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THE ROLE OF THERMAL POWER PLANTS IN SELECT ELECTRICITY MARKETS

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Conclusions and Recommendations

i. Despite significant growth in wind and photovoltaic power generation, thermal power plants continue to play an important role in electricity systems for both base load production and ancillary services. Historic investment trends, availability of resources and government policy continues to play an import role in electricity system development.

ii. The ongoing transition from conventional power plant technologies to variable renewables, particularly among OECD member countries, will result in additional decrease of capacity thermal power plant capacity factors and, consequently, higher levelised costs of electricity (LCOE)of fossil-fuelled power plants. As a result, further investments on new thermal generation capacity should consider reduced operating hours and potentially build smaller, more flexible and less capital-intensive units. This may result in a transition from coal-fired power plants with higher capital expenditures to a more technical and flexible alternative using natural gas.

[1] In this report, the term thermal power plant is made in reference to plants using fossil fuels. The term "conventional power plants" is also used to refer to the same type of generation.

iii. The increased need for flexible operation of all power plants is an increasingly important design factor – from a technical, market and economic perspective. How to address this technically is reasonably well understood, but increased focus on market design to support the economic viability of lower capacity factors is needed. A greater focus on technology agnostic approach to addressing climate goals rather than a focus on given solutions – such as wind and solar – will be useful to address the environmental impacts of thermal power while decreasing the potential to strand these assets and reduce costs to tax payers.

iv. Investments to achieve high ratios of interconnections should be considered and allocated as they promote better cross border competition and will theoretically lead to the convergence and lowering of market prices, higher security of supply and reduction of backup-related costs and of capital expenditures with power systems enlargement.

v. Coal-fired backup solutions should be cautiously assessed due to their harmful CO_2 emission outcomes. Using Denmark as an example, it should be noticed that despite Denmark's high wind production penetration (41.0% in 2014) and considerably efficient coal-fired power plants which were refurbished and adapted to provide balancing services, Denmark's emissions - 299.9 gCO_2/kWh, in 2013 - are still way above the considered low-carbon electricity emission's factor threshold - 50 gCO_2/kWh. The same can be said for using any fossil fuel for such balance services.

vi. Higher operation flexibility of coal power plants and plentiful fuel supply currently represent a challenge to most of the gas-fired facilities, which rely on a more expensive fuel with fewer sources of supply which can threaten security of supply. However, recent events which resulted on the broadening of gas markets and diversification of supply should be seen as an opportunity to operate a transition to natural gas power generation.

vii. Policy makers should be aware of the important role fossil fuels will continue to play in the long-term, and have in mind the necessity of deploying CCS technologies to provide baseload and support variable power production. As a matter of fact, the mere transition from backing wind with coal to cleaner gas backup won't certainly result in enough carbon cuts to achieve a low-carbon electricity system. Consequently, even new and highly efficient gas-fired generators should be originally designed to host CCS technologies;

viii. The current oversize of generation systems in some regions/countries and the considerable leeway it provides to grid operators are an open opportunity for the decommissioning of facilities with high CO_2 and other emissions. Savings arising from energy efficiency measures and the consequent and gradual decoupling between economic growth and electricity consumption will most probably mitigate major growth of electricity demand in the next years in some regions and can be seen as an additional contributor to a nearly stabilisation of generation levels, stressing the opportunity for some strategic decommissionings.

ix. The economic growth and isolated nature of the Korean power markets has greatly influence generation choices. It will be very important to monitor the success of demand response and energy efficiency measure that can be deployed to support the provision of adequate capacity and reduce electricity system emissions.

Introduction

Regional geopolitics, geographical barriers and availability of natural resources shape the diversity and characteristics of electrical systems across the world. Given that recent modernisation of electricity generation fleets (and related infrastructures) include increased deployment of variable or intermittent renewables-based production aimed at reducing carbon emission in the power sector, increased pressure is often put on existing and new conventional generation. Improving the sustainability[2] and decarbonising the electricity system must be assessed based on primary requirements of cost-efficiency, economical relevance, environmental awareness and social welfare and should not impose specific technical solutions, but rather use the broadest range of appropriate methods.

Alongside renewables deployment, investment on cleaner fossil-based technologies is a key-alternative to attain a more sustainable electricity system. As fossil fuels represented 65% of the world's electricity mix in 2015, the deployment of cleaner fossil based electricity production technologies can be part of a clear and logical pathway towards the decarbonisation of the power sector. The IEA's forecasted scenarios for climate change mitigation, released under the "*Energy Technology Perspectives 2015*" (ETP 2015) publication, stated that, under a 2-degrees scenario (2DS[3]), in 2050 fossil fuels will still play an important role as the source for 20% of the electricity production globally, whereas, considering a 6DS, fossil fuel shares would remain stable and continue to lead as the main source for electric generation. Despite the importance hydrocarbons are expected to play even in a 2DS, only 7% of the electricity produced by fossil-fuel thermal plants is generated by facilities without CCS by 2050 - mainly gas-fired facilities with low capacity factors, running occasionally when renewables balancing and/or back-up is necessary.

The average CO_2 intensity of the global electricity system in 2050 in the 2DS is about 40gCO_2/kWh in 2050 (533 gCO_2/kWh in 2012). In order to achieve such an ambitious goal, countries must then start to act and pave the way with strategic plans to contain and reduce greenhouse emission gases (GHG's). On the contrary, if a strong dependency on unabated fossil fuels endures, leading to a 6DS, an average CO_2 intensity of 480gCO_2/kWh will be the most probable scenario.

As different drivers influence each country's electricity mix, it is essential to compare parallel contexts of how electric systems are being developed and managed according to country or regional constraints. While global analysis provides important insights, it is equally important to consider the differences between regions and countries on respective pathways to decarbonisation of electricity systems. Figure 1 illustrates that within the 2DS of the IEA's ETP analysis there is a broad suite of technologies used, and that the shares vary widely across countries. Key factors that influence decisions on this technology deployment include available indigenous energy resources, historic investment profiles, industrial policy for energy system technology development, existing development status, and other factors.

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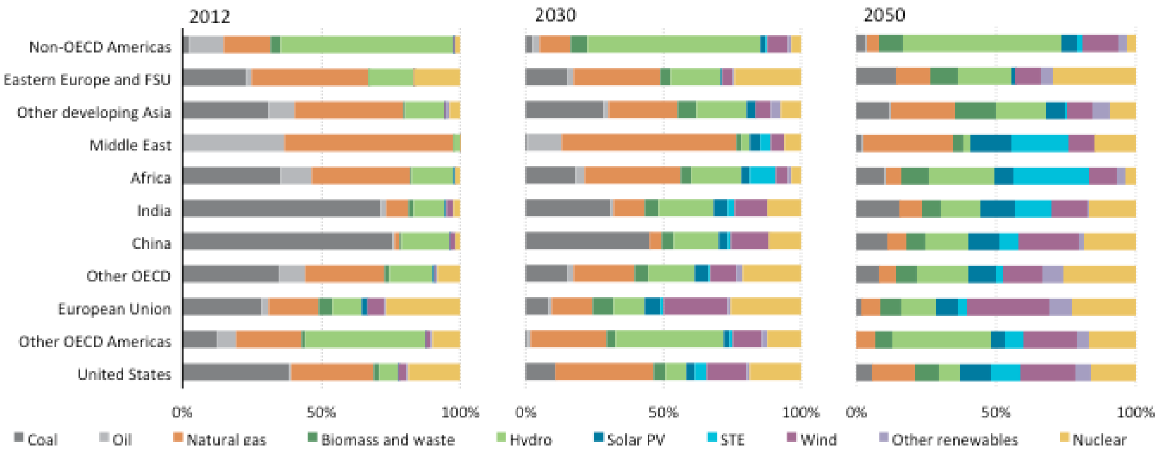
[2] Sustainability encompasses the three pillars of economic, environment and social aspects. Focus on these aspects should be done in a balanced manner.

