CHESTER

Compressed Heat Energy Storage for Energy from Renewable sources

Detailed PESTEL and PORTER analysis of the CHEST system

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Glossary, Abbreviations and Acronyms

aCAES	Adiabatic Compressed air energy storage
CAES	Compressed air energy storage
COP	Coefficient of performance
CO_2	Carbon dioxide
CO_2-eq	Carbon dioxide equivalent
CHEST	Compressed Heat Energy Storage
CHP	Combined Heat and Power
CWE	Central Western Europe
DC	Direct current
DERA	Danish Energy Regulatory Authority
DH	District Heating
DSO	Distribution System Operator
EE	Energy Efficiency
EEG	Renewable Energy Source Act (from German *Erneuerbare-Energien-Gesetz*)
EES	Electrical energy storage
ETS	Emission Trading System
FIT	Feed-in tariff
GDP	Gross domestic product
GHG	Greenhouse gas
HP	Heat Pump
HT	High Temperature
LCOS	Levelized Cost of Storage
NO_x	Nitrogen oxides
NIMBY	Not in My Backyard
MIBEL	Mercado Ibérico de Electricidad (Iberian Electricity Market)
PCM	Phase Change Material
PHS	Pumped Hydro Storage
PPP	Purchasing Power Parity
PSO	Public Service Obligations
PV	Photovoltaic
ORC	Organic Rankine Cycle
RE	Renewable Energy
RES	Renewable Energy Sources
RP	Reference price
SO_2	Sulphur dioxide
TSO	Transmission System Operator
TES	Thermal Energy Storage
VRF	Vanadium Redox Flow

1. Introduction

1.1. Purpose and Scope

The PESTEL analysis describes the political, economic, social, technological, environmental and legal boundary conditions of the electricity market, in particular with respect to the integration of the CHEST technology. In fact, the advent of new technical solutions needs better support from the policy perspective, in order to fully harness the potential. Besides, the new solutions have to fit within the existing regulation framework. A particular focus is given to the current and expected level of penetration of non-dispatchable renewable energy sources in the electricity generation mix, technical and legislative issues regarding electricity storage technologies, interconnection with neighboring countries, electricity prices, etc. The PESTEL analysis is relevant for identifying how the current (and expected) boundary conditions in a country can favor or limit the development of the CHEST concept in this country, currently and in the near future.

In addition, the Porter analysis is relevant for summarizing the strengths and potential benefits of the CHEST system, and for identifying the market forces that can help the CHEST system enter in the different markets and applications. Because the CHEST technology was regarded here as a means of storing electricity, its potential was compared to other electricity storage technologies.

1.2. Structure of the document

This document is divided in two main sections.

Section 2 is divided into five subsections, one for each of the European countries represented in the Consortium of the CHESTER project, i.e. Spain, Denmark, Germany, Belgium and The Netherlands. Each of these subsections presents a detailed PESTEL analysis of the electricity market in one of these countries.

A short subsection describing the current status of the district heating technology in each of the above-mentioned countries is also present at the end of each PESTEL analysis. This was added as district heating is a key element for the integration of the CHEST system.

Section 3 presents the Porter’s Five Forces analysis of the CHEST technology. Subsection 3.1 shortly describes the theoretical principles on which the Porter's analysis is based, briefly presenting the five forces that explain the competitiveness within a sector, i.e. threat of new competitors, power of suppliers, power of customers, threat of substitutes and industry rivalry.

Subsection 3.2 applies the Porter’s Five Forces analysis on the CHEST technology, as a means of storing electricity. The analysis presented in Subsection 3.2 is purely technological, so it does not consider the different boundary conditions, which could affect the CHEST competitiveness in different countries. This aspect is, on the other hand, treated in Subsection 3.3, where the information collected in the PESTEL analyses are used to evaluate the potential of the CHEST system in the considered countries.

2. PESTEL Analysis

2.1. Spain

2.1.1. Political factors

The Spanish energy policy has quite stagnated in the 2016 and 2017 period because of the institutional impasse following parliamentary and presidential elections in 2015. Therefore, the regulatory framework of the electricity sector is mainly based on the Royal Decree 2013/24. Some few developments have been made since then, e.g. the Royal Decree 2016/56, which partially transposes the Energy Efficiency EU Directive 2012/27/EU as well as the Ministerial Order IET/359/2017 which fixes the energy savings targets of energy efficiency national funds, and some other Ministerial Orders.

However, concerning long-term energy plans, the Spanish Government has not publicly stated their intentions and objectives. There is no ongoing Energy Strategy Plan for the next years, which should guide the energy sector and stakeholders towards clearly identified objectives. There are only occasional actions, such as the program to promote self-consumption of electricity, including storage systems, that are launched occasionally, but the country lacks a long-term planning strategy.

On the other side, the Catalan Government has published a National Pact for Energy Transition (ICAEN, 2017) in order to increase the country's resilience to adapt and respond to the environmental and economic changes. This Energy Transition Pact is in line with all strategic axes published at the 'Clean Energy for all Europeans' legislative package, and aims to achieve:

- 100 % of the energy generation from renewable energy sources (RES) by 2050;
- To fulfil the objectives present in the "Clean Energy for All Europeans" Package (European Commission, 2016):
    - 27 % of the gross final energy consumption generated by RES by 2030;
    - 30 % increase in energy efficiency by 2030;
    - 40 % reduction of GHG emissions in the energy sector compared to 1990 by 2030.

It should be noted that the Spanish electricity market is partially merged with the Portuguese electricity market. A cooperation process between the Portuguese and the Spanish Governments, started in 1998, led in 2007 to the launch of the Iberian Electricity Market (MIBEL), with the aim of promoting the integration of both countries' electricity systems. The MIBEL has brought to a successful conclusion the harmonisation of requirements between the two Iberian electricity systems, with the expectation that this operation would bring benefits to the consumers of both countries within a framework for providing access to all interested parties.

2.1.2. Economic factors

General economic situation

After having contracted in 2012 and 2013, Spanish GDP grew by 1.4 % in 2014 and more than 3 % in 2015, 2016 and 2017 (Eurostat data). The inflation rate remained in negative values in 2014, 2015 and 2016, but has increased to reach an average of 2% in 2017, partly due to the energy component of prices.

Despite the economic growth in the last years, some important factors are putting pressure on the Spanish economy, such as an unbalanced national budget, with a high fiscal deficit (2.5 % of GDP in 2018) and public debt (99% in 2017), and pensions growing at a very low rate, which decreases retail sales and the consumer confidence index. There is a lack of investment in science and R&D, which hinders Spain's international competitiveness. The Spanish unemployment rate has fallen, but it was still high at 17 % in 2017 (Eurostat data).

Electricity market

The electricity market in Spain has undergone a deep transformation in the last 20 years, because of two main elements: the decarbonization of the electricity system and the liberalization of the electricity market, which have not necessarily led to higher competitiveness in the sector.

The first element has been extremely important. The development of R&D policies, combined with a policy to increase RES in the electricity sector, created a structure of higher costs, though substantially improving the energy mix for Spain (Figure 1). This increase, together with an energy reduction trend caused by the economic crisis of 2010, imposed a strong weight on the electric system (IEA, 2009).

	2016	2017
NUCLEAR	22.6	22.4
COAL	14.2	17.1
COMBINED CYCLE	10.3	13.6
COGENERATION	10.3	11.3
PUMPED STORAGE	1.3	0.9
NON-RENEWABLE WASTE	1.0	1.0
WIND	19.0	19.1
HYDRO	14.5	7.4
SOLAR PHOTOVOLTAIC	3.1	3.2
SOLAR THERMAL	2.0	2.2
OTHER RENEWABLES	1.4	1.5
RENEWABLE WASTE	0.3	0.3

	2016	2017
RENEWABLE	40.3	33.7
NON-RENEWABLE	59.7	66.3

Figure 1: Electricity mix distribution (%) in Spain (REE, 2017).

As a second point, it is important to state the historical consequences of a change in the market from 1998 (Law 54/1997), moving from a fully state-controlled energy system to a liberalized system. Until 1997, the electricity supply was a regulated business. The government established the price the consumers had to pay, and thus the income of the electricity companies (Regal, 2012). This framework was called "Marco Legal Estable" or Legal Stable Framework (REE, 2008).

However, the liberalization of the electricity market has not led to a reduction in costs as initially expected. Users experienced higher costs, with increases by more than 80 %. In Europe, only in Germany, Ireland and Denmark do household consumers pay higher prices for electricity. Considering only the electricity cost without taxes, Spain has the 4th highest electricity cost in Europe, for both residential and non-residential consumers (Eurostat, 2017a)

The cost increase probably arose due to the poor regulations embodied in the legislation, and the structure of the electricity market in Spain, which is an oligopoly. As observed in Figure 2, 67 % of the total generation capacity and 87% of the total electricity commercialisation are controlled by five companies (they created an association called UNESA, which is currently renamed to AELEC). The expected price reduction and cost optimisation was not achieved.

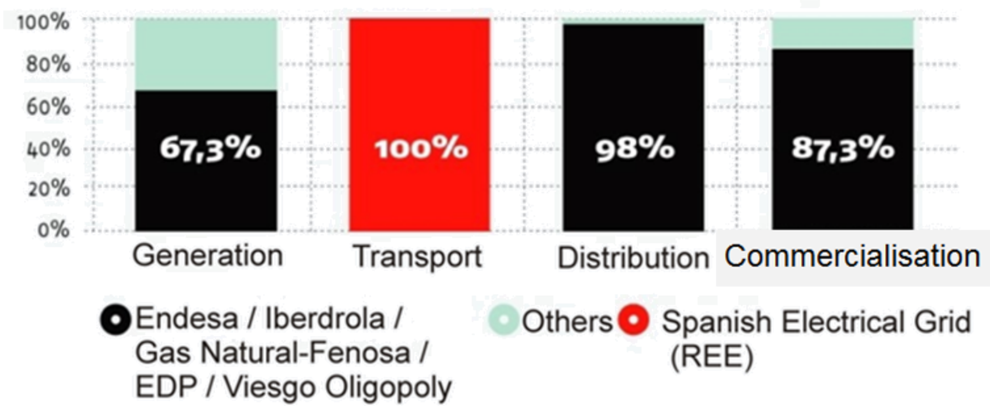

Figure 2: Structure of electricity market in Spain [Source: www.odg.cat]

The four main mechanisms facilitating the transition from a regulated market to a liberalized market increased prices and did not help consumers according to the intention.

- The first was the cost of transition to the liberalized market (in which the companies had to fund to change their processes from the regulated market). The companies claimed that the process to get into the liberalized market could imply a great loss. So, in order to avoid those extra costs, the government designed the Competency Transition Cost. This cost was passed to the final user and they were cancelled a few years ago.
- The second was the tariff cap, through which the government established a regulated price. The DSOs, given their costs, required extra payment (converted into debt) from the administration. There were two main problems with this debt: it was unsecured and only covered part of the costs.
- The third was the increase in the renewable energy production to accomplish the Kyoto objectives (United Nations, 2018), which implied a cost increase of the electricity production.
- The fourth was the price setting mechanism, which made no difference between technologies. Large power plants that had had government investments, and with already amortised investments (hydro and nuclear mainly) competed under the same conditions as non-amortised installations. This market structure makes it quite difficult for new actors and new energy companies to enter the market, and it does not favour the decrease in electricity prices (ODG, 2016).

Energy-related industry

The energy market evolution has been characterized by the appearance of new players (ESCO, Aggregators, Brokers, etc.) encouraging customers to change their behaviour and to require new services (energy diagnosis, monitoring, load shifting, multi tariff, etc.).

Moreover, new business models in the retail market have been developed thanks to new ICTs and the sector liberalisation. Some relevant practices concern tailored multi-tariffs, the possibility to buy and sell energy in a virtual micro-grid and peer-to-peer energy exchange (Stoneman, 2016).

The renewable energy sector industry in Spain is slowly recovering from the sharp decay induced by the notable changes in the subsidies scheme introduced in the years of the financial crisis and has seen a sustainable growth in the period 2014-2017. Figure 3 shows the evolution of the contribution of the renewable energy sector to the GDP for the period 2010-2017, where it can be seen that the contribution for 2017 was 0.80 % (9.3 G€), far from the maximum of 1.02 % reached in 2012 (APPA, 2017).

