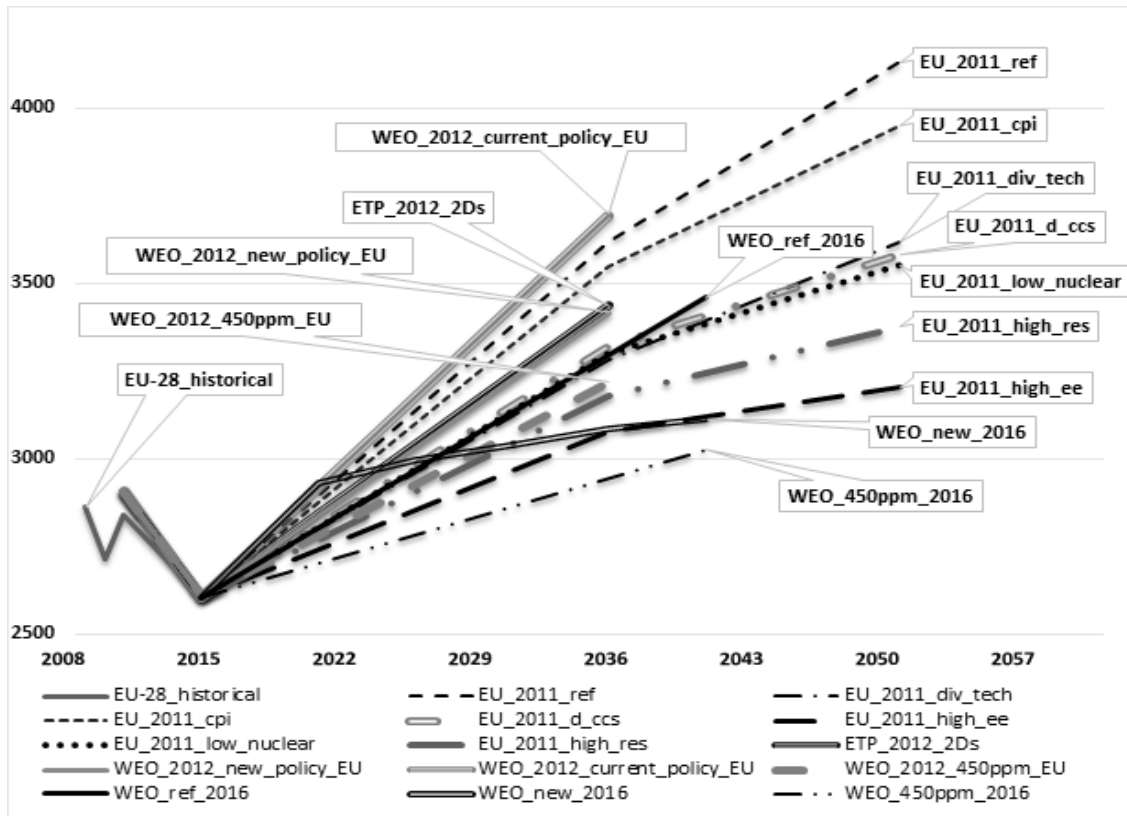


Source: own summary based on IEA (2009, 2010), Greenpeace & EREC (2009), Eurelectric (2009), EU DG ENER (2010), and ECF (2010)

Figure 6. Estimates of development of electricity demand in scenarios published before the Fukushima Daiichi accident