[3]The 2DS lays out an energy system deployment pathway and an emissions trajectory consistent with at least a 50% chance of limiting the average global temperature increase to 2°C. The 2DS limits the total remaining cumulative energy-related CO_2 emissions between 2015 and 2100 to 1 000 GtCO2. The 2DS reduces CO_2 emissions (including emissions from fuel combustion and process and feedstock emissions in industry) by almost 60% by 2050 (compared with 2013), with carbon emissions being projected to decline after 2050 until carbon neutrality is reached. **Source:** *International Energy Agency (2015), Energy Technology Perspectives 2015, OECD/IEA, Paris*

FIGURE 1 - EVOLUTION OF REGIONAL ELECTRICITY GENERATION MIXES IN THE 2DS



Source: International Energy Agency (2015), Energy Technology Perspectives 2015, OECD/IEA, Paris

By understanding the main trends and policies currently being adopted in electricity system development, conclusions may be made and used as guidance for regions that are considering a switch to cleaner electricity production. Such understanding will be essential, regardless of whether an approach largely comprised by renewables or cleaner fossil-based generation is chosen - to meet the commitments made at the *Twenty-first Conference of the Parties* (*COP 21*) and defined by the *United Nations Sustainable Development Goals* (*SDG's*). The following overview will analyse three different systems in three different parts of the world:

- **Northern European Electricity Market** (*NORDPOOL*) –one of the World's most efficient electricity markets and a ground-breaking example of cooperation on electricity across national borders. This is particularly due to its countries' extremely high interconnection ratios and volumes of non-dispatchable electricity production from wind sources backed by highly flexible hydropower fleet. Under both day-ahead and intraday market platforms, NORPOOL totals nine member countries: **Norway**, **Sweden**, **Finland**, **Denmark**, **Estonia**, Latvia, Lithuania, **Germany** and the **United Kingdom of Great Britain and Ireland**(**UK**) [4].

- **Iberian Electricity Market** (*MIBEL*)- comprising the once independent electricity markets of **Portugal** and **Spain**, MIBEL has been a breakthrough case study since 2007, showing non-dispatchable renewable production technologies deployment that results in high shares of variable electricity production -particularly from wind (19.5%, 2014), solar (4.3%, 2014) [5] , as well as hydro. Under a context of low interconnection ratios with neighbouring regions (1.5% - of the overall Iberian capacity - with France[6]),hydropower and pumping storage as well as natural gas-fired production are responsible for maintaining considerable standards of reliability and security of supply.

[4] The analysis of NORDPOOL addressed in this document does not include the countries of Latvia and Lithuania.

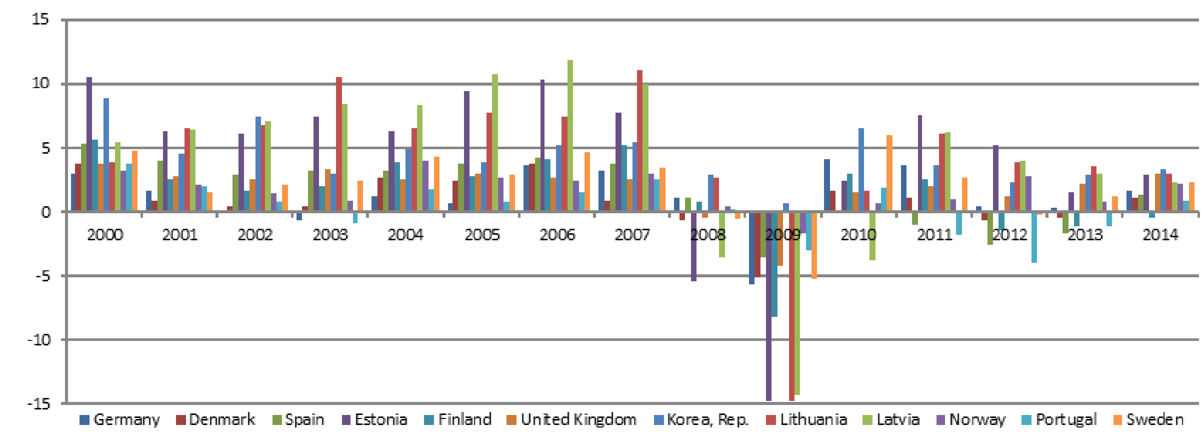
[5] IEA Statistics, OECD, Electricity and Heat Generation Summary

[6] Energy Policies of IEA Countries, Portugal, 2016 Review, IEA, April 2016

- **Korean Electricity System** - being completely isolated in terms of interconnection[7], the Republic of Korea's electrical system is highly reliant on nuclear- and fossil-fuelled electricity production to supply its growing demand pushed by a strong economy. The lack of domestic renewable and mineral resources dictates an extreme dependence from the imports of fossil fuels of about 97% of the total primary energy consumption and radioactive material. In order to mitigate the necessity of building new generation capacity, the country has plans to further develop interconnections and deploy demand response and energy efficiency measures.

FIGURE 2 – ELECTRICITY SYSTEMS EVALUATED IN THIS REPORT

Figure 3 – National Growth in GDP (annual %)



Source: *World Bank*

[7] Energy Policies of IEA Countries, The Republic of Korea, 2012 Review, IEA, 2012

TABLE 1 REGIONAL ECONOMIC AND ELECTRICITY SYSTEM OVERVIEW - 2014

Socio-economic Overview		Population	GDP per capita (USD)	Energy Intensity (USD/koe)[8]	Generation Capacity (MW)[9]	Annual Generation (GWh)[9]
	Denmark	5 638 530	60 718,4	14,7	13 656	31 905
	Estonia	1 314 545	20 147,8	5,8	3 096	12 444
	Finland	5 461 512	49 842,7	6,2	16 245	68 032
	Germany	80 970 732	47 773,9	11,6	198 416	614 613
NORDPOOL	Latvia	1 993 782	15 692,2	-	-	-
	Lithuania	2 932 367	16 489,7	-	-	-
	Norway	5 136 886	97 299,6	10,9	33 651	142 327
	Sweden	9 696 110	58 898,9	9,1	38 736	154 139
	UK	64 559 135	46 297,0	13,9	97 009	335 025
Total		177 703 599	-	-	400 809	1 358 485
MIBEL	Portugal	10 401 062	22 124,4	12,9	19 125	52 886
	Spain	46 476 032	29 721,6	13,0	106 470	277 759
Total		56 877 094	-	-	125 595	330 645
Korea		50 423 955	27 970,5	6,4	99 833	545 146

[8]"*GDP per unit of energy use (constant 2011 PPP $ per kg of oil equivalent*") World Bank Data; GDP per unit of energy use is the PPP GDP per kilogram of oil equivalent of energy use. PPP GDP is gross domestic product converted to 2011 constant international dollars using purchasing power parity rates. An international dollar has the same purchasing power over GDP as a U.S. dollar has in the United States. The ratio of gross domestic product (GDP) to energy use indicates energy intensity. To produce comparable and consistent estimates of real GDP across economies relative to physical inputs to GDP - that is, units of energy use - GDP is converted to 2011 international dollars using purchasing power parity (PPP) rates.