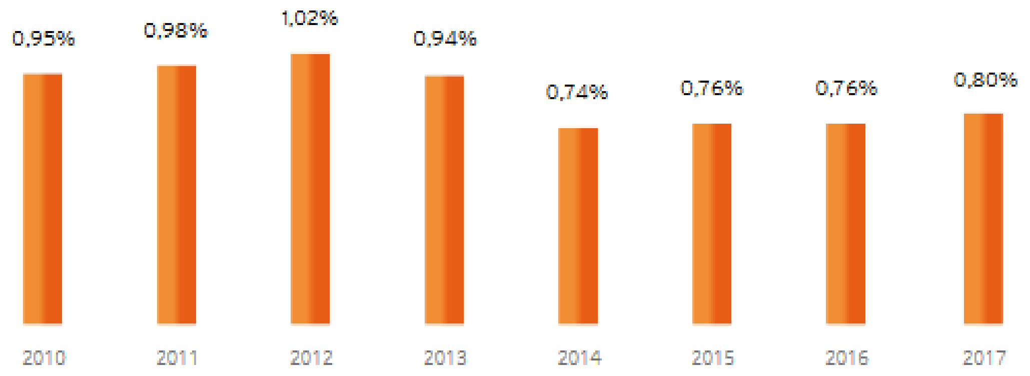

Figure 3: Contribution of the renewable energy sector to the GDP (APPA 2017).

The net contribution to the national current account has a positive balance of 3.1 G€, and the employment associated to the sector is 78,667 employments, which is approximately 50 % of the renewable energy sector employment in 2008 (APPA, 2017)

Energy R&D in Spain has received funds in the last few years, which placed the country in the middle of the Organization for Economic Co-operation and Development (OECD) country ranking. Despite the step change in renewable energy investments (fostered by the feed-in tariff structure) and the development of renewable energy companies, the impact of energy R&D in Spain during 2000-2010 has been relatively low (Figure 4).

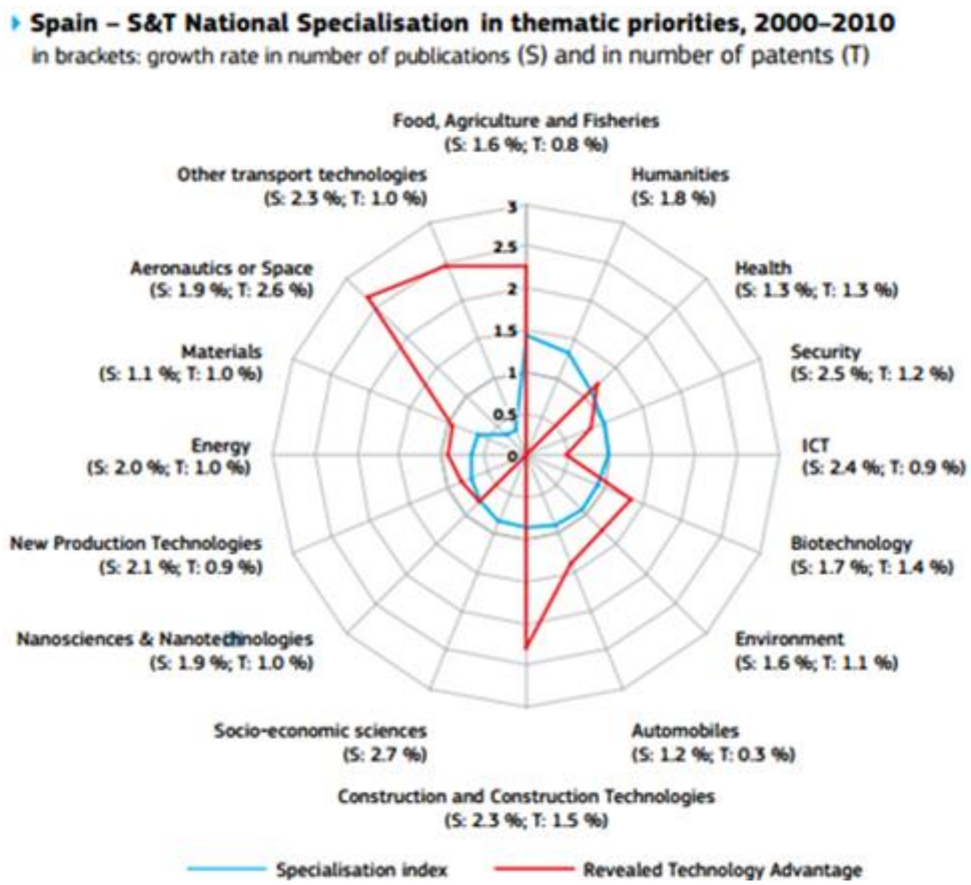

Figure 4: Level of energy investments and top priorities in Spain [Source: http://www.odg.cat].

Nevertheless, the rise in regional technological centres dedicated to energy in recent years (CTAER, in Andalucía; Circe, in Aragón; the Instituto de Energías Renovables, in Castilla-La Mancha; el Instituto Tecnológico y de Energías Renovables, in Canarias; Ceder, in Castilla y León; ITE, in Valencia; Cener, in Navarra; el Centro Tecnológico del Medio Ambiente y la Energía, in Murcia, Tecnalia in the Basque Country, IREC in Catalonia, CARTIF in Castilla León and the Ciemat I IDEA in Madrid, amongst others) has pushed Spain to a very high rate of participation in the international programs of R&D in the European Commission. Figure 5 summarizes investment roadmap in Spain.

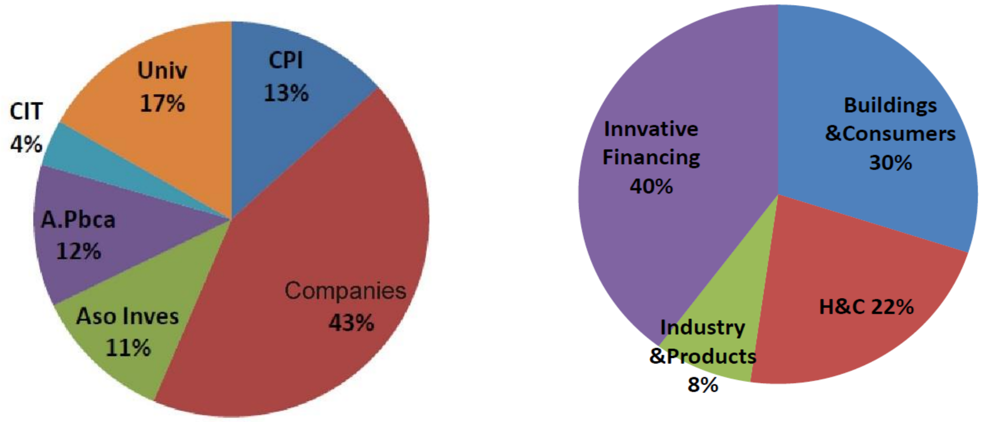

Figure 5: Investment roadmap in Spain [Source: Preparación WP2018-2020 ENERGIA H2020].

Energy taxation

Energy and carbon taxes in Spain are levied within the framework of the 2003 EU Energy Tax Directive, which sets minimum rates for the taxation of energy products in member states (OECD, 2018a). Within this framework, the main taxes on energy use in Spain are the following:

- Taxes applied to oil products, natural gas and coal and coke consumption, at different rates depending on the users and fuel
- An excise Tax on Electricity (Impuesto Especial sobre la Electricidad) applies to electricity output (per MWh).

Besides, Spain participates in the European Union emissions trading system (ETS). The rates at which these taxes apply differ for fuels and users, with the transport sector being the one with a highest rate of taxation. Figure 6 summarizes national taxes.

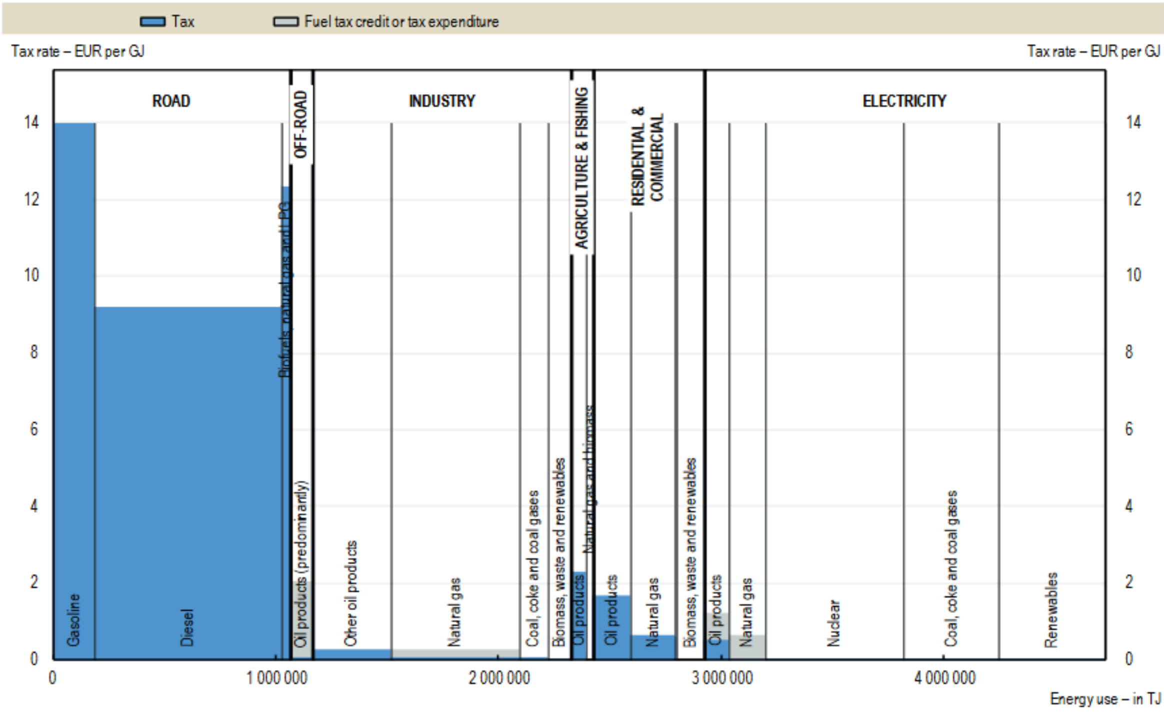

Figure 6: Energy taxation in Spain(OECD, 2018a).

For electricity, the production is taxed for electricity delivered to the grid (neither self-consumption nor any inner grid system electricity is taxed). Fuels used for electricity production are untaxed, except for diesel and heavy fuel oil, which are taxed but at a smaller rate than for other uses.

The last Eurostat report on electricity prices places Spain as one of the European countries with the lower share of taxes (Figure 7) applying to the electricity consumption, around 21 % of the final consumer costs.

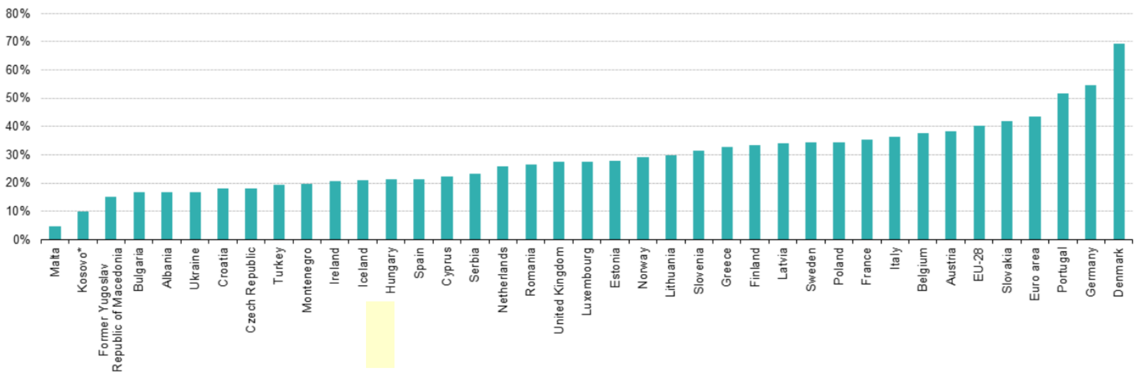

Figure 7: Share of taxes and levies paid by household consumers for the electricity in the 2nd half of 2017 (Eurostat, 2017a).

However, the same report shows that Spain is one of the European countries with higher electricity prices for household consumers (Figure 8).

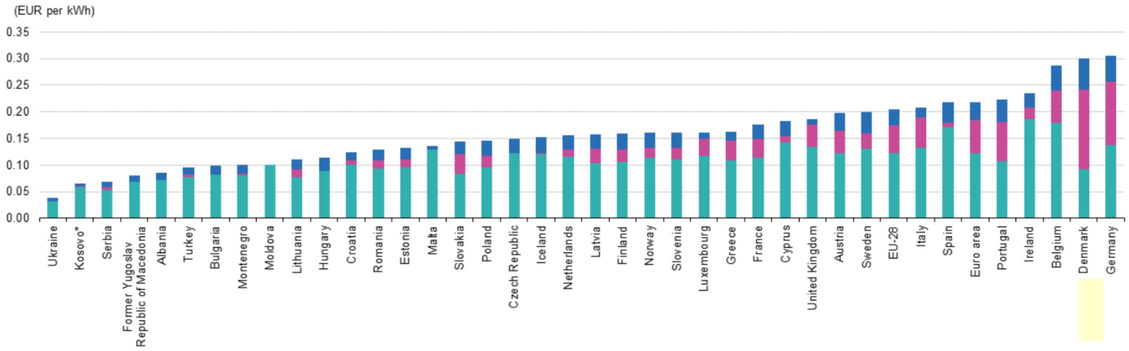

Figure 8: Electricity prices for household consumers in the 2nd half of 2017 (Eurostat, 2017a).