Despite the fact that changes in the development of electricity generation and in its structure highly depend on the different assumptions used in the scenarios regarding renewable energy targets, GHG targets, limitations of new plant constructions and their cost structure, renewable energy sources are expected to play a major role across all scenarios in delivering electricity in 2050. In almost all the scenarios from Prognos (2011) and those released after the Fukushima accident, wind power technologies provide the major share of electricity from renewable sources. Electricity generation from fossil fuel sources will decline by 2050, according to all scenarios being analysed. According to the EU's Energy Roadmap 2050 (EC 2011),

the share of oil in net electricity generation will decline from 30% (in 2005) to 2.1-15.2% by 2050, while in all scenarios of EU Roadmap 2050 the share of gas and coal in power generation will also decrease by 2050 compared to 2005, to 15.1-19.5% and 2.1-15.2% respectively. In nearly in all scenarios (with the exceptions of Eurelectric's Power Choices scenario, ECF's 40% RES scenario, and EU's Reference scenario) renewable energy sources contribute more to electricity supply in 2050 than fossil fuels or nuclear power; however, the role of Carbon Capture and Storage varies across the scenarios (Förster et al. 2012).

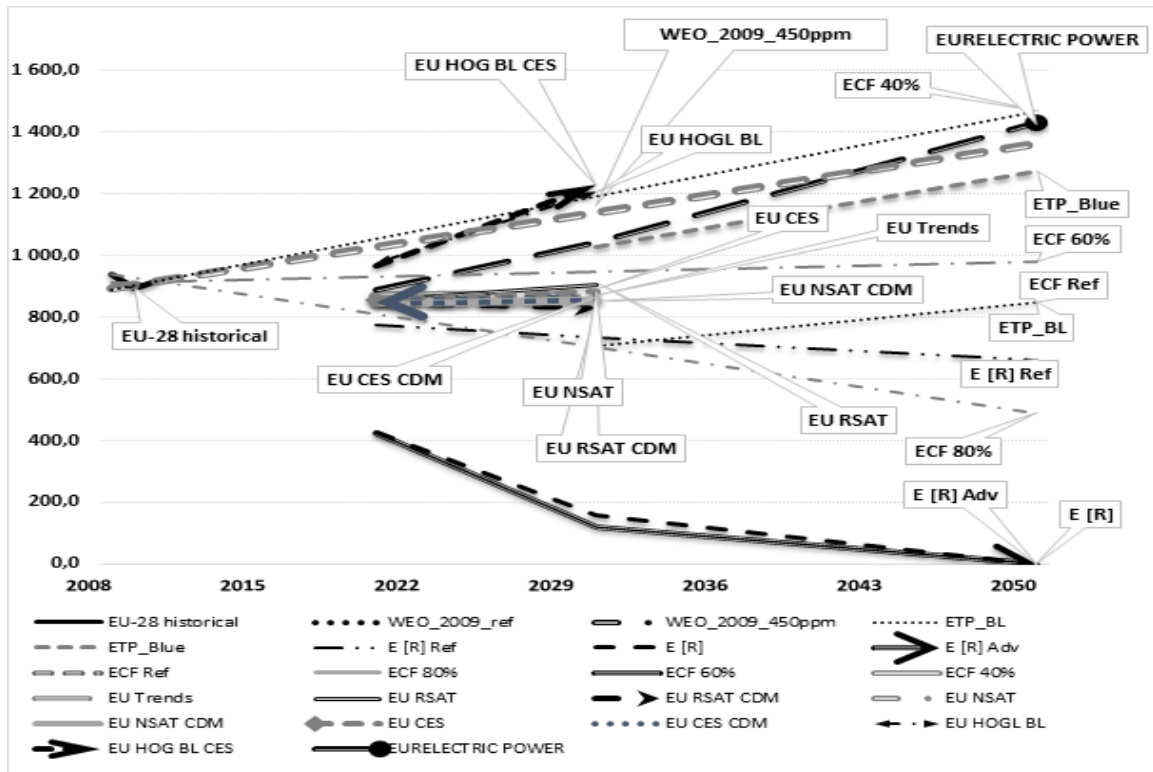


Source: own summary, based on EC (2011), IEA (2012a, 2012b, 2016), EC (2011)

Figure 7. Estimates in development of electricity demand in scenarios published after the Fukushima accident