[9] IEA Statistics, OECD, Net Electrical Capacity and Generation

TABLE 2 REGIONAL ELECTRICITY GENERATION SHARES - 2014

Generation Capacity		Steam	Internal Combustion	Gas Turbine	Combined Cycle	Nuclear	Hydro	Wind	Others
NORDPOOL	Denmark	37,6%	9,7%	4,6%	7,8%	0,0%	0,1%	35,8%	4,4%
	Estonia	88,0%	0,9%	0,0%	0,0%	0,0%	0,2%	11,0%	0,0%
	Finland	42,5%	0,6%	8,0%	8,1%	16,9%	20,0%	3,9%	0,1%
	Germany	49.0%				6,1%	5,7%	19,8%	19,5%
	Latvia	-	-	-	-	-	-	-	
	Lithuania	-	-	-	-	-	-	-	
	Norway	0,2%	0,1%	4,5%	0,0%	0,0%	92,6%	2,6%	0,1%
	Sweden	13,8%	0,0%	4,7%	2,3%	24,5%	41,3%	13,2%	0,2%
	UK	23,7%	0,1%	2,1%	34,8%	10,2%	4,6%	13,4%	11,0%
	NORDPOOL	46,5%				8,6%	16,5%	16,0%	12,5%
MIBEL	Portugal	12,9%	5,5%	3,1%	20,9%	0,0%	29,9%	25,4%	2,3%
	Spain	46.8%				6,9%	18,1%	21,6%	6,7%
	MIBEL	46.1%				5,9%	19,9%	22,2%	6,0%
Korea		40,6%	0,4%	0,3%	27,9%	20,8%	6,5%	0,6%	2,9%

Source: IEA Data

Trends and System Specific Indicators

In order to provide a context and evaluate the current pathways followed by the considered regions, commentary will be provided on electricity demand, electricity generation (for nuclear, renewables, hydro and thermal power) and interconnections. This will enable a high level consideration and focus on the impacts of key drivers on electricity system development. The figures found in appendix 1 provide a visual representation of the data reflected in the discussion.

Electricity Demand

Electricity generation and respective investments follows distinct trends throughout the considered markets/regions as countries experience different economic momentums that directly impact the demand for electricity. In some cases, deployment of energy efficiency measures has already led to a decoupling of some level between economic growth and energy consumption.

a) Northern European countries have also been experiencing the effects of economic stagnation or modest growth since the end of the 2000's. In fact, both MIBEL and NORDPOOL have been curbing levels of electricity production since the economic crisis and are now clearly following a downward trend - and, for the case of NORDPOOL, are only now getting back to production levels registered in 2000.
b) Iberian countries have considerably suffered from the European financial crisis in the late 2008 - and subsequent economic contraction have resulted in a significant fall on electricity demand (down 8.1% since 2008 [Figure A 12]). This situation has resulted in the increase in the share of variable generation. Solar and wind power production shares have reached 4.3% and 19.5% respectively in 2014, as units, such as thermal power plants, that are later in the merit order are less frequently able to remain below the market clearing price.
c) On the other hand, **Korea**'s growing economy has pushed electricity generation (+22.1% [Figure A 12], 2008-2014) over the time, even during the financial crisis. The considerable energy-intensive nature of its economy (*Korea*: 6,391 USD/koe compared to the average *OECD*: 9,047 USD/koe), is still one of the factors that contribute for a strong coupling between energy consumption and economic growth. Prospects of electricity demand growth estimated by the Korean Government point to an annual growth of 2.2%[10] until 2029.

Electricity Generation Systems

A number of OECD countries are demonstrating some level of decarbonisation of their economies, with particular focus on the power sector. The Southwestern and Northern European regions are examples of how these policies have resulted in significant growth in generation capacity, whereas South Korea still struggles to address the issue of climate change while providing electrical energy to an ever-growing economy and

[10]"*South Korea*", U.S. Energy Information Administration (EIA), October 2015

electricity demand. A concerted effort by countries, during the last decade, towards the sustainability of the electricity sector led to an important deployment of renewables, specially wind (across several NORDPOOL members, Portugal and Spain) and photovoltaic systems (particularly in Germany and Spain). However, CO_2-free generation technologies used to help mitigate greenhouse gas (GHG) emissions vary from region to region. In that sense, Sweden, Germany, Finland, United Kingdom, Korea and Spain's main source of clean electricity production comes from nuclear, whereas Denmark is mostly reliant on wind and Norway and Portugal on hydro. Despite large investments in solar technology, it has yet been deployed to a scale to provide the largest impacts of GHG emission reductions.

The downturn in electricity demand, particularly among the considered European countries, has counteracted national forecasts of growth and the expected need for generation fleet's enlargement plans. Hence, some countries are now dealing with a problem of oversized electricity generation systems, which can threaten their economic sustainability and lead to increased costs.

a) The ratio of peak demand to capacity of the overall generation fleet is also quite low in NORDPOOL countries. **Denmark** (43.5%[11]), **Germany** (44.4%[12]), **Estonia** (50.3%[11]) and the **United Kingdom** (55.5%[11]) are examples of overcapacity resulting low capacity factors of some power plant facilities within the NORDPOOL region. Nevertheless, **Norway** (71.3%[11]) and particularly **Finland** (88.4% [11]) show high and considerably high levels of installed capacity usage to supply peak demand - a situation backed by high ratios of interconnection between NORDPOOL countries that enable system operators to rely on imports to supply power when required;
b) MIBEL shows indicators of considerable overcapacity, as in 2014 its peak load power corresponded to just above 37.4%[14] of the total installed generation capacity;
c) Despite its lack of interconnections, **Korea** faces high shares of capacity usage during peak demand - 80.3%[10] in 2014. In fact, this is partly due to a system that has faced adequacy issues in recent past. **Korea**'s rapid demand growth over the last decades, delayed investments on generation capacity and low electricity prices have resulted that - according to the Korea Energy Economics Institute - reserve ratios have fallen below 10% on an annual basis between 2007 and 2013, contributing for the recent power shortages during peak seasons. This might represent an ongoing security problem considering the prospects of electricity demand growth estimated by the Korean Government (+2.2%[13] annually until 2029). **Korean** authorities have underlined the necessity to develop mechanisms of demand response that will help to mitigate the necessity of building new capacity, reducing peak demand (-12%) and consumption (-15%) by 2027.

Thermal Power

Despite the recent CO_2-free electricity production deployment, fossil fuels still play an important role in **NORDPOOL, MIBEL** and **Korea** with capacity shares of 47.8%, 46.1% and 69.2% respectively (2014), largely comprised of coal and natural gas facilities. In Europe, coal-fired capacity has followed a decreasing trend

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[11](Peak Load Demand)/(Overall Installed Capacity);IEA Statistics, OECD, Net Electrical Capacity,
[12]Relative to the year 2013; "*Report on the German power system*", Agora Energiewende;
[13] "South Korea", U.S. Energy Information Administration (EIA), October 2015

but, for the case of **NORDPOOL**, production has remained stable and it still accounts 51.7% (2014) of the overall production. Last decade's effort towards the sustainability of the electricity sector led to an important deployment of cleaner-production capacity to replace older and dirtier technologies of generation from coal, oil or waste. A closer look at the evolution of generation capacities unveils a consistent growth of natural gas. This commitment to look for cleaner ways to generate electricity can already be witnessed by "recent" trends on the construction of new fossil-fuelled generation facilities (Figure A 17). A pattern of steam power plants decommissioning and construction of new combined cycle gas turbines (CCGT) and gas turbines can be noticed. Capacity to burn coal (coal, coal products and solid/liquid fuel burning power plants) has been decommissioned over the last years (2008-2014), with substantial focus on the UK (-8 226 MW[5]) and Denmark (-2 074 MW[5]).