This is caused by the fact that the electricity bill contains also costs which are not related to the supply of electricity to final users. For example, in August 2013, the fixed part of the electricity bill (standing charge), related to the contracted power supply, increased by 100 % according to a Ministerial Order, which did not give private citizens and small/medium enterprises an incentive to reduce electricity usage, as the cost increase was irrespective of the actual consumption.

Figure 9 summarizes the different concepts that a household consumer pays. The figure represents the different weight of each concept in the final electricity bill. The four main components that a consumer pays are:

- Regulated Cost. All the concepts that the government includes in order to secure the economic and technical future of the electrical system. It includes, mainly:
  - Feed-in-Tariffs for RE producers.
  - DSO's service payment.
  - A solidarity mechanism to provide affordable electricity in the Canary Islands.
  - Subsidies to coal producers
  - Electrical system deficit payment
- Market Cost. Mainly the SPOT market, despite that the OTC markets or the PPA markets have very similar costs. In the Spanish market, 8-10 % (capacity mechanisms, for example) of this market cost is related to governmental decisions.
- Taxes. They are proportional to the previous two concepts. They suppose an additional 28 % to the previous aggregated costs. There are 3 taxes:
  - A municipal tax (not always applied by all municipalities) represents the 1.5 % of the gross revenue earned by the utility.
  - A Tax on Electricity of 5 % of the combined regulated and market costs. This money goes to the local regions directly.
  - A VAT of 21 % is applied to all elements included in the electricity bill.
- The gross profit for the utility, which represent about 5 % of the bill.

Figure 9: Weight of different costs that are contained in an energy bill in a Spanish household.

This situation reflects the lack of effective control and regulation by the public authorities of a liberalised electrical market dominated by the electrical Spanish oligopoly.

Subsidies for RES

In 2014, Spain had the tenth highest share of RES in electricity generation among the IEA countries (Figure 10).

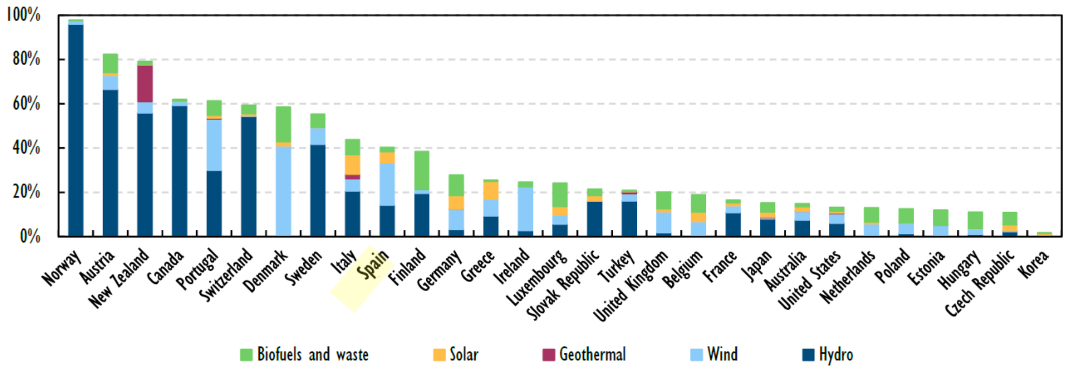

Figure 10: Contribution of RES to the electricity generation in IEA countries (IEA, 2016b).

Thanks to a very favourable policy from the Spanish Government between 2005 and 2012, based on a system of feed-in tariffs and premiums, the installed capacity of renewable electricity increased by 70 %. Currently, wind energy represents Spain's third largest power generation source and contributes with a gross production of around 48 TWh (both in 2016 and 2017), covering around 20 % of the country's electricity demand. For 2020, Spain has the target of producing more than 40 % (Figure 11) of its electricity through RES, mainly wind energy (REE, 2017)

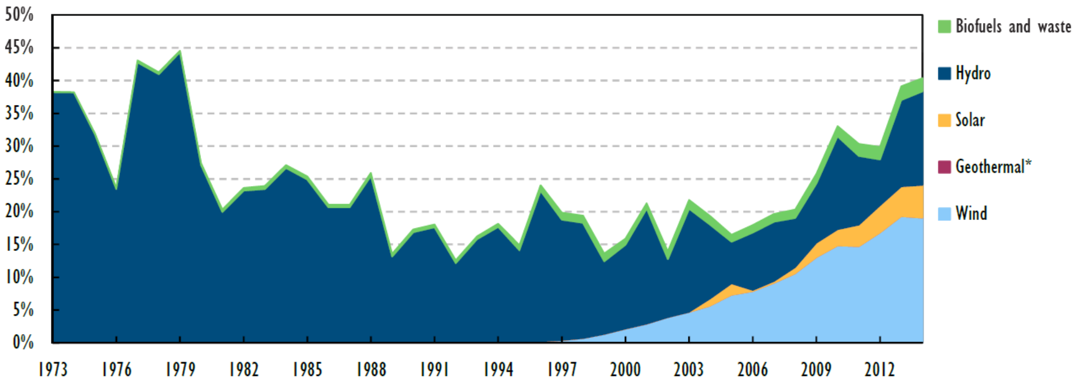

Figure 11: Renewable energy as percentage of total primary energy supply in Spain, 1973-2014 (IEA, 2016b).

However, after a period of exponential growth of RES installations, in 2010 the government introduced several energy policy changes, eliminating the support to RES, with the paralysation of new RES installations in 2012 (Real Decreto ley 1/2012). Furthermore, the government defined a new retribution scheme for RES in 2013 (Real Decreto 413/2014), which included retroactive cuts in economic support for existing plants, by restricting the maximum number of productive hours per year. These policy changes have basically interrupted new RES investments and deployments in the country. Additionally, they have caused almost 30 lawsuits from foreign investors against the Spanish government.

More recently, a new decree (Real Decreto de Autoconsumo Energético 900/2015) introduced strong barriers for connecting decentralised electricity production, such as PV and other small-scale RES technologies, to the grid. In fact, the decree introduced new taxes (in Spanish *cargo por autoconsumo*) on the electricity produced by these sources and self-consumed by the user. Legal battles are ongoing, some of which are resulting in changes to the legislation. For example, the Spanish Supreme Court declared one of the points of the decree illegal: forbidding group self-consumption from the same generator. At the time of writing (October 2018), the Spanish Government has approved the Royal Decree-Law 15/2018. Among other decisions in this Royal Decree, they have approved the grouped self-consumption model, and rejected the tax charged to the self-consumed share of energy).

In 2017, a new public bidding has fostered more than 5 GW of new RES installations, but the only reason for the public call for tenders was to fulfil the European Directives and reach the 2020 objectives. The bidders required the guarantee to be connected to the grid as soon as their installations are being finished.

At the time of writing (October 2018), there are no direct public subsidies for RES electricity. However, the whole renewable generation is bought at the electricity market pool at a "regulated reasonable price", which could be understood in some cases as an indirect public subsidy for the cheapest technologies. This guarantees a minimum price, just in case the market drops down.

Finally, another important trend in the Spanish market in 2018, considering the regulatory insecurity and the market volatility, was the increase of Power Purchase Agreements among retailers and producers or big consumers and energy producers. The CO_2 cap & trade increasing the market's price is fostering these private contracts.

Imports and exports of electricity

In 2017, around 96.4 % of the electricity demand was covered by national generation. Cross-border exchanges are constant, with a total balance (Figure 12) which differs depending on the country: Spain imports electricity from France and Portugal, and exports to Andorra and Morocco.

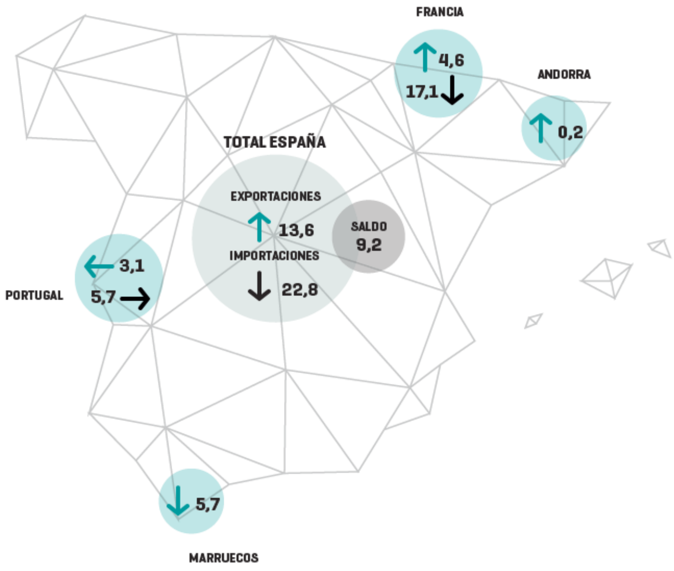

Figure 12: International electricity exchanges in 2017 (GWh) (REE, 2017).

After some years of continuous exports, Spain is currently a net importer of electricity (Figure 13), and it seems unclear whether this situation will change in the coming years.

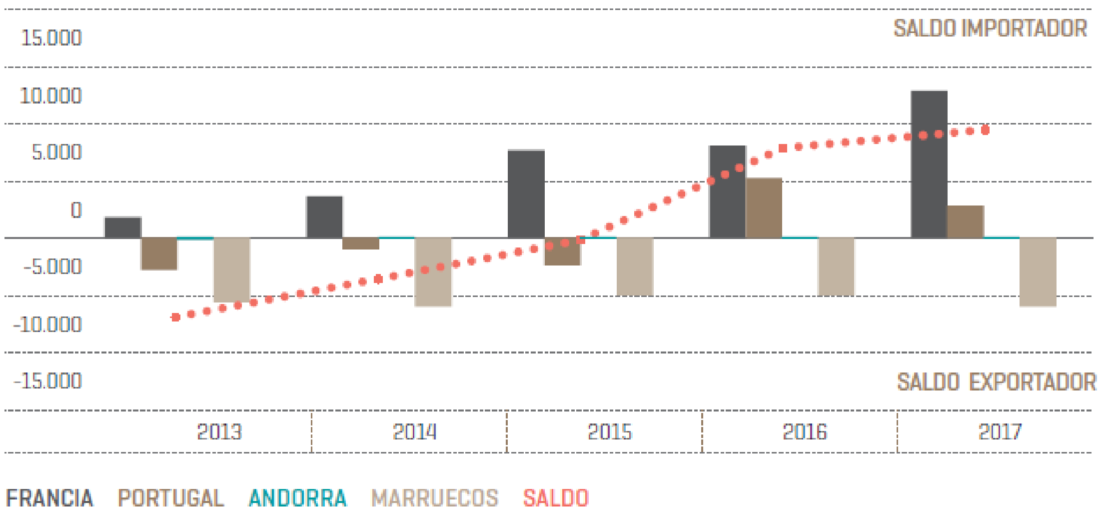

Figure 13: International electricity exchanges comparison (GWh) (REE, 2017).

The total interconnection capacity represents 6 % of the installed generation capacity (6 GW of around 100 GW). The EU recommends increasing this amount to 10 % between the countries. There are some projects like the Spain-France submarine interconnection, but these projects do not attract public acceptance.

Wholesale market

The Spanish wholesale market comprises an organized market: the spot market managed by OMIE (Operador del Mercado Ibérico Español), the electricity market operator, and a non-organized market for bilateral trade.

The regulated market is composed of a series of markets, where market agents buy and sell electricity. This market includes a day-ahead market followed by six intraday auctions. Although the continuous hourly market has been adopted recently, the participation nowadays is marginal. Most of the operations happen around the OMIE, where short-term operations take place. The geographical scope of the market is the entire Iberian Peninsula, i.e. Spain and Portugal have an integrated market. As explained before, it is all integrated in the MIBEL market. The day-ahead spot market is currently coupled with Portugal and the North-West Europe region.

Concerning the non-regulated market, physical bilateral contracts or PPA are possible between consumers and producers qualified as such on the spot market. In order to participate in this non-regulated market, it is mandatory to be a 'market subject' in the Spanish Electrical Law. What changes is the way the two sides design and agree a 'market-price' but they must fulfil all the requirements (legal, economic and technical) related to the electricity market.