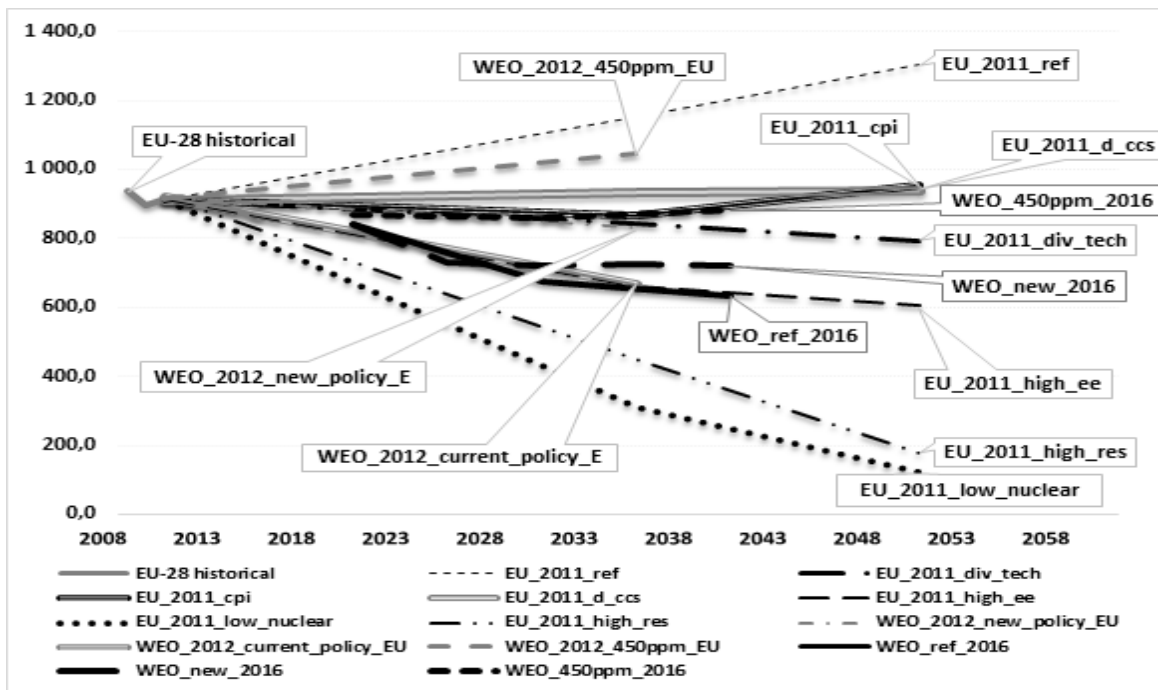
Figures 8 and 9 display nuclear capacity estimated in the scenario studies examined. For nuclear power capacities and generation, in contrast to the global picture, the situation for the EU shows a large degree of variation. Looking at the baseline or reference scenarios before 2011, Eurelectric (2009), IEA (2009, 2010) and ECF (2010) scenarios project the continuing growth of nuclear generation. Nuclear generation and capacities tend to be highest in scenarios which have to reach ambitious emission targets. The use of nuclear power increases in almost all alternative scenarios published before 2011. These scenarios suggests that nuclear power plants are expected to be an economical option to provide baseload power, whereas fossil-fuel plants are mainly used for load-following, with the exception of coal-fired plants with CCS (Prognos 2011, p. 74). The Eurelectric's Power

Choices Scenario projects an initial decline in nuclear power before a rapid rate of growth in the period 2020-2050. Overall, it can be stated that in the scenarios examined in the Prognos (2011) study, nuclear energy based electricity generation tends to expand in the European Union, reaching shares of 35-45% of electricity generation. However, these scenarios generally do not calculate with the potential lifetime expansions of nuclear power plants and do not analyse in detail the relevant frameworks or contexts in which nuclear power can develop. While among the studies published before 2011 the range of scenario projections is wide due to different assumptions, European scenarios of the EC (2011) and IEA (2012a, 2012b), presume that nuclear power generation and capacities will stabilise or even decrease by 2030 or 2050.