Coal and gas usage is highly variable in Northern European and Iberian countries due to their strong dependence on weather conditions. Hence, it can be observed that wet/windy years favour hydro/wind production, reducing the need for thermal-based generation to meet demand levels. On the other hand, dry/non-windy years are characterised by higher shares of gas and coal. In Korea generation from coal and gas has demonstrated ongoing growth since the beginning of the century.

a) **Denmark**'s continuously growing wind share and the shrinking electricity demand over the last years caused a significant decrease in the share of natural gas compared to coal for electricity generation. This event was largely motivated by high prices of gas when compared with coal, but also due to Denmark's program to increase the flexibility of coal-fired power plant operation. Efforts were made to achieve higher generation ramps, work efficiently at lower minimum loads and provide quick response to sudden load/supply imbalances. Since coal-PP are now capable of balancing wind output variations, expensive natural gas holds very few technical advantages the share of natural gas in electricity production fell from 24.3% in 2000, to nearly 6.9% by 2014.[14] Denmark's high wind production penetration (41.0% in 2014) and considerably efficient coal-fired power plants which were refurbished and adapted to provide balancing services have resulted in an average emissions factor of 299.9 gCO2/kWh, in 2013
   From 2008-2014, **Germany** – probably perceived as the most active country on the clean energy transition within the NORDPOOL – registered a 6.13GW increase of natural gas capacity (+26.9%[15]). Despite these new investments, capacity factors of Germany's coal-fired power plants have increased due to higher volumes of energy produced in recent years, causing the gas share on electricity generation to plummet and, thus, lowering gas-fired power plants' capacity factors – a trend that can be observed all over the NORDPOOL - and contributing for the rise of emissions. (Figure A 15)

   Electricity generation in **Estonia** is extremely reliant on internal shale oil production (82.3% share in 2014), being also fuelled, in smaller shares, by solid biofuels and waste. Estonia's generation capacity is expected to meet safety of supply's requirements at least until 2020, obviating the need of new facilities in a near future[16]. Electricity generation from bituminous coal and peat in **Finland** has been used to manage seasonal hydro electricity production fluctuations. At the same time, natural gas has been losing share since the beginning of the millennium (from 14.2% in 2008 to 7.9% in 2014). Finland

[14] Agora Energiewende – "The Danish Experience with Integrating Variable Renewable Energy", 09/2015
[15]Fraunhofer data (confidential data in IEA for capacity of Germany and Sweden)
[16]"*Scenario Outlook and Adequacy Forecasts 2015*", ENTSOE, June 2015

has also a relatively stable amount of electricity with origin on solid biofuels (around 10TWh/year, 15.8% of the mix in 2014).

Despite **Sweden's** significant capacity fuelled by combustible fuels (20.8% in 2014), its production accounted only 9.0% of the electricity energy generated in 2014, which clearly describes the low usage of these facilities (capacity factor was19.6% in 2014). Among Sweden's CHP fleet there are some of most efficient gas-fired power plants. For instance, the Öresundsverket power plant (440MW) has an efficiency of 58% - however, when at full cogeneration, the efficiency is as high as 90%[17]. Stockholm has one of the largest district heating and cooling systems, powered by Värtaverket CHP-plant, the last coal-fuelled power plant in Sweden but with growing contribution from biofuels. Built in 1903, the infrastructure has been continuously refurbished and aims to 2030 as the year when it will become climate neutral [18]. The trend of refurbishing fossil-fuelled PP and adapt them to biomass is likely to be continued in the following years.

The **United Kingdom** has registered a 5 593 MW development of gas from a capacity share of 32.9% in 2008 to 34.8% in 2014.The region has also considerably reduced its coal-fired capacity, decommissioning 3 260 MW during the same period, reducing the share of coal and coal products' capacity to 21.6% in 2014. Additionally, 4 966 MW of generation capacity from solid and liquid fuels were decommissioned from 2008 until 2014. The UK has the highest share of electricity generation from natural gas (30.2% in 2014, around 58% of NORDPOOL's electricity from gas). However, such share is far from the 45.3% achieved in 2008, when gas usage peaked after a steady growth during the early 2000's.

b) Aiming at a profound decarbonisation of the power system in recent years, **Portugal** and **Spain** have increased their gas-fired capacity, increasing the overall generation capacity while decommissioning liquid-fuelled capacity since the beginning of the century. **Portugal** has been particularly active on the commissioning of new gas-fired power plants, with an increase of generation capacity of about 2098MW from 2008 to 2014 (+83.2% to 4620 MW). In order to prepare for the current plans for the decommissioning of the two remaining coal-fired power plants Sines (2017) - one of the thirty dirtiest power plants in Europe[19]- and Pego (2021), two new CCGT power plants are expected to start operating by 2017 (with a nameplate capacity totalling 1 766MW)[20]. These investments in gas power are supported by that fact that Portugal has made investments in LNG terminals (Sines, Portugal). This has been supported by the European Commission who encouraged the broadening of gas import sources to Europe through the development of LNG terminals, promoting stronger competition between suppliers.

No new investments on conventional power plants are expected to happen in Spain until 2025. However, the decommissioning of some coal-fired capacity is expected from 2020 on. Spain is currently phasing-out subsidies and incentives to coal by recommendation of the European Commission. Additionally, a Royal Decree has been revoked in late 2014's in order to open the

[17] "*Scenario Outlook and Adquacy Forecasts 2015*", ENTSOE, June 2015
[18] http://fortum.com/en/energy-production/combined-heat-and-power/sweden/Documents/Download%20V%C3%A4rta%20CHP%20power%20plant%20brochure.pdf
[19]"Europe's Dirty 30", CAN, WWF, European Environmental Bureau, November 2015
[20]*"Relatório de Monitorização da Segurança de Abastecimento do Sistema Eléctrico Nacional 2013-2030", REN, March 2013*

Spanish coal market (including the demand from the power sector) to foreign competition since there was a strong protection of the Spanish coal industry.

c) **Korea**'s ever-growing electricity demand, relatively sparse generation capacity and high gas prices in the Asian regional market are major factors that don't allow further replacement of coal-fired capacity by gas-fired technologies. In fact, **Korea**'s coal capacity has been increasing as result of a growing electricity generation ($CAGR_{2008\text{-}2014}$ = +3.4%) pushed by its strong, resilient and industrialised economy. Coal is by far the most used primary energy source to electricity production and experienced a considerable increase of usage after the national scandal with nuclear licensing certificates, in the late 2012, which led to a temporarily closure of some nuclear capacity. In an opposite direction of most of the considered European systems, gas consumption in Korea has been soaring. Korea has been working on its diversification of gas origins: Australia, U.S. and the Middle East look as the most probable origins to integrate Korea's imports portfolio. As a result, The Korean Gas Corporation (KOGAS) is planning to import gas from the Sabine Pass in Louisiana (2.8 Mt/year), starting next 2017 with a horizon of 20 years. Similarly, imports from new liquefaction projects such as Prelude LNG and Gladstone LNG are likely to happen in the next few years[21]. Agreement on gas imports from Freeport LNG, in the US Gulf Coast, has already been signed and will be materialised by 2019. Despite an expected growth of gas capacity, EIA forecasts that LNG will most likely loose share in the next years.