Concerning the wholesale power market in the Spanish zone, around 253 TWh were sold in the day-ahead spot market (192 TWh excluding bilateral agreements), while 31 TWh were sold in the intraday market. The weighted average spot market price was around 60.6 €/MWh in 2017 (25.1 % higher than in 2016), and the daily market price has represented 88 % of the final price of the electricity market, while the remaining 12 % corresponds to the intraday market price and some system services, like reserve capacity services (Figure 9). The share of bilateral agreements is around 24 %, with no significant evolution from last years (REE, 2017).

From the demand point of view, Spain has a poorly flexible system regarding load management. The only program that allows demand management is the interruptible service provided by the Spanish TSO (Red Eléctrica de España – R.E.E.). The new regulation for this service introduces a competitive allocation mechanism managed by the TSO. An auction system with face-to-face bidding is used to allocate the service. Two interruptible capacity products are auctioned: a first one consisting of reductions in consumption of 5 MW and another of 90 MW. Besides the interruptible demand service from the demand side, the TSO allows other ancillary services to power producers, such as power reserve, load control (there are 3 different mechanisms to participate, depending on the temporal horizon of the response) and voltage quality service. According to the TSO, all the ancillary services have an impact on electricity generation costs of 2.4 €/MWh(REE, 2017) .

2.1.3. Social factors

Given the current market structure, customer engagement has been difficult. The dominant position of the former monopolies in the market and the growing concern of the Spanish citizens towards these companies means that cooperation between customers and companies is not usually welcome.

However, some interesting initiatives have started, driven by the market liberalisation, in which final users become active and conscious customers, more involved and engaged in the electricity market in different ways.

These initiatives were developed as energy cooperatives. The first cases date back to the beginning of the 20th century, when the first DSOs were created by municipalities. Some of these cases have prevailed, mainly in the Valencia region. In Europe, these types of cooperatives flourished after the energy crisis in the 1970s, but not in Spain. After market liberalisation, the third wave has started in Spain regarding energy cooperatives. In 2010, the first of these new initiatives was SOM ENERGIA in Catalonia. Afterwards GOIENER was created in the Basque Country and Navarra. Currently almost all the cooperatives have joined the *Union Renovables* association, and they gather more than 100,000 consumers, sensible to RES (Ateneo de Energia, 2018).

These cooperatives are joining the RESCOOP.EU model and trying to spread a new energy model based on renewable electricity consumption and production, including some shared reinvestment of economic profits (RESCOOP.EU, n.d.).

Even if these new initiatives are changing public opinion on electricity and energy markets, market liberalisation is characterised by lack of transparency for the final users. This tendency is also witnessed by a general lack of confidence from users towards retailers and operators, concerning billing accuracy and fear for extra costs (Stoneman, 2016).

In recent years, following social empowerment and cost reduction of RES technologies, an increasing number of citizens installed RES production units in their homes, even though they cannot satisfy their energy needs mainly because of intermittence of generation and the unfavourable regulation (self-consumption coupled with export of excess electricity from local generation is forbidden).

2.1.4. Technological factors

Current situation

After some years of continuous decrease, the electricity demand in Spain has increased in the last three years (Figure 14).

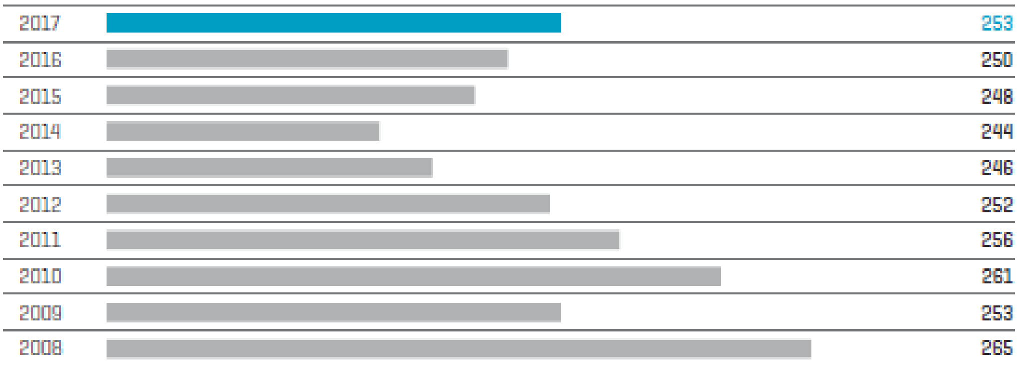

Figure 14: Evolution of peninsular electricity demand at power station busbars in peninsular Spain (in TWh) (REE, 2017).

The maximum energy demand is in winter and has two main peaks, one at around 12 a.m. and the other at around 9 p.m., as shown in Figure 15.

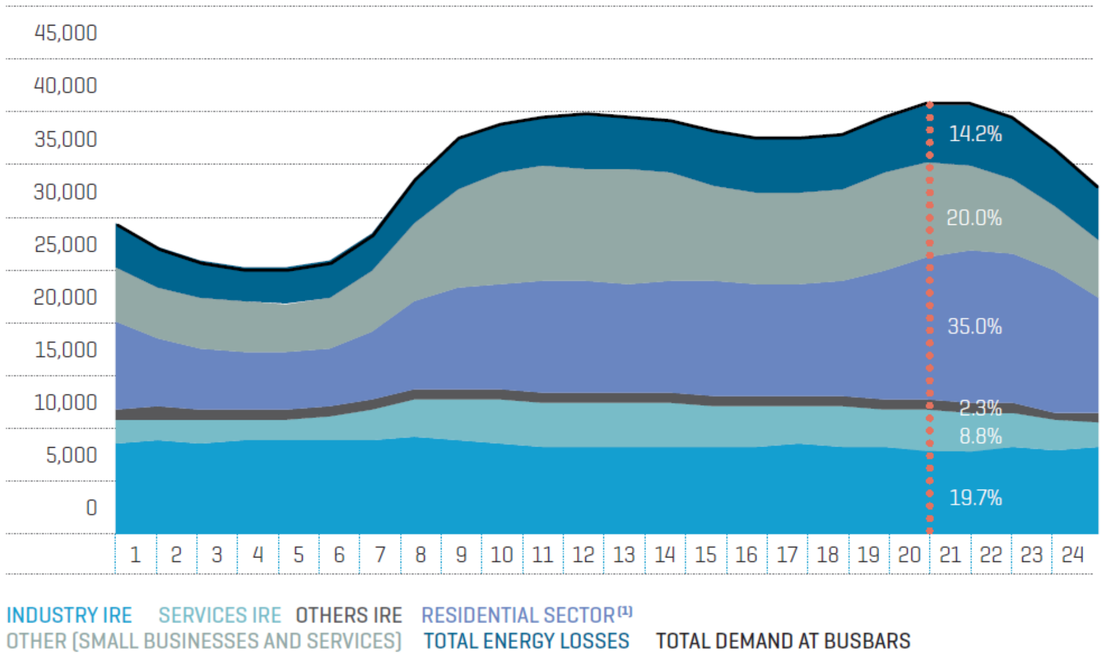

Figure 15: Breakdown of the electricity maximum hourly electricity demand in January 18th (MWh) (REE, 2017).

The primary energy supply in Spain (Figure 16*Figure 16*) is characterised by a low share of renewable energy production.

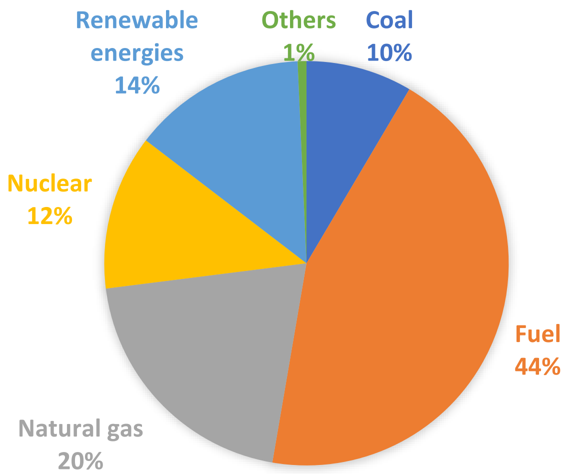

Figure 16: Spanish Primary Energy Mix, total = 123.446 ktep (REE, 2017).

Concerning the electricity generation mix, RESs (Figure 17) have a more significant share, even if their contribution has been reduced from 2016.

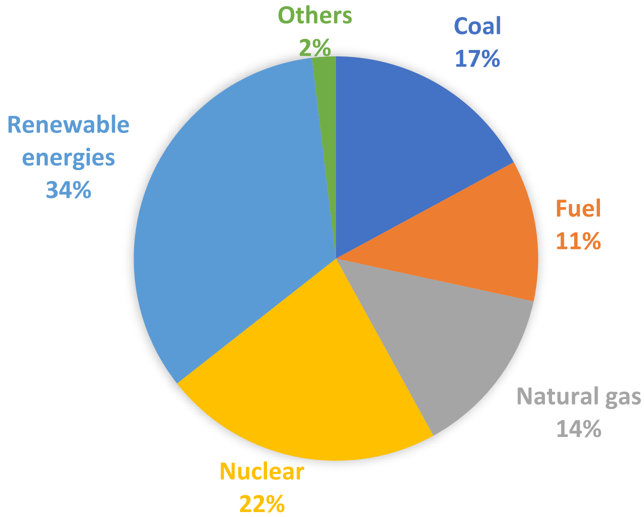

Figure 17: Spanish Electrical Energy Balance, total = 262,645 GWh (REE, 2017).

The contribution to RES electricity in the generation mix is strongly affected by weather conditions, which influence the performance of hydro-power plants and wind farms (Figure 18).

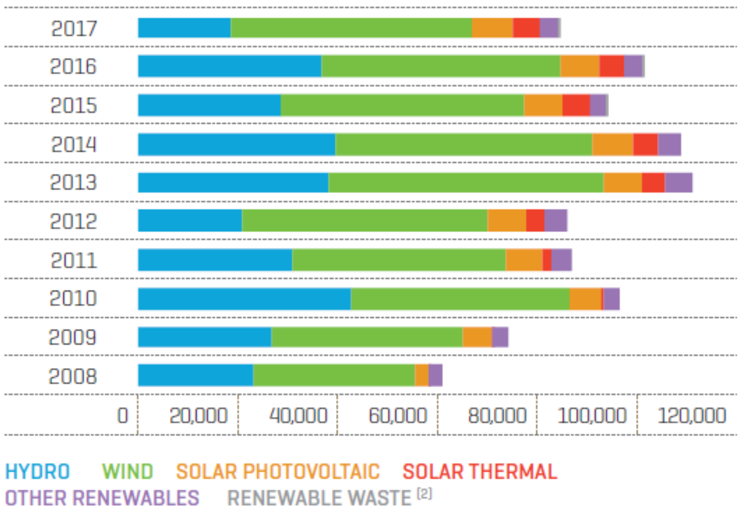

Figure 18: Evolution of renewable electricity generation share (GWh) (REE, 2017).

Wind electricity production represents around 20 % of the national electricity consumption and in 2017 it was the second largest electricity source. However, the ability of dispatching the whole wind potential is still an issue to be solved. The Spanish TSO (Red Eléctrica de España – R.E.E.) pointed out that depending on the energy demands, the Spanish system could not use the entire renewable electricity production and that 2 % of this electricity could be wasted. Already since 2008, wind farms have been disconnected in several occasions at night-time due to low demand. The Spanish TSO has also expressed the need to optimise the existing pumped storage as a way to accommodate wind electricity production.

Electrical grid

The transmission grid includes around 20,000 km of high voltage 400 kV lines and around 20,000 km of <220 kV, as seen in Figure 19.

The Spanish TSO Red Eléctrica de España (R.E.E.) is certified as an ownership-unbundled TSO. It is a publicly listed company, and to guarantee its independence, ownership in it is limited by law. The state has around 20 % of the shares, while the other 80 % is diversified with multiple small owners (the largest one has around 3 % of shares) (IEA, 2016b).

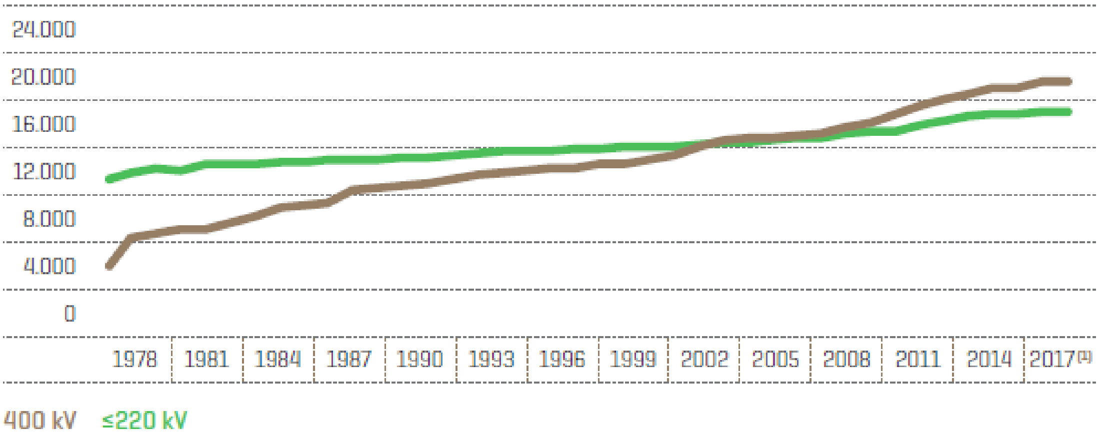

Figure 19: Evolution of the electricity transmission network in peninsular Spain (in km) (REE, 2017).