Source: own summary based on IEA (2009, 2010), Greenpeace & EREC (2009), Eurelectric (2009), EU DG ENER (2010), and ECF (2010)

Figure 8. Development of European nuclear power generation in scenarios released before the Fukushima Daiichi accident (TWh)

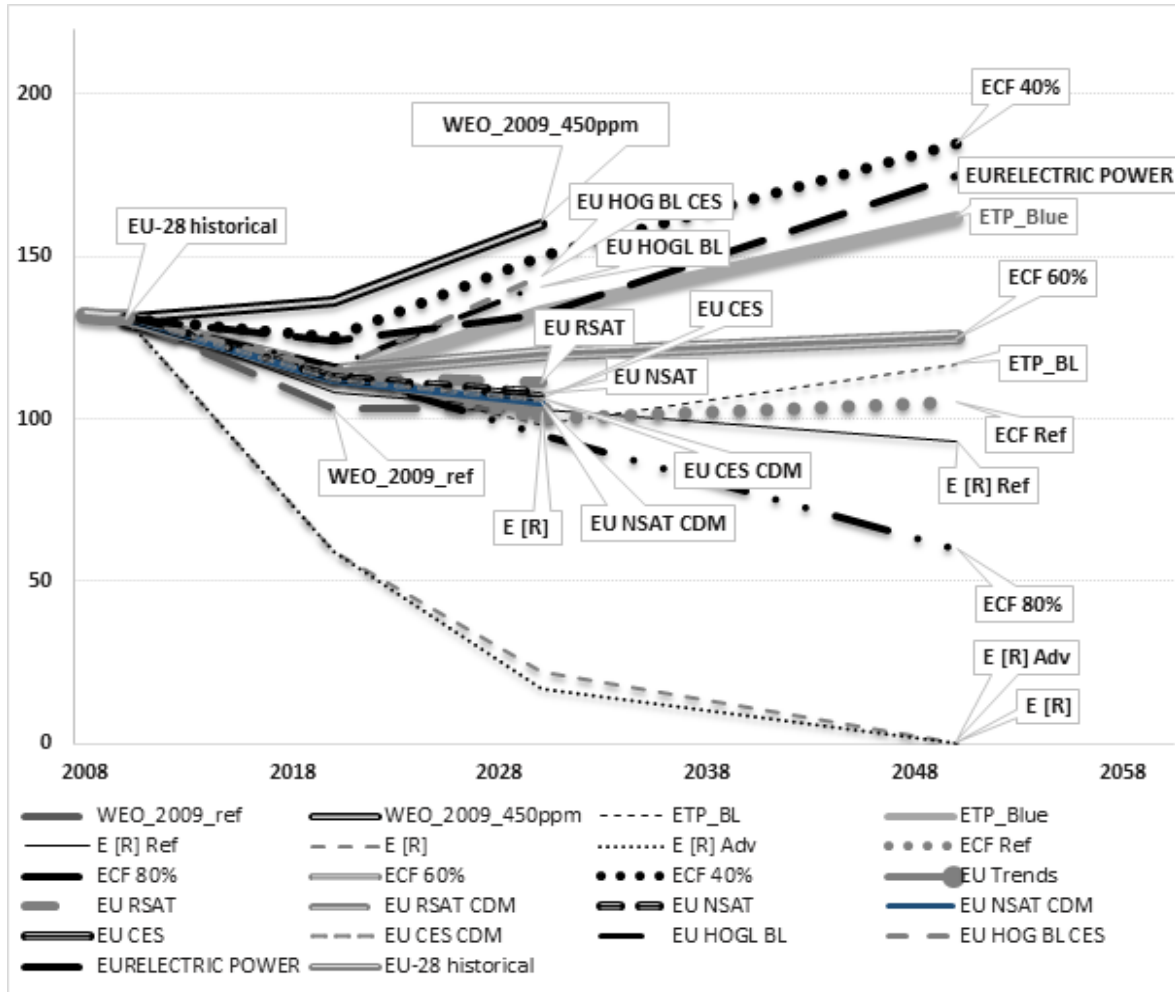


Source: own summary, based on EC (2011) and IEA (2012a, 2012b, 2016)