Renewables

Renewables, particularly wind and solar power, have been deployed at significant scale in a large number of European countries (figure A 9). In 2014, **Denmark** was the World's leader on wind penetration share (35.8% of the overall generation fleet's capacity), followed by **Portugal** (25.4%) and **Spain** (21.6%). **Germany**, **Sweden** and the **UK** have also deployed large amounts of wind capacity. Production variability is however managed differently according to the characteristics of the systems: while MIBEL countries have to rely on pumped hydro and gas-fired capacity to balance production, NORDPOOL countries benefit from extremely high interconnection ratios, which permit the harmonisation of the grid flows.

a) During the period 2008-2014, NORDPOOL grew its wind capacity by 100.9%, reaching a joint capacity of 64.0GW in 2014, with major contributions from Germany (39.2 GW), Sweden (5.1 GW) and the United Kingdom (13.0 GW). High levels of solar PV capacity can also be found among NORDPOOL member countries, as it increased by about 38.1 GW[22] - particularly supported by the feed-in tariffs' policies led by Germany (+32.1 GW). In fact, **Germany**'s wind and solar capacity accounted together for 39.0% of the overall installed capacity in 2014, due to combined growth of 77.4 GW since 2008. For the case of **Denmark**, whose annual production share from wind is 41.0%, it should be emphasised that this is currently being supported by a long-term national initiative of requalification of all coal-fired power plants in order to increase production flexibility. Furthermore, a net capacity

[21] *"South Korean KOGAS cuts Jan-Sep LNG imports 13.9% on year on weaker demand", Platts McGraw Hill Financial, Nov 2015*

[22] Solar installed capacity in Norway not accounted (data not available);

of interconnection of 6.4GW (approximately 105% of the peak demand in 2014) represents an invaluable asset for grid balancing, allowing reliable accommodation of high shares of variable production. In **Sweden**, prospects point at an expected large increase of wind and biomass capacity, as a consequence of the Swedish green certificate system[23].

b) Wind generation is highly represented in **Portugal** and **Spain** due to optimum resource conditions and significant installed capacity: MIBEL's wind capacity grew 43.4% from 19.4 GW in 2008 to 27.8 GW in 2014, accounting for 21.9% of the overall capacity, and 59.9% of the peak demand capacity in 2014. Also in 2014, the electricity generated in **Portugal** from wind reached 22.9% and was the second largest contributor for electricity supply after hydropower. **Spain**'s electricity generation registered a 18,8% contribution from wind, making it the 3rd main source of generation after hydro and nuclear power. On the other hand, solar capacity for electricity production has registered a 113.8% growth between 2008 and 2014, reaching 7 502 MW in 2014 in the MIBEL market. However, only 5.5% of this capacity is located in **Portugal**. Solar power contributed 4.3% of the generated electricity in the MIBEL region in 2014. After the financial crises in the late 2010's, both countries had to review their incentive policies to renewable generation, reducing drastically the access to feed-in tariffs, which led to a reduction of new wind and solar.

c) **Korea** has grown its wind generation capacity to 615MW by the end of 2014 (+102.3%, 2008-2014). Despite demonstrating significant growth, **Korea**'s wind capacity is still low in 2014, limited by economic and environmental feasibility of the Korean wind potential, estimated at about 2.7GW. Solar capacity (exclusively PV) has also registered a considerable growth from 357 MW in 2008 to 1 555 MW in 2014 - but it still represents a small share (2.5%) of the overall capacity.

Hydropower

Hydropower production plays an important role within NORDPOOL's and MIBEL 's regions, contributing with shares of 16.5% and 19.7% of the respective overall capacities. Contrarily, hydro power production is significantly lower in the **Korean** electricity system (6.5%, 2014), but has grown by about +17.5% from 2008-2014.

To balance variable renewable generation, hydropower plants equipped with reversible systems are often a solution to quickly adapt supply and demand oscillations. However, pumping capacity has remained stable or even decreased during recent years across the majority of considered countries.

a) For the case of the NORDPOOL, **Norway**'s hydropower is a main asset, working as a natural battery and providing backup whenever needed due to the high dispatchability of its portfolio. In fact, the large share of NORDPOOL's flexible capacity is provided by Norwegian hydro power plants.

b) Improvements on the hydro power plants' flexibility were an important consideration to support reliable grid management and balancing. Unlike all other countries, **Portugal** has registered a pumping capacity growth of 29.4% (2008-2014) that already represents 24.8% of the overall hydro capacity in 2014. According to the "*Relatório de Monitorização da Segurança de Abastecimento do Sistema Elétrico Nacional 2013-2030*", the Portuguese authorities plan to add 1837MW of new hydro capacity by 2017 – including 1 295MW of reversible capacity - and an additional capacity of 1100MW

[23] "Scenario Outlook and Adequacy Forecasts 2015", ENTSOE, June 2015

(reversible) by 2022. In **Spain**, pumping capacity registered a slight decrease of 2.4% since the beginning of the millennium. Pumping capacity in Iberia represented 13.9% of the peak demand and 23.6% of the overall wind capacity in 2014.

As Portugal and Spain are considerably reliant on hydropower production (29.9% and 28.1% respectively in 2014), the necessity of fossil fuels -mostly natural gas and coal -to fuel and balance the electricity generation system in the MIBEL's region is intimately dependent on hydrological years. Therefore, CO2 total emissions are also highly dependent on hydrological years and availability of water, registering low emissions in 'wet years' and comparatively higher emissions in 'dry years'. This is also demonstrated in the box below with a focus on Denmark.

HYDRO, THERMAL POWER AND RENEWABLES: A FOCUS ON DENMARK

The consistent and steady deployment of wind power production facilities in Denmark has been possible due to a combination of factors that allowed the balancing of the grid. Accordingly, Denmark's high penetration of wind power production (41.0%, 2014) benefits from the availability of interconnections with neighbouring countries – particularly Norway – and from the existence of highly flexible coal fleet which is technically able to operate considerable production rampages. As a result of the implementation of a national program - *grønomstilling* - launched during the 1990's, Denmark proceeded to the refurbishment of a considerable number of coal-fired power plants in order to achieve greater operation flexibility higher power output ramps (3 - 4% P_n/min)[i] and lower minimum loads, making them suitable to provide balancing services.

Since the beginning of the century, some episodes of abnormally high CO_2 emissions in **Denmark** can be associated to 'dry' years in Norway and to the necessity to generate and export - coal-based electricity to balance the Norwegian system. These events triggered the rise of emissions in 2003 and 2006 by 28% and 56% in relation to the previous year, respectively.

Notes:

i. The Danish Experience with Integrating Variable Renewable Energy", Agora Energiewende, September 2015

Interconnections

The considered regions are quite distinct regarding interconnection ratios. Interconnections enable the trading of electricity and can enable the sharing of resources – both for bulk production and for balancing of the electricity system. The successful operation in the NORDPOOL market based on high levels of interconnection has influenced the European electricity system design approach. Focus has been given to a market union achieved under a scenario of comfortable net interconnection capacity to accommodate transactions defined by the market. Intra- and interconnection developments have been one of the main consensus areas among national authorities and the European Commission, reflected in the change from 550-850MW of interconnection in 2003 to 2000-2100MW in 2014.

a) In NORDPOOL countries have significant interconnections, which allow closer and beneficial collaboration among countries. In 2012, **Germany** had a total interconnection capacity of about 21.3GW, comprising of interconnections with Austria, Switzerland, Czech Republic, Denmark, France, Luxembourg, the Netherlands, Poland and Sweden. This capacity is crucial to enable a comfortable grid management, accounting for 25.6% of the annual demand peak and 65.3% of total PV installed capacity. In Denmark a net capacity of interconnection of 6.4GW (approximately 105% of the peak demand in 2014) represents an invaluable resource to balance high shares of variable renewables. A new cable connection between **Norway** and the **UK** is expected to be operating by 2021 (730 Km, 1 400MW, EUR 2b[24]), whereas a new connection with Germany will be completed by 2019.

b) The Iberian Peninsula and, therefore, the MIBEL market, are fairly well equipped with intraconnections - linking **Portugal** and **Spain** (97.57% of price-coupling in the day-ahead market[25] in 2015). The Iberian Peninsula is scarcely connected: interconnections with Morocco and France amount 2.4% of the overall MIBEL's capacity[26]. This constrains exchange operations with neighbouring markets and makes it impossible to export wind power generation surplus. New interconnection capacity is expected to be added to the Spanish system: a gradual increase form the 4 700MW available in 2014 to 6 400 MW in 2017 and 11 600 MW in 2020.[27] Accordingly, MIBEL's interconnection capacity is expected to reach 4.1% of the overall installed capacity in 2020 [6].

c) **South Korea** is an "electrical island", meaning no interconnections with neighbouring countries exist. The Korean Electric Power Corporation (KEPCO) is pushing forward a plan to develop an interconnection line between Busan (Korea) and Kyushu (Japan), passing by the Tsushima Island. Additionally, on a long-term point of view, an interconnected grid that would couple South Korea, China, Japan, Russia and Mongolia's power grids is being considered. This project would be supported by the fact that Russia, China and Mongolia have immense natural resources (either fossil or renewable) that can be used to generate electricity that would be imported by Japan and Korea[28].