R.E.E developed an operation unit (called CECRE) integrated in the main control centre to manage RES generators with a minimum nominal power of 5 MW. CECRE is equipped with sufficient control and command capacity to act as aggregators of information with nearly real-time communication (12 seconds) with facilities. This is a powerful instrument to maximise renewables dispatch, but further steps are needed for a full implementation.

The DSOs are responsible for operating, maintaining and developing the distribution network, which is used by retailers (supply companies representing end-users) for delivering electricity to end-users.

Some improvements on the energy grid have been undertaken related to electricity metering. The most important one is a full rollout of smart meters, which should replace conventional meters. The substitution should have been done in three phases, the first one with 35 % of the meters to be changed between 2011 and 2014, 35 % more between 2015 and 2016 and the last 30 % between 2017 and 2018. However, the last data from the "*Informe de Seguimiento y Aplicación de los Datos Procedentes de Equipos de Medida Tipo 5 correspondiente al año 2017*" (CNMC, 2018) showed that at that moment, there were 25.8 million smart meters (91 %) in place, which is very plausibly the whole deployment to be done by the end of 2018.

This smart meter system denoted as AMI (Automated Meter Infrastructure) has not been considered as a remote reading only, but also as a bidirectional communication channel between DSO/Supplier and Customer. However, the three main DSOs today in Spain are adopting their own protocols and standards for metering: PLC Prime, Meters and More, Cosem, limiting the possibilities to deploy new services by third parties.

Future scenarios

The recent political change in the Spanish Government (July 2018), after seven years of conservative management, opens the door to significant regulation changes. However, there is not enough information on what the main milestones of the new government will be concerning the energy transition. The lack of any clear energy strategy for the short and long-term also introduces important uncertainties on the future evolution of the electricity sector. Only a draft of a “Climate Change and Energy Transition Law” has been presented mid-2018 at the Spanish Parliament, but the change on the government team should introduce significant delays on its final approval. Some of the drafts that are circulating among the sector professionals include initiatives like these:

- 2030 objectives: Final energy consumption (35 %); electricity from RES (70 %); GHG reduction referred to 1990 (20 %); energy efficiency improvement (35 % at least);
- Electrical system 100 % renewable by 2050;
- Considering energy efficiency:
    - Between 2021 and 2030, 100,000 household/year refurbishment,
    - Long term refurbishment strategy in order to reduce the energy consumption,
    - Fostering RE use in buildings.

There is also uncertainty related to the key concept of reasonable return; the reform of the electricity system undertaken in 2013 removed the FIT scheme to promote the RES, and the new scheme introduced the concept of “reasonable return”. This regulated “reasonable return” is used to set the minimum price that the RES technologies will receive on the electricity market pool. Currently fixed to the national bond rate of +3 %, it could be modified unilaterally by the government by 31/12/2019.

The new government wants to tackle the shutdown of nuclear plants that are already at the end of their technical lifetime but considering a longer life (more than 40 years). It is not clear how they will tax fossil fuel consumption (coal plants have a significant share on electricity generation).

Distribution Control Centres are implementing updated solutions for a better monitoring and control power sources and ADMS (Advanced Distribution Management Systems) are becoming tangible assets today.

2.1.5. Environmental factors

In 2015 (Figure 20), the total GHGs emissions in Spain were 335.6 Mton of CO_2-eq, with the energy sector (77 %) being the main contributor, followed by agriculture (10 %), industry (9 %) and waste (4 %). That means an increase of around 4 % compared to 2014. Compared to 2007, the total emissions have decreased by more than 20 %.

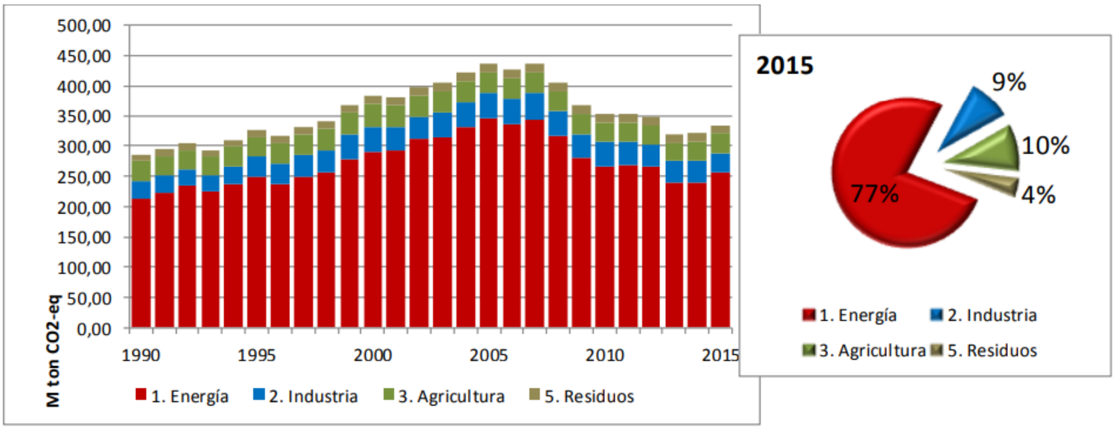

Figure 20: Yearly total GHG emissions by sector (Ecológica, 2017).

The main GHGs emission activities are transport (26 %) and electricity generation (21 %). Carbon dioxide is the main GHG (Figure 21) and represents 81 % of the total CO_2-eq emissions.

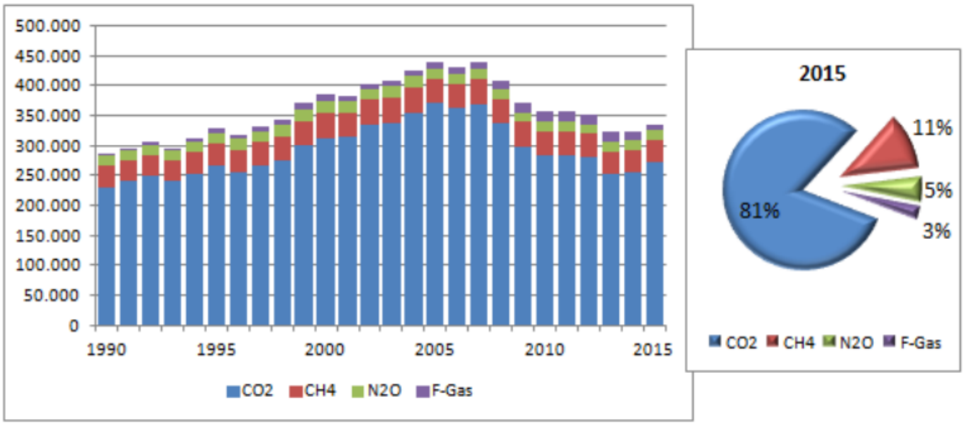

Figure 21: Yearly GHG emissions by gas (Ecológica, 2017).

2.1.6. Legal factors

In Spain, several legal factors are affecting the performance and flexibility of the electricity market and the development of cost-efficient solutions. Electrical energy storage (EES) does not have a clear legal framework, with almost no behind-the-meter electricity storage initiatives. Only indirect storage by hydro pumping is currently being developed.

The current legislative framework, established by Act 24/2013 of the Power Sector, represents the consolidation of the single TSO model in the Spanish Electrical System. This model is protected by some equity limits, which fix the share of capital ownership of the TSO. The same legislative framework sets the unbundling requirements for DSOs in line with the EU Directive 2009/72.

Following this framework, there is only one TSO (Red Eléctrica Española) and 3 main DSOs (Endesa, Iberdrola and Gas Natural Fenosa).

Aggregation is not legal in the Spanish electricity system and the demand-side resources are not allowed (they cannot provide upward/downregulation by deviating from their committed consumption schedule) to participate in the electricity market. There is just one scheme allowing the explicit demand response: the interruptible load scheme, which has not been called for several years. The scheme, which is reserved only for large consumers connected to the high voltage network, is managed by the TSO. The programme acts as an emergency action, in case the system lacks generation and there are insufficient balancing resources.

The rest of the balancing and ancillary services can only be accessed by generation, affecting the flexibility of the current Spanish electricity market.

The TSO and relevant stakeholders have started conversations for the future opening of these services to flexible demand. Spain is the first country in the world where there is an electricity tariff for households (i.e. Precio Voluntario al Pequeño Consumidor, PVPC) based on hourly spot prices, which opens the possibility for users to modify the demand considering market prices, thus overcome the demand aggregation issue. This price can be chosen by consumers with less than 10 kW of contracted power, and it is a way to protect the consumers from the free market companies that take advantage of technical unawareness of consumers.

The Spanish regulation for distributed generation power curtailment requires the DSOs to request the TSO to reject a distributed RES generation schedule as part of the network constraints solution process conducted by the TSO to the day-ahead market solution. In any case, the final decision to reject that distributed RES generation schedule belongs to the TSO. Only in the case of an emergency, the DSO can remotely trigger a relay (compulsory for installations larger than 5 MW), isolating the generation unit from the grid.

In the same way, the Spanish regulation for reactive power injection defines a general calendar and timetable aimed to adjust distributed generation reactive power through incentives. Both calendar and timetable are defined at the power system level irrespectively of the effect on the distribution network.

2.1.7. Heating sector – District Heating

Currently in Spain, there are 352 DH networks, with a vast majority of small urban closed networks (as Ispaster), with a total length of 600 km (ENERGIAS RENOVABLES, 2018) and a capacity of around 1,280 MW which supply around 4,400 buildings. The development of DH since 2013 has been quite important, with a total increase from 2013 to 2017 of more than 150 %, as shown in Figure 22.

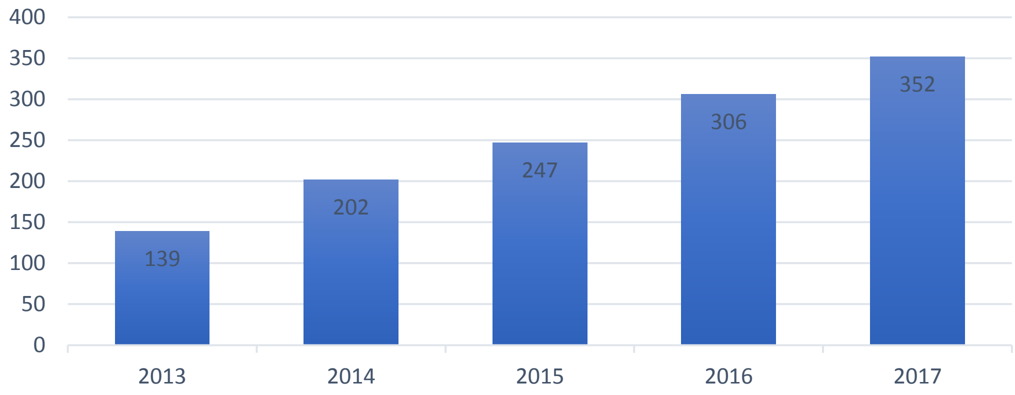

Figure 22: Historical evolution in the number of installed DH networks (ADHAC, 2017).

Most of them deliver energy to the tertiary sector, as represented in Figure 23. About 75 % of the heat for DH is generated by RES, mainly biomass (73 % of the heat supply).

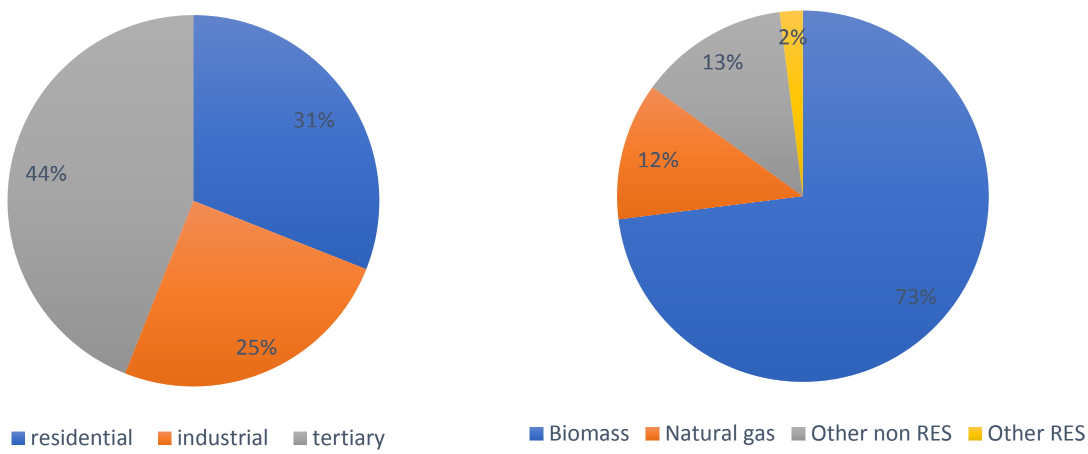

Figure 23: Installed power per sector and energy source in the DH (ADHAC, 2017).