Figure 9. Development of European nuclear power generation in scenarios released after the Fukushima Daiichi accident (TWh)

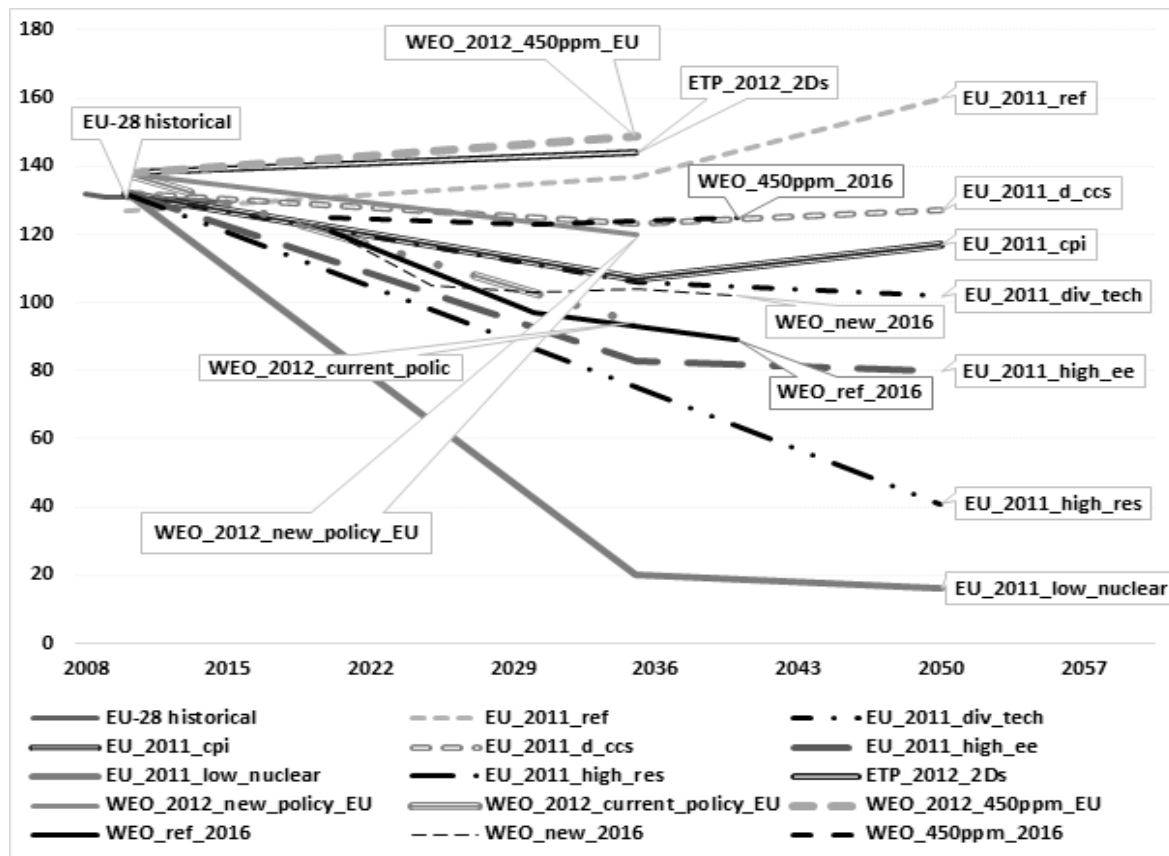
As Figures 10 and 11 show, nuclear power generation and nuclear power capacity development in the European Union according to all scenarios released after 2011 will remain well under the level of 1,350 TWh and 160 GWe respectively, which are much lower compared to the earlier. In the WEO New Policy Scenario it is assumed that in the European Union installed capacity of nuclear power will reduce from 129 GW to 120 GW by 2035 as a result of the expected reduced competitiveness of nuclear power and higher rate of retirements. In contrast, the WEO 450 ppm scenario of IEA (2012a) expects the highest