Nuclear Power

The regional markets in Europe follow a different trend from Korea regarding nuclear power. Since 2008, the Korean nuclear fleet was increased by 16.9% and represented 20.8% of the overall capacity in 2014, while the Iberian nuclear capacity slightly increased by 0.5% and NORDPOOL's fell by 20.1% (figure A 8). The fall in

[24] *"UK and Norway to build world's longest undersea energy interconnector",* The Guardian, March 2015
[25] "*Relatório de Preços 2015*",OMIE, 2015
[26] *"Energy Policies of IEA Countries, Portugal"*, 2016 Review, IEA, April 2016
[27] "*Energy Policies of IEA Countries*", Spain, 2015 Review, IEA, 2015
[28] "*KEPCO wants grid linked to Japan*", Korean Daily, August 2014 http://koreajoongangdaily.joins.com/news/article/Article.aspx?aid=2993919

the NORDPOOL market is particularly driven by the phasing-out of nuclear generation in **Germany.** Nuclear now represents 6.1% of the German system and 8.6% of the overall NORDPOOL system capacity.

a) The *Energiewende* plan currently being implemented in **Germany**, which declared the nuclear phasing-out to be concluded by 2022, has already reduced the share of this technology to 6.1% in 2014. **Sweden** has also indicated a gradual decrease of nuclear power in the future as older facilities will begin to be decommissioned. Heading in a different direction, **Finland** is increasing its nuclear capacity with the construction of a 1200MW[29] reactor (*Olkiluoto 3*), which is expected to be operating by 2018 and will be the first Evolutionary Power Reactor (EPR). The **United Kingdom** is facing considerable contention on the construction and commissioning of two new nuclear reactors at the Hinkley PointPower Plant. This infrastructure, with a nameplate capacity of 3.2GW and designed to supply 7% of Britain's electricity, was meant to open in 2017 but that deadline was postponed until 2025, due in part to questioning about the harm that the £18bn investment would cause on the EDF's already fragile financial situation and to disputes with unions and security issues.[30] [31]
b) The 7 121 MW of nuclear power installed and operating in the MIBEL region are exclusively located in **Spain**. According to the current licenses expirations, by the end of 2021 this market will be deprived of 6 118 MW of the currently installed power. Due to difficulties arising from the indebted **Spanish** electric system (who had accumulated a tariff deficit of about EUR 26b by 2014, more than 2% of the GDP), in 2011 the Spanish government removed a provision that limited nuclear power plant operation to 40 years in order to maintain low marginal costs of electricity for a longer period of time. This situation was followed by an industry report which recommended in principle 20-year life extensions.
c) Despite the relatively recent Fukushima disaster and the scandal with false security certificates, **Korea** has 23 nuclear operating power plants, with a combined capacity of 20 716 MW, ranking in fifth largest among the nuclear fleets in the World[32]. Additionally, there are five new nuclear power plants (≈ 6.6GW) under construction that should initiate activity in the following years and a total of 10 units (≈ 15.4 GW) planned for the subsequent years, aiming at the target of 43GW of nuclear capacity by 2035[33]. After four main coal projects with a combined power of about 3740MW were cancelled back in 2015 for fuel and transmission facility issues, the country looks keen to continue developing nuclear generation[34]. In 2015, Korea and the USA renewed, for 20 years, their agreement on nuclear fuel supply[35].

[29] "*Scenario Outlook and Adequacy Forecast*", ENTSOE, 2015

[30]"*Hinkley Point C: French union opposition casts fresh doubt on project*", The Guardian, 27 June 2016
[31] "*EDF's top managers tell MPs that Hinkley Point should be postponed*", The Guardian, 17 June 2016
[32] "South Korea", U.S. Energy Information Administration (EIA), October 2015
[33] "Republic of Korea", Nuclear Energy Agency, OECD,
[34] "South Korea plans two nuclear units and cancels 4 coal-fired projects", Enerdata, Jun 2015
[35] Korea Electric Power Corporation

THE IMPACTS OF INTERCONNECTIONS ON THERMAL POWER: A FOCUS ON GERMANY

Germany's investments in power generation demonstrate an effort to shift from fossil-based economy to a renewable-based. They have invested EUR 18.8b in 2014 for the construction of renewable energy generation capacity [i] and installed capacity (47.5GW, from 2008 to 2014). Despite these investments Germany has seen its CO_2 emissions from electricity production rise during the period from 2010-2013 (both absolute and normalised emissions), being the largest absolute polluter in the region (304.9 Mton CO_2, 2013) and the second largest polluter per electricity unit (486.1 gCO_2/kWh, 2013), (Figure A 18) threatening the achievement of GHG emissions reduction goals.

The high ratio of interconnection capacity has enabled that low marginal price of Germany's coal and lignite power plants induce strong competition in neighbouring electricity markets, passing cleaner technologies in merit order based electricity systems. In 2015, Germany's net exports (mainly to France, Switzerland, The Netherlands and Austria) were equivalent to 9% of Germany's overall electricity production. The lower prices of coal-based power relative to gas-based power, not only from its domestic market but also from neighbouring countries, has highly stressed gas power production. Low carbon prices, have also been an important contributor for the increase of coal usage on power generation and the raised CO_2 emissions [ii].

The German Advisory Council on the Environment argues that there is space for a massive closure of 9GW of coal- and lignite-fired power plants due to excess of installed capacity in Germany (10GW) as well as in the neighbouring countries and Italy, totalling 60GW[iii]. The same council estimated the need for balancing services of 60GW under a 100% renewables scenario in Germany. 42GW of this capacity could be provided by storage and transmission capacity between Norway and Germany [iv]. Power-to-gas (PTG) projects are a target for Germany, aiming to develop cost effective mechanisms of energy storage (as hydrogen and methane). PTG is a mature technology that can play an important role providing balancing services: Germany has currently 14 pilot PTG projects and 17 more under construction. [v] [vi]

Notes:

i. "Investment in renewable energy increased in 2014", BMWi, May, 2015 https://www.bmwi-energiewende.de/EWD/Redaktion/EN/Newsletter/2015/02/Meldung/infograph-investment-in-renewable-energy-increased.html
ii. "The German conundrum: renewables break records, coal refuses to go away", EnergyPost, 24/03/2016; http://www.energypost.eu/german-conundrum-renewables-break-records-coal-refuses-go-away/
iii. "The future of Coal through 2040", German Advisory Council on the Environment, June 2015
iv. "The Potential of Pumped Hydro Storage in Norway", Ingebretsen et al.
v. GTAI, German Trade & Investment https://www.gtai.de/GTAI/Navigation/EN/Invest/Industries/Smarter-business/Smart-energy/power-to-gas.html
vi. DENA, Deutsche Energie-Agentur, http://www.powertogas.info/english/