Only 20 % of the DH networks are entirely owned by the public entities; 40 % is completely privately owned and the remaining 40 % present a mixed ownership (public and private). DH networks with mixed ownership are conceived following two main business models: public concession (with a private company responsible of the construction, operation and maintenance of the system) or public-private partnership (at least 5-year agreements, where the private company is responsible for operation and maintenance, while construction cost is shared between public and private partners).

2.2. Denmark

2.2.1. Political factors

From a political perspective, the Danish electricity market is affected by the long-term goals and objectives that the national government has set for the entire energy sector, which also includes heat generation and transport sector.

In 2012, the Danish government drew up an energy agreement with the large majority of the Parliament with the aim to completely get rid of fossil fuels by 2050 (Danish Ministry of Energy Utilities and Climate, 2012). A new Energy Agreement was signed on 29 June 2018, according to which the 2050-target was abandoned (Danish Government, 2018), although it was agreed that Denmark will aim at a net-zero-emission target by 2050. An intermediate milestone is set for 2030, when coal should be phased out and RES should represent about 55 % of the total demand, 100 % of the electricity consumption and at least 90 % of district heating generation. Financing of the green transition will partly come from the continued exploitation of the oil and gas resources in the North Sea.

To phase out fossil fuels in the near future, Denmark will act on several fronts. A key role will be played by a lower and more efficient energy consumption, with a focus on the residential sector. Secondly, electrification will be strongly encouraged: district heating, individual heating and many industrial processes could be electrified with heat pumps, and in the long term, most of the private transport could switch to electric and hybrid cars. To this purpose, the taxation on electricity will be reduced (Danish Government, 2018). The interconnection across different sectors (not only the electricity system, but also heat, gas and transport) will be promoted through investments for the development of smart grids. Moreover, new interconnectors to the neighbouring countries are under construction or under investigation, such as a connection from Denmark to the Netherlands, one to Germany through the offshore wind farm of Kriegers Flak and the DC Viking Link between West Denmark and the UK (Figure 24). Thirdly, RES (biomass, biogas, wind and solar) will be promoted and supported for both electricity and heat production, but subsidies will be phased out as the technologies become competitive on market terms. An important role is recognized for offshore wind energy, which should develop further in the coming years with new and larger wind farms with an installed capacity of about 800 MW each (Danish Government, 2018). Finally, investments in research, development and innovation are expected to improve existing technologies and to overcome challenges such as efficient electrical energy storage (EES), smart regulation of the electrical grid and green means of transportation (Danish Government, 2011; IEA, 2017a).

Besides its own targets, Denmark has commitments under the United Nations Framework Convention on Climate Change and EU regulations. These include (IEA, 2017a):

- reduction of GHG emissions from non-ETS (ETS=Emission Trading Scheme of the EU) sectors by 20 % by 2020 compared to 2005. The target is projected to be reached;
- increase in the share of RES in gross final energy consumption to 30 % by 2020 (it was 16 % in 2005). The target is expected to be overachieved based on current trends;
- share of RES in land-based transport of at least 10 % by 2020. It is projected that existing measures will lead to 9 % by 2020.

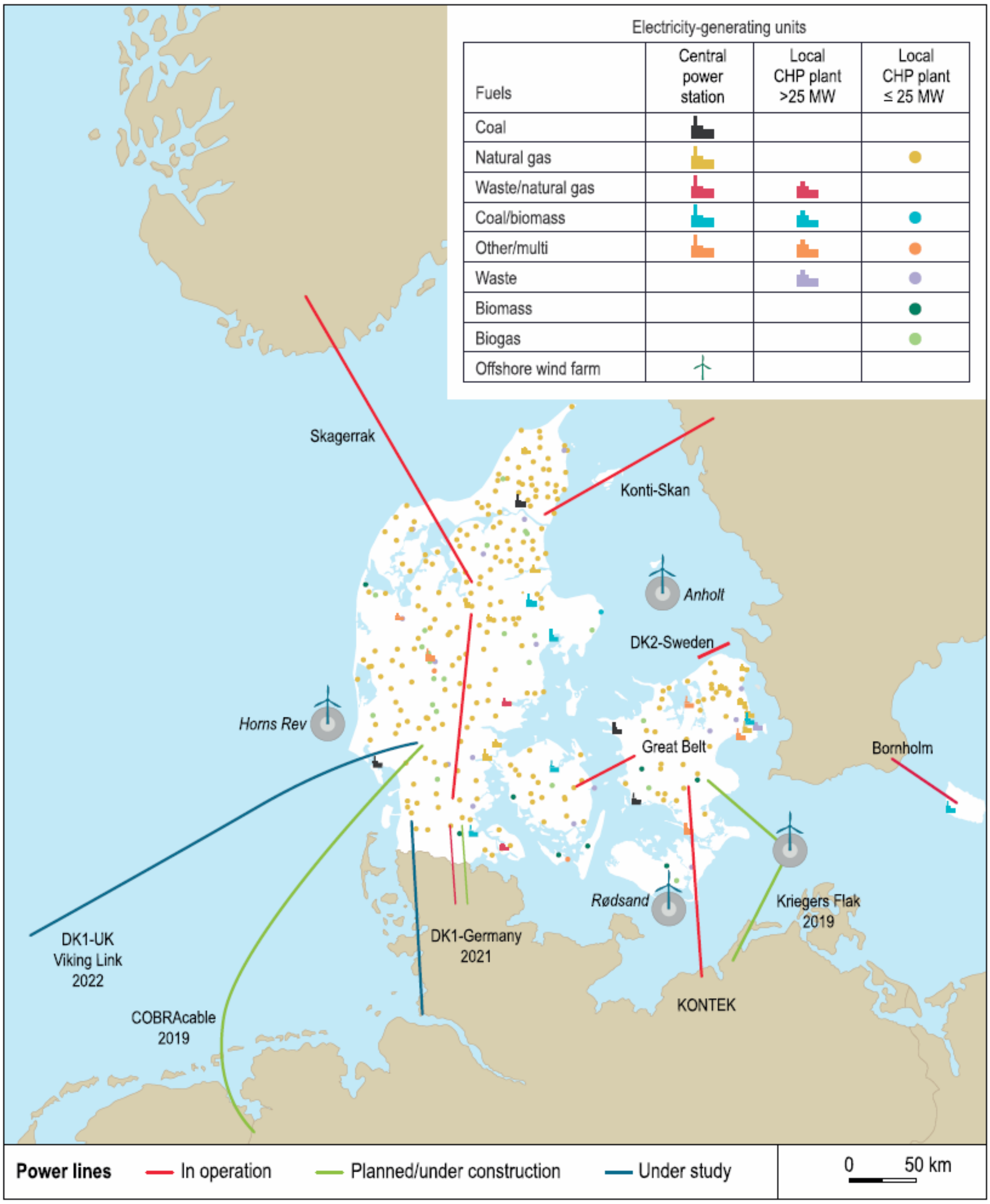

Figure 24: Present and future transmission lines between Denmark and neighbouring countries (IEA, 2017a).

2.2.2. Economic factors

General economic situation

Denmark's economy grew by 2.2 % in 2017, while a growth of around 1.8 % is expected for both 2018 and 2019. Private consumption grew by 1.5 % in 2017, and it is expected to increase by 2.0-2.2 % in 2018 and in 2019. The unemployment rate was 5.7 % in 2017 and should further decrease to 5.2 % in 2019. Difficulties in finding skilled workers are encountered in several sectors (European Commission, 2018).

Investments have expanded at a solid pace and recorded a 3.7 % growth in 2017, driven by the housing and machinery sector. Investments in machinery and equipment are expected to grow by around 4.4 % over the coming years, due to growth in Denmark's main export markets. Moreover, public investments fell by 8.4 % in 2017, as these had previously reached historical high levels (European Commission, 2018).

Inflation increased by 1.1 % in 2017, but is forecast to dampen to 0.8 % in 2018, also due to the lowering of various taxes. Consumer prices are forecast to rise by 1.4 % in 2019, on the back of solid wage growth. Public gross debt should decline from 36.4 % of GDP in 2017 to 32.3 % in 2019, due to a reduction in the general government's cash reserves, low interest rates and economic growth (European Commission, 2018).

Energy-related industry

Enterprises operating in the green energy sector have been positively affected by the ongoing energy transition toward a low-carbon society. Danish enterprises operating in the energy sector have been successful on the global markets and in 2016 exported technology and equipment (wind turbines, DH pipes, pumps, etc.) for about 10 G€, corresponding to 12 % of Denmark's total exports (Danish Energy Agency, 2017). Among the exported technologies, those related to wind energy have a major role. In 2014, the turnover from the Danish wind industry was about 11 G€, of which about 7 G€ came from export. In the same year 29,000 people were employed in the industry (Ministry of Foreign Affairs of Denmark, 2015). As production of renewable energy is generally more labour intensive than conventional energy production, employment in the energy sector is expected to keep on growing.

Energy taxation

Energy taxes are an important source of revenue in Denmark, but also an instrument to influence the behaviour of consumers and suppliers. Energy taxes were introduced in the 1970s at the time of the energy crisis, to reduce the demand for fossil fuels and promote energy efficiency. When oil and gas prices dropped at the end of the '80s, the tax level was increased for these fuels, so that consumers continued to be motivated to use energy in a responsible way and prefer environmentally friendly energy sources (Danish Energy Agency, 2016c).

In 2018 the following energy taxes were present in different applications: energy tax, CO_2 tax, NO_x tax, SO_2 tax and PSO levy. An overview of such taxes is presented in Table 1 for the industrial and power generation sector. All values reported for industrial purposes refer to 2018 and can be looked up online (Danish Energy Agency, 2018c; Danish Ministry of Taxation, 2018). Values of taxation on power generation were retrieved from (Danish Ministry of Taxation, 2016).

Fossil fuels for electricity and/or heat generation are subject to an energy tax. Biomass fuels are not taxed, which gives Danish electricity producers and DH companies an incentive to use biomass rather than fossil fuels. Industrial excess heat that is used for heating is also taxed. Industrial excess heat is also taxed. The industrial excess heat tax is effectively payed by the company that generates the heat. However, a company selling industrial excess heat to a DH network would likely require a reimbursement for this tax from the DH company. Additionally, fossil fuels and biomass are subject to taxes related to the emissions arising from their combustion.

Regarding the NO_x tax, companies which do not measure the NO_x emissions pay taxes based on fuel consumption. Otherwise a tax of 0.68 €/kg_{NOx} is paid on the amount of the emitted NO_x.

The SO_2 tax is expressed in terms of sulphur content in the fuel for fossil fuels. However, a tax compensation is paid, if the emission of SO_2 is reduced through the capture of sulphur. For biomass, the tax is always based on the amount of the measured emitted SO_2.

The CO_2-tax, introduced in 1992, applies to several types of energy products according to their CO_2 intensity, but industrial processes benefit from a tax reduction. In 2010 the CO_2-tax scheme was modified, and the tax was increased following the EU-ETS. In 2013 waste incineration plants were included in the EU-ETS and, therefore, exempted from the CO_2-tax to avoid double taxation (IEA, 2017a).

Table 1: Taxation for different energy applications in 2018.

	Energy tax	CO_2 tax	NO_x tax	SO_2 tax	PSO
Industrial Processes					
Fuel Oil	0.60 €/GJ	1.86 €/GJ	0.09 €/GJ	3.14 €/kg_S	0
Natural Gas	0.60 €/GJ	1.37 €/GJ (+0.23 €/GJ if used in an engine)	0.03 €/GJ (+0.08 €/GJ if used in an engine)	3.14 €/kg_S	0
Coal	0.60 €/GJ	2.20 €/GJ	0.07 €/GJ	3.14 €/kg_S	0
Straw, Wood, Etc.	0	0	0.07 €/GJ	1.57 €/kg_{SO2}	0
Electricity	0.53 €/MWh	0	0	0	19.7 €/MWh
Power Generation					
Within ETS sector	0	0	0.07 €/GJ	0-0.67 €/GJ	0
Outside ETS sector	0	1.30-2.16 €/GJ	0.07 €/GJ	0-0.67 €/GJ	0

The PSO levy on electricity was introduced in 1999 to finance the expansion of renewable electricity. It is added to the electricity bill, hence paid by all consumers. In 2016 —when about 1 G€ was collected through this levy (Danish Energy Agency, 2017)— the Parliament decided to gradually phase out the PSO over the period 2017-2021 and support the development of RES through the national budget (IEA, 2017a).