nuclear capacity development (120 GW) and the second highest share of nuclear power in total electricity generation (1,045 TWh) by 2035. According to the ETP's 2DS scenario, in 2050 nuclear energy could account for around another one fifth of the electricity mix; however, it is also stressed in the forecast that while it is expected that most of the member states with nuclear power remain committed to its use despite the Fukushima accident, nuclear deployment by 2025 will be below levels required to achieve the 2DS objectives (IEA 2012b, p. 14).



Source: own summary based on IEA (2009, 2010), Greenpeace & EREC (2009), Eurelectric (2009), EU DG ENER (2010), and ECF (2010)

Figure 10. Predicted development of European nuclear capacities released before the Fukushima Daiichi accident (GWe)



Source: own summary, based on EC (2011) and IEA (2012a, 2012b, 2016)

Figure 11. Predicted development of European nuclear capacities released after the Fukushima Daiichi accident (GWe)

The EU’s Roadmap scenarios suggest that nuclear energy will be needed to provide a significant contribution in the energy transformation process in those member states where it is pursued (EC 2011, p. 9). Compared to the Reference Scenario, which expects the highest growth rate of nuclear development by 2050, in the Current Policy Initiatives scenario the share of nuclear power is lower due to a change in nuclear assumptions and policy changes after the Fukushima Daiichi accident. While nuclear power remains a key source of low carbon electricity generation, its contribution is expected to be lower than it was in the previous European scenarios. The highest penetration of nuclear comes in delayed EU’s Carbon Capture and Storage and Diversified Supply technologies scenarios (18% and 15% in primary energy, respectively); however, in the Diversified Supply Technologies Scenario nuclear generation is projected to decline after 2035 (EC 2011).

In general all scenarios from Prognos (2011) stick only to the phase-out policies that were implemented before 2011. Although some scenarios (e.g. Greenpeace & EREC 2010) assumed total nuclear phase-out in the EU, in most of the studies nuclear phase-out assumptions are focused only on Belgium and Germany. A country-specific analysis is only revealed in EU DG ENER (2010) scenarios, in which Austria, Cyprus, Denmark, Greece, Ireland, Latvia, Luxembourg, Malta and Portugal are

assumed to not to take into consideration nuclear power plants, while in Italy and Poland new nuclear power plants are expected to be developed, and the remaining European member states are assumed to have the possibility to further invest in nuclear power (Prognos 2011, p.112). Nuclear power capacities and the share of nuclear energy in electricity production are expected to significantly decline in most of the scenarios released before March 2011 (except in the ETP Blue Map), indicating that generation share will increase slightly by 2030, with EU DG-ENV NSAT and EU DG-ENV NSAT CDM scenarios assuming minor development of nuclear power until 2020 and roughly stable generation until 2030, and the Eurelectric scenario which presuming a 42% increase in generation by 2050. In the scenarios of IEA (2012a, 2012b) and EC (2011) released directly after the accident, the most important problems and questions of nuclear power utilisation in the European Union are associated with public acceptance and waste management. All scenarios take into consideration the current and expected policy reactions of the member states to the nuclear accident in Fukushima. It is also expected in the scenarios (except for EU_ref_2011) that political reaction after Fukushima and the increasing importance of security issues after stress tests might lead to a lower investment in nuclear power due to higher investment costs. In *Energy*