Appendix 1: Electricity System Figures

Figure A 1 - Electricity Generation Capacity (2014)

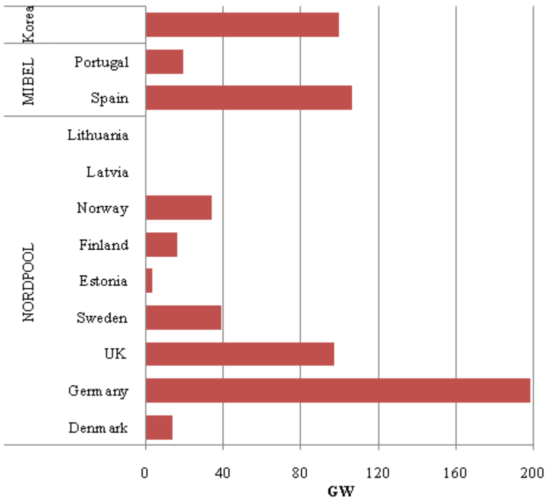

Figure A 2 - Dispatchability of Electricity Generation Capacity (2014)

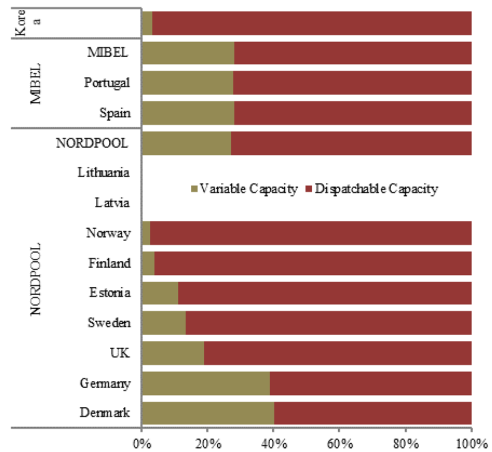

Figure A 3 - Dispatchability of Electricity Production (2014)

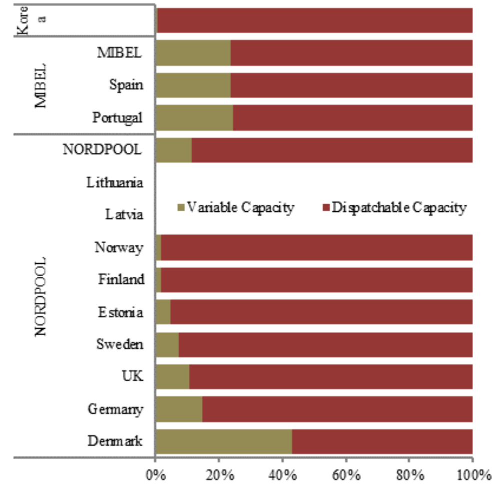

Figure A 4 - Electricity Generation by Source (2013)

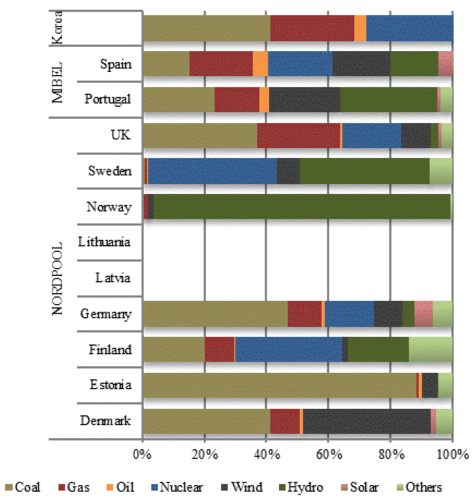

Figure A 5 - Share of CO_2-free Electricity Generation (2013)

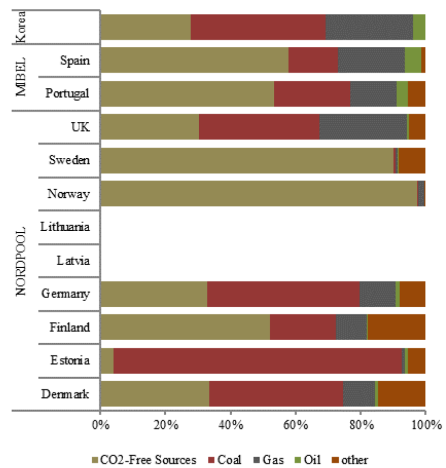

Figure A 6 - Origin of CO2 Emissions (2013)

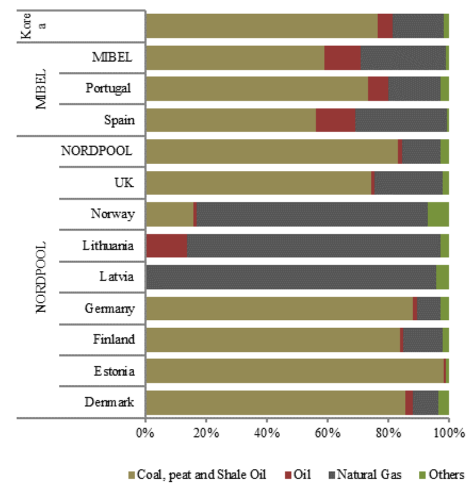

Figure A7 - Growth of Electricity Generation Capacity (2008-2014)