Energy saving initiatives by energy companies (see Section 2.2.6) are financed via grid tariffs, therefore through energy bills sent to consumers (Danish Government, 2011).

Due to the heavy taxation, the final prices of energy in Denmark are among the highest in Europe, despite the relatively low production costs. For example, Denmark has one of the lowest prices for natural gas before taxes (Eurostat, 2017c), while its final price is one of the highest in Europe. When using natural gas in a CHP plant, the total taxation makes this fuel approximately twice as expensive as the gas itself (Bava, 2017).

Considering electricity, in January 2016 a household consuming 4000 kWh/year paid in taxes (VAT included) about 71 % of the electricity bill, while an industry consuming 100 MWh/year paid in taxes (VAT excluded) about 41 %. The average electricity price was 295 €/MWh (VAT included) for households and 119 €/MWh (VAT excluded) for industrial consumers (EA Energy Analysis, Energinet.dk, & Danish Energy Agency, 2017). Prices are progressively lowering, with the PSO being gradually phased out. Another recent example of a lowering of the electricity tax is that the tax level for electricity used for heating is being lowered, giving increased incentives for using large-scale heat pumps for heat generation in DH.

Subsidies for renewable energy sources

The wind power sector has always received support from the State, although the subsidy schemes have changed over time. The current scheme for onshore wind turbines took effect on January 1st, 2014. A ceiling on the sum of the market price and the feed-in-premium was introduced. Hence, onshore wind turbines connected to the grid from 2014 receive a feed-in premium of 3.35 c€/kWh with a ceiling of 7.78 c€/kWh. The feed-in-premium is paid for the first 6600 full-load hours plus an amount of electricity, which is a function of the rotor swept area. The dependence on the rotor size was introduced to promote the most beneficial relation between nominal capacity and production (EA Energy Analysis et al., 2017).

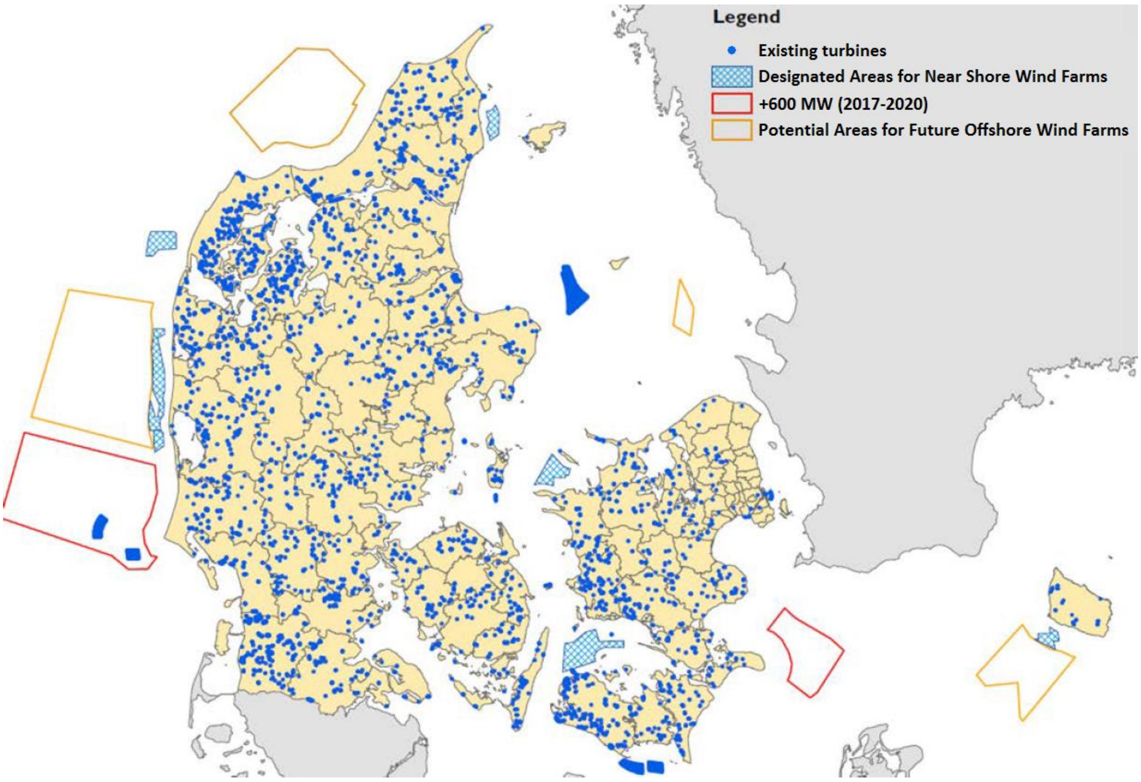

Figure 25: Onshore and offshore wind turbines in Denmark (EA Energy Analysis et al., 2017).

Regarding offshore wind power, two different schemes are possible. In the open-door scheme, a project developer submits an unsolicited application for a license to carry out a preliminary investigation for an offshore wind farm in a specific area. Offshore wind turbines under the open-door scheme receive the same support as onshore wind power. The developer pays for the transmission line to land.

Special large offshore wind farms are developed and supported differently. These are commissioned through a call for tenders, announced by the Danish Energy Agency for a specific area and a certain installed capacity. The applicants submit a quotation for the price at which they are willing to produce electricity in the form of a fixed feed-in tariff (FIT). The cheapest price wins and the winner receives his bid as a guaranteed fixed FIT for the first 50,000 full-load hours, after which he receives the market price only (EA Energy Analysis et al., 2017).

However, the subsidy system for wind power may change again in the near future, because the sector has reached a level of development that it may be soon able to stand on its own without public support (Danish Government, 2018).

A map of the onshore and offshore wind turbines installed in 2017 and potential areas for future development is shown in Figure 25.

Biomass is exempt from most taxes (see Table 1), and additionally electricity produced from biomass receives a premium of 0.02 €/kWh on top of the market price. Biogas is also supported, but through complex and different schemes. Support does not depend on the biogas production, but on its use (e.g., upgrading to natural gas grid, production of electricity, industrial processes, transport purposes, heating, etc.) and on the natural gas price (IEA, 2017a). For example, electricity producers using biogas can receive support in the form of a fixed FIT or a surcharge on the electricity market price. More information on the support schemes for biogas can be found online (Danish Energy Agency, 2018e). These support policies have been fairly effective, and many biogas plants have been built in the recent years (Figure 24).

Import and export of electricity

As mentioned in Section 2.2.1, there is strong interchange of electricity between Denmark and the neighbouring countries (Norway, Sweden and Germany). The amount and direction of the exchanged electricity is determined by the different electricity prices in the different countries and by the capacity of the interconnectors. In 2015, Denmark was a net importer of electricity for 5.9 TWh, which represented 17 % of total supply (highest net import since 1990). Denmark was a net importer from Sweden (3.6 TWh) and Norway (5.0 TWh), and a net exporter to Germany (2.7 TWh). This was also due to the high electricity generation from hydroelectric plants in Sweden and Norway.

Denmark typically has a generation surplus in winter, when the wind blows more and there is electricity production from CHP plants, which operate to cover the heat demand of the DH networks. On the contrary, there is a generation deficit in the summer months.

Wholesale market

Most of Danish electricity is bought and sold on the Nordic electricity market Nord Pool, which also includes Norway, Sweden, Finland, Estonia, Latvia and Lithuania. Overall, more than 75 % of the electricity consumption in the Nordic countries is traded on the Nord Pool market (Danish Energy Regulation Authority, 2018). Nord Pool has two markets: Elspot, the day-ahead market; and Elbas, the intraday balancing market. Most of the trading takes place in the Elspot market: in 2016, Elspot purchases in Denmark were 31.2 TWh, while Elbas purchases were 0.9 TWh.

Nord Pool is part of the Multi-Regional Coupling, so it is coupled to the rest of Europe. This means, among other things, that wholesale prices in Nord Pool and the rest of Europe should reflect the expected direction of power flows.

Wholesale prices in Denmark tend to be higher than in the rest of the Nordic region, but lower than in the rest of Europe. For example, in 2015 the average price in Denmark was 23.7 €/MWh, compared to a Nord Pool average of 21.0 €/MWh and an EPEX SPOT average of 31.7 €/MWh. This is mainly because Denmark lies between Norway (with its relatively inexpensive hydro) and the rest of Europe (with more expensive thermal generation).

Electric grid services

In addition to selling electricity to the wholesale, electricity producers are also offered the possibility of selling auxiliary services to the electrical grid. These services are purchased by the Danish TSO Energinet.dk. These services are balancing power and frequency regulation. Producers that have power plants that can respond on a short notice (from the order of seconds and up to 15 minutes) can place bids on the balancing power market. Producers that are able to regulate their electricity production within milliseconds to seconds can place bids on the frequency regulation market. In case the electricity production of the CHEST system is able to respond on such short time scales, there could be possibilities of additional revenue to the CHEST system operator by selling grid services to the TSO.

2.2.3. Social factors

The Kingdom of Denmark consists of Denmark and the two autonomous constituent countries of Greenland and the Faroe Islands. In 2018, Denmark had a population of 5.75 million, not including Greenland (56,300) or the Faroe Islands (49,700). The current population growth rate is about 0.4 % per year.

Danish society has traditionally been keen on sustainable and renewable energy technologies. At the start of the wind industry in Denmark in the late ‘70s, the initiatives to erect wind turbines came mainly from local citizens. The early ‘80s saw the creation of many cooperatives of small communities, who jointly invested in a shared wind turbine and received support through a tax incentive, if they generated electricity to the local community. The local support for wind power has been difficult to maintain, as the wind sector has evolved towards large wind turbines owned by utilities. Despite the general favour of the population towards RES projects, many cases of the so called NYMBY (Not In My Backyard) syndrome have occurred, with the strong opposition of local communities against the installation of wind farms close to their homes (Tortzen, 2012). Because the support of the local community is essential to ensure development of wind power, initiatives to secure local involvement have been taken in more recent years, e.g. the option for private people to purchase shares of new wind power projects built near their homes (in Danish “Køberetsordningen” (Danish Energy Agency, 2018b)), and —until February 2018— the possibility for a municipality hosting wind power installations to apply for funds to promote initiatives aiming at increasing the acceptance from the local community (in Danish “Grøn ordning” (Danish Energy Agency, 2018a)).

The 2018 Energy Agreement pays much attention to the social acceptance of wind turbine projects: the distance from the coastline within which a municipality can make opposition against the installation of an offshore wind farm was extended from 8 km to 15 km. Additionally, according to the Agreement the number of onshore wind turbines should be halved by 2030 (Danish Government, 2018). The installed capacity will, however, not be halved, because old, smaller turbines will be decommissioned, to give space to fewer but larger new turbines.

2.2.4. Technological factors

Current situation

The Danish electricity system is characterized by a high share of RES. In 2016 the gross electricity generation was 30 TWh, with a generation mix composed mainly of wind energy (42.5 %), coal (28.8 %), biofuels and waste (17.9 %), natural gas (7.3 %), solar (2.5 %). In 2015 the electricity consumption was 31.7 TWh and the peak load 5.6 GW, against an installed capacity of 14 GW

(Figure 26). Of the installed capacity 57 % is represented by combustible fuels plants and 36 % by wind turbines (IEA, 2017a).

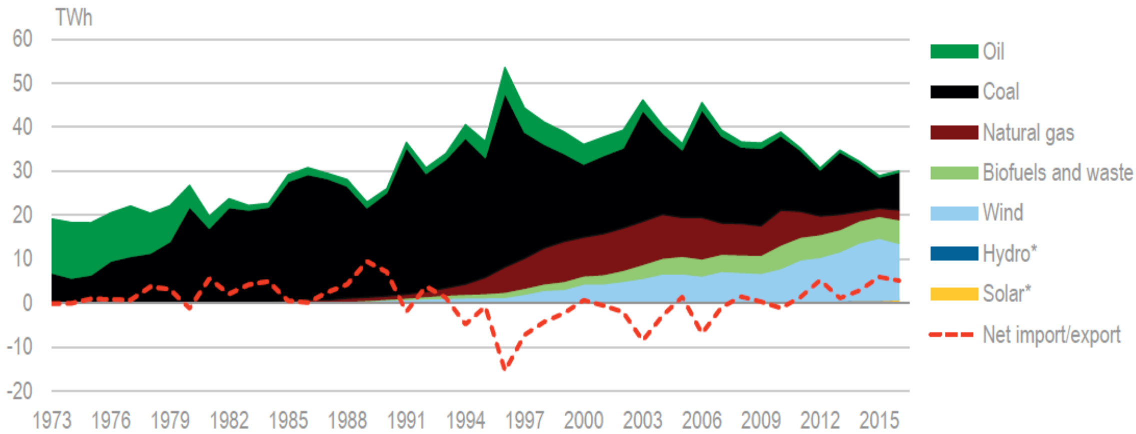

Figure 26: Gross electricity generation by source, 1973-2016 (IEA, 2017a). *Asterisk * in the legend denotes negligible contribution.*

In 2017, wind energy production set a record, representing 43.4 % of the national electricity consumption (Danish Ministry of Energy Utilities and Climate, 2017). Despite the high share of this fluctuating energy source, the electrical grid has proven to be extremely reliable. In fact, Denmark, The Netherlands and Germany are the European countries with the shortest periods of electricity interruption per consumer. Among other things, this is also due to the high fraction of the electrical grid which is buried in the ground. In 2017 the average Danish consumer experienced 25 minutes interruption per year (Energinet.dk, 2018).

Natural gas has traditionally been one of the main energy sources in Denmark, but its importance has diminished over the past decade due to the growth of RES. Denmark is a net exporter of natural gas, selling to Germany, Sweden, the Netherlands and buying it from Norway. Power and heat generation remains the largest gas-consuming sector, absorbing 29 % of the total gas consumption, although from 2000 to 2015 natural gas consumption in this sector decreased by 62 %. The second consumer is the industrial sector with 23 % of the total consumption (IEA, 2017a).

Power and heat generation is also the sector where most of the coal (95 %) is used. In 2016 coal contributed to 29 % of the power generation and 12 % of the total primary energy supply. On the other hand, oil has a minor role in the power and heat generation sector (only 1.7 % of the total oil consumption) (IEA, 2017a).

Electrical grid

The 400-kV transmission grid is managed and owned by the TSO Energinet.dk, an independent public enterprise owned by the Danish State, represented by the Minister of Energy, Utilities and Climate. Energinet.dk is responsible for maintaining security of supply and ensuring the smooth operation of the electrical grid. Additionally, the company owns the natural gas transmission network (and through a subsidiary Danish Gas Distribution large parts of the distribution network) and co-owns the interconnectors to Norway, Sweden and Germany together with the relevant neighbouring TSO.

The Danish electricity transmission network is divided into two grids. The grid DK1 (West Denmark) covers Jutland and Fyn and it is synchronized with the rest of continental Europe. The grid DK2 (East Denmark) covers the islands of Zealand and Bornholm and it is synchronized with the rest of the Nordic region. The two grids are connected through the Great Belt Power Link, a 400-kV DC line of 600 MW. Compared to the demand, the generation capacity in DK2 is smaller than in DK1. Therefore, DK2 is often importing power from DK1 (in 2016 DK2 imported from DK1 96 % of the time). The transmission capacity of the Great Belt Power Link is often constrained. In 2016, the thermal limit of the interconnector was reached 32 % of the time, and 52 % of the time the exchanged power was within 5 % of the limit. As a consequence wholesale prices of electricity are generally slightly higher in DK2 than in DK1 (IEA, 2017a).

Of the current six cross-border interconnectors three are with Sweden (one from DK1, two from DK2: Zealand and Bornholm), two with Germany (one from DK1, one from DK2); one between DK1 and Norway (Figure 24). New interconnectors are under construction or investigation (see Section 2.2.1).

Finally, the low voltage (<120 kV) distribution network is operated by 49 relatively small DSOs, serving around 3.3 million customers (see Section 2.2.6).

Future scenarios

In the coming years, wind energy is expected to increase even more, as new wind farms are built, such as Horns Rev 3 next to Esbjerg, Kriegers Flak in the Baltic Sea, North Sea South by Ringkøbing and North Sea North by Harboøre (Danish Ministry of Energy Utilities and Climate, 2017). Additionally, according to the 2018 Energy Agreement, there is a plan for an offshore wind farm of 800 MW to be built by 2027. Calls for tenders for other two offshore wind farms of at least 800 MW each will be held in 2021 and 2023.

Until now, the Danish electricity system has been characterized by a large installed capacity. But with the increasing share of wind and solar electricity, the production from power plants will diminish, also because many of them are reaching their technical lifetime. In recent years, more than 2 GW of older power plants have been decommissioned. This development is expected to continue, so the period of large overcapacity is about to end (Danish Energy Agency, 2014). With high shares of intermittent electricity production and fewer power plants ensuring system stability, the electrical grid will face technological and economic challenges.

First, as electricity cannot be directly stored, there is a need for mechanisms that can increase the flexibility and regulation capability of the grid. These mechanisms must be able to absorb the excess electricity, when there is plenty of wind energy production, and vice versa ensure efficient and secure power supply in case of little wind. Interconnectors already connect Denmark to Sweden, Norway and Germany and new ones are planned (see Section 2.2.1). Therefore, when the wind electricity production is higher than the demand, the excess electricity can be sold to the neighbouring countries, to be instantaneously used or converted in potential energy and stored in the Norwegian water reservoirs. The reservoirs can be emptied later, when required. Through the same interconnectors, electricity can be imported, for example from German solar and wind fields, and Swedish nuclear power plants. This ensures a production price that is one of the lowest in Europe (Eurostat, 2017b). However, the possibility of creating water reservoirs is limited by environmental legislation and/or landscape configuration: for example, Denmark has none, due to its flat landscape. Hence, alternative solutions are likely to attract much attention in the future, e.g. batteries or conversion to gas (e.g. hydrogen or methane) and/or liquid bio-fuels for later use in the electricity sector or in other sectors of the energy system. In this context, an EES technology such as the CHEST concept seems extremely interesting. Currently, however, the Danish TSO do not seem to regard large-scale EES as a priority for the management of the grid, as demand side management (central electric boilers, central and individual heat pumps) and energy storage in electric vehicles batteries are seen as the main tools to match supply and demand (Sorknæs, Mæng, Weiss, & Andersen, 2014).

Secondly, the increase in intermittent renewable electricity production requires a larger transmission capacity to carry electricity away from areas when there is strong wind and low consumption, to areas where there is high consumption and quiet weather. This is a slow but constant development and modernization of the electrical grid, which has already been going on in Denmark for several years. As the grid is restructured, this will be able to handle increasingly larger amounts of wind electricity (Danish Energy Agency, 2014).

Thirdly, the need for power generation from thermal power plants and CHP plants is decreasing (see Section 2.2.6). So, the profit of CHP plants coming from the electricity market is reduced and this increases the cost of the heat for DH. Due to their fast capacity regulation, CHP plants are expected to become more a backup and balancing mechanism than the suppliers of the base load of the electrical grid. CHP plants would run only when the balance of the electrical grid and the electricity prices make their operation profitable. Nevertheless, heating supply is required by the DH network throughout the year. The need to cover the heat demand may force a CHP plant to operate even at low electricity prices. For this reason, in the last years many Danish DH companies have invested in biomass boilers, large solar thermal plants and heat pumps, so to decouple electricity and heat generation.

In the operation of the electrical system, the immediate balance between consumption and production is ensured by the so called “system services”, which include voltage control, reactive power control and frequency control. These services are primarily provided by central power plants, but with fewer power plants available, system services should be provided in a different way. The Danish TSO Energinet.dk estimates that in normal situations the electrical system in Eastern Denmark in 2020 could be operated without power plants (Danish Energy Agency, 2014). This does not mean that power plants will be completely unused, but that the dependence on their operation will be significantly reduced. In fact, in some situations there will still be a need for power plants, among other things to regulate the reactive power that cannot be supplied by synchronous compensators. Flexibility will be required from other power plants as reserve capacity and for regulation, if unit failure occurs or when there is neither wind nor sun. In addition, there must be emergency start-up options, to restart the network after a blackout. Currently, international rules require that an area has domestic reserves, but these rules may change in the future. The future electrical systems might therefore develop so that there will no longer be a need for domestic power plants, if it is more convenient to use flexible plants located in other countries (Danish Energy Agency, 2014).

There is an ongoing internationalization of the markets for system services, especially purchases of reserve capacity, so that the most economical plants can be activated across national borders. A more interlinked operation with neighbouring countries is expected, with each country contributing a proportionate share of the overall need for reserve capacity with quick ramp-up (Danish Energy Agency, 2014).

2.2.5. Environmental factors

In 2015, the total GHGs emissions in Denmark were 51.9 Mton of CO_2-eq, with CO_2 being the main contributor (75 % to the total). Emissions of CO_2 were distributed across the sectors as follows: transport, 36 %; power and heat generation, 33 %; industry, 17 %; commercial and residential, 14 %. Over the past decade, total GHG emissions have been reduced by 27 % (IEA, 2017a).

The government has adopted various measures to reduce emissions, such as supporting RES and promoting energy savings and energy efficiency (see Section 2.2.6). Denmark's participation in the EU-ETS and implementation of EU-driven standards and requirements also contribute to the national efforts.

Considering the power and heat production sector alone, CO_2 emissions halved between 2005 and 2015. In power generation, this was due to the large increase in wind electricity, which replaced coal and gas generation. In 2015 CO_2 intensity in electricity generation was 163 g/kWh (45 % lower than in 2005), which is less than half of the IEA average (about 390 g/kWh) (IEA, 2017a). Additionally, the total electricity production decreased by 20 %, because of decreased demand and increased imports. In heat production, CO_2 emissions reduction was mainly achieved through increased use of biomass, which increased by 58 % and now represents more than half of the total DH generation (IEA, 2017a).

Economic growth has been decoupled from carbon emissions for years now. From 2005 to 2015, the GDP (PPP) increased by 7 %, but energy-related CO_2 emissions declined by 34 %. In 2015 carbon intensity (the ratio between energy-related CO_2 emissions and GDP) was 38 % lower than in 2005 and the fifth-lowest among the IEA countries, after Switzerland, Sweden, France and Norway (the first three countries have a high share of nuclear power, and Norway and Sweden a high share of hydropower).

2.2.6. Legal factors

The Danish Energy Agency is responsible for implementing the European legislation in the Danish legislation. As in the rest of EU, also in Denmark the electricity market has been liberalized and is now increasingly interconnected to the other European electricity markets.

However, the electric network (and its operation) is a natural monopoly that is not subject to competition. The Danish Energy Agency develops the framework for the prices that the TSO and DSOs can charge consumers for the transport of electricity, as well as the requirements to be fulfilled by TSO and DSOs. This framework is meant to ensure low-price electricity for the consumers, in addition to robust network infrastructure. Besides, the Danish Energy Regulatory Authority is responsible for the financial regulation of the TSO and DSOs (Danish Energy Agency, 2018d).

Regarding power producers, electricity production from plants with a capacity of more than 25 MW can only be carried out by companies that have obtained authorization from the Danish Ministry of Energy, Utilities and Climate, which is given for at least 20 years. Owners of power plants and CHP plants must pay all the costs for connecting the plant to the nearest transmission network over 100 kV. However, in case of decentralized power plant and CHP plants that use municipal waste or produce renewable electricity, the owner of the plant must only pay the expense associated with connecting the plant to the 10-20 kV grid. Other costs are borne by the DSO, if the costs relate to the distribution network, or by the TSO, if the costs relate to the transmission grid (Danish Energy Agency, 2016b).

Energy Savings Obligation Scheme

Since 2006, the grid and distribution companies operating in the sectors of electricity, natural gas, DH and oil are subject to the Energy Savings Obligation Scheme, which aims at progressively reducing the use of energy of the signatory parties. In the latest agreement in 2016, the reduction target was 10.1 PJ/year from 2016 to 2020 (Danish Energy Agency, 2016a). The total target is spread among the parties according to their volume of distributed energy. Trading of savings credits among parties is allowed: a credit is given to the purchasing party and subtracted from the performance reports of the selling party.

Signatory parties can use a variety of measures to reach their reduction target, but to favour measures giving long-term benefits, weighting factors which vary based on the lifetime of the measure are applied. The costs of the energy saving obligation (around 2.68 €/MWh) can be included in the grid tariff and charged on the end-user. For this reason, some stakeholders have argued that distributors do not necessarily aim at cost-efficient solutions, as the costs are recovered anyway (IEA, 2017a). Maybe also for this reason, the 2018 Energy Agreement does not renew this scheme when it expires in 2021 (Danish Government, 2018).

Change in legislation for decentralized CHP

During the 1980s and '90s, many DH plants were converted to gas-fired CHP plants, and a lot of new CHP plants were built (Figure 24). An electricity subsidy for small-scale CHP gave financial incentive to invest in this type of plant. Besides being an efficient way to simultaneously produce heat and electricity, the decentralized CHP plants provided flexibility in the power system, allowing a large amount of wind power to be integrated with negligible curtailment.

Until now, decentralized CHP plants have received two subsidies (called *Grundbeløb* in Danish) for their electricity production/capacity availability. The reason for this is that natural gas generation has declined dramatically since 2004 (9.8 TWh