Technology Perspectives published by IEA in 2012, it is also stated that low investment in nuclear power generation and capacity by 2050 might lead to higher energy prices, higher CO₂ emissions and higher import dependency in importing regions, i.e. it would make the achievement of sustainability targets more expensive and more difficult to reach (IEA 2012b, p. 178). These scenarios assume accelerated nuclear phase-outs in at least Germany and Switzerland. However, regarding the share of nuclear energy in electricity generation the studies are divided: while some scenarios presume that nuclear power will play a substantial role in the decarbonisation of the European electricity sector, others predict that the contribution of nuclear generation to total electricity generated in the EU will decrease by 2030 and 2050. The latest scenarios of the IEA (2016) forecast that nuclear capacities in the EU overall will decrease by 2035 but that capacities will increase in the UK, Finland and the Czech Republic and stabilise in France and Slovenia. Retirement of all nuclear plants in Germany will be achieved by the end of 2025. In Hungary and Slovakia nuclear capacities are expected to increase until 2030 and then decrease according to the IEA (2016) forecasts.

CONCLUSIONS

After the Fukushima Daiichi accident EU member states revised their energy policies associated with nuclear energy utilisation. The accident resulted in unprecedented efforts to review the safety of nuclear installations and legislation in Europe. Nuclear energy plays an important role in the European Union as the second largest source of electricity; however, the ageing of the reactors requires actions from each member state. Due to the fact that member states retain sovereignty over the use of nuclear power, some of the countries (e.g. France and Finland) are still expanding their nuclear capacities, building (Slovakia) or planning to build new nuclear reactors (Bulgaria, Romania, Czech Republic, Slovenia, the UK), or investing in nuclear fleet life-extension, upgrade or uprate activities (e.g. Hungary, Sweden, Slovakia, Spain), while after the Fukushima accident Germany and Belgium agreed to phase out nuclear generation by about 2022 and 2025, respectively. This study outlines the differences among the different medium and long-term scenarios released before and after the Fukushima accident regarding the future role of nuclear energy, taking into account the main advantages and disadvantages of nuclear power in the EU. The following conclusions can be drawn after the analysis:

- Nuclear power is seen as an important source of low-carbon electricity, supporting energy security goals; nuclear power plants contribute to competitive base-load electricity supply,

- Lifetime-extensions, plant upgrade and uprate, plant retirements and licence renewals need common rules, standards and policies and financial support,
- For the member states wishing to encourage new nuclear power plants and maintain nuclear options in the long term, new and innovative financing models must be stimulated,
- Direct impacts of policy changes after the Fukushima Daiichi accident did not fundamentally change the tendencies drawn up from earlier energy scenarios, since capacity shut-downs were already taken into account, at least in the case of Belgium and Germany.
- Most of the scenarios released after the Japanese accident indicate a higher rate of reduction in nuclear capacities in the EU by 2030 or 2050 and a smaller share of nuclear power in electricity generation than the studies published before 2011, while low-carbon scenarios still presume that nuclear power will play a substantial role in the decarbonisation of the European electricity sector as manifested in a larger share of nuclear power in electricity generation in the EU,
- Higher rates of uncertainty associated with the direction of future trends and status of EU-ETS system, electricity prices, or fuel prices are assigned in the latest scenarios examined compared to the assumptions of earlier studies.

Abbreviations

- EC:** European Commission
ECF: European Climate Foundation
ENEF: European Nuclear Energy Forum
EU-ETS: The EU Emission Trading System
Foratom: European Atomic Forum
GWe: gigawatt electric, electric output of a power plant in gigawatt
GHG: Greenhouse Gas
IAEA: International Atomic Energy Agency
IEA: International Energy Agency
MWe: megawatt electric, electric output of a power plant in megawatt
NAE: Nuclear Energy Agency
OECD: Organisation for Economic Co-operation and Development
RD&D: Research, Development & Demonstration
RES: Renewable Energy Sources
SWU: Separative Work Unit
tU: tonne of Uranium
tSW: tonne of Separative Work
TWh: terrawatt-hour, power in terrawatts multiplied by the time in hours
WEC: World Energy Council
WNA: World Nuclear Association

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