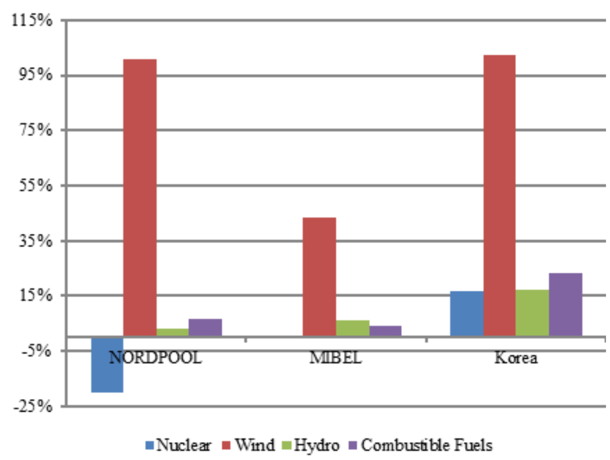

Figure A 8 – Regional Nuclear Capacity

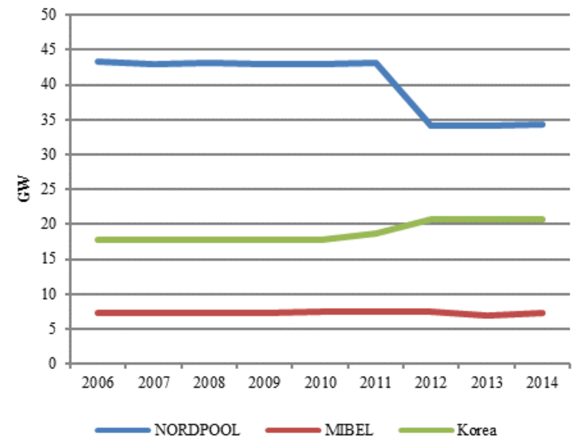

Figure A 9 - Wind Capacity Development

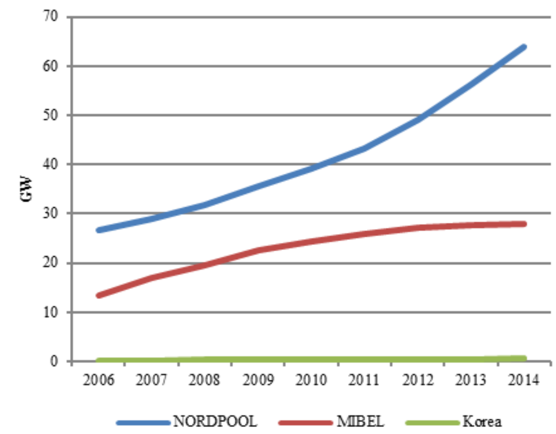

Figure A 10 - Hydro Capacity Development

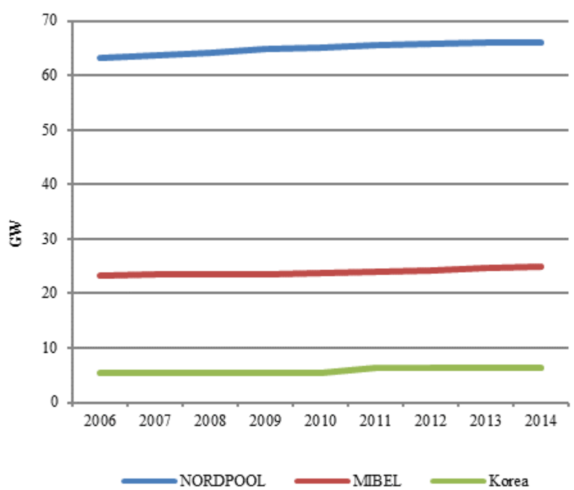

Figure A 11-Combustible Fuels-fired Capacity Development

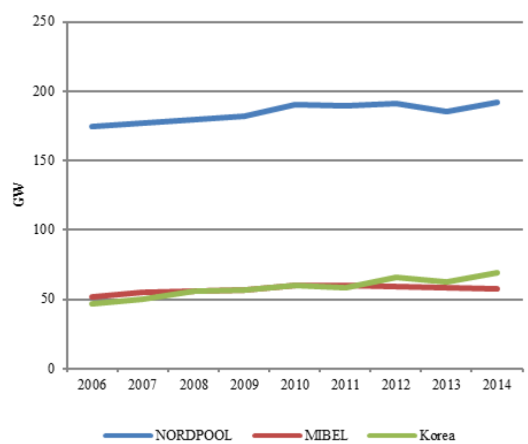

Figure A 12 - Growth of Electricity Generation

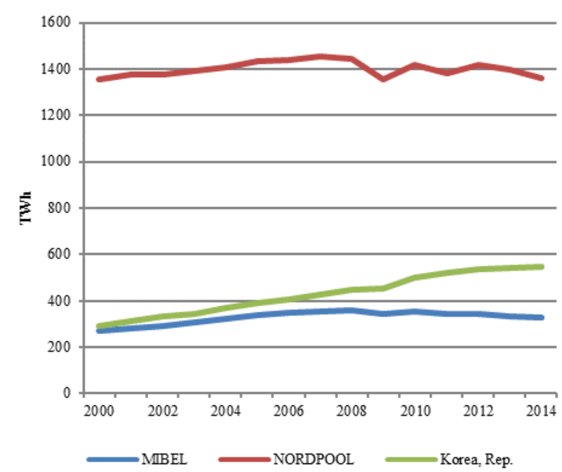

Figure A 13 - Generation Fleet's Capacity Factor

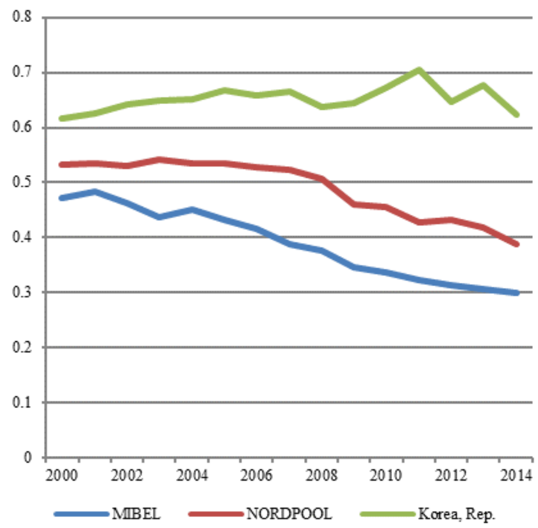

Figure A 14- Average Hours at Nominal Power (2010-2014)

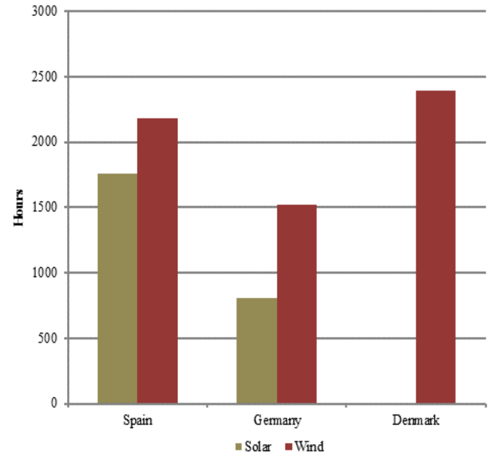

Figure A 15 - NORDPOOL's Thermal Capacity Factors

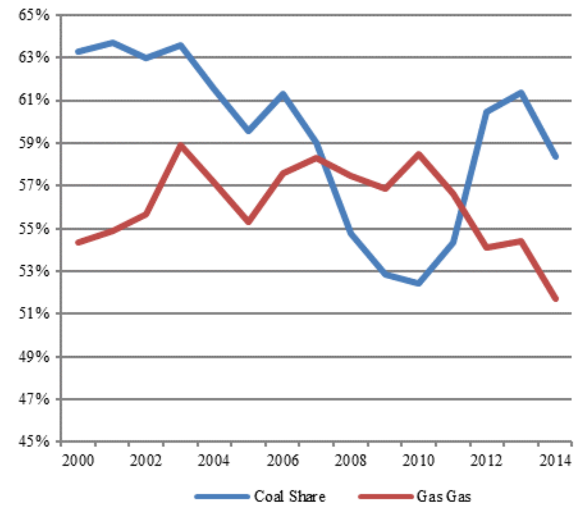

Figure A 16 - Thermal Power Plants' Capacity Factor

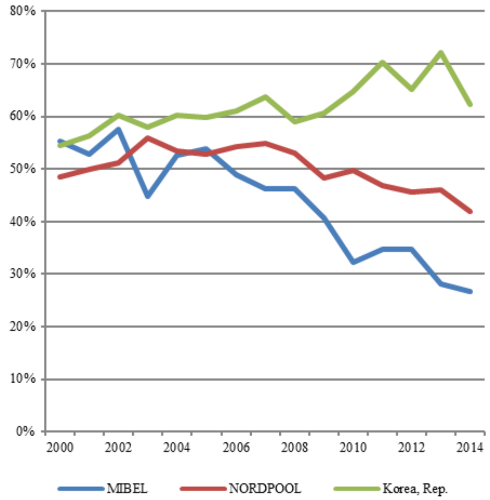

Figure A 17- Thermal Capacity Growth by Technology (2008-2014)

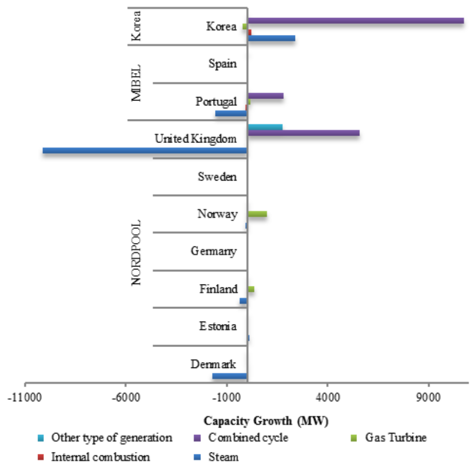

Figure A 18 - Normalised CO2 Emissions from Electricity Generation (2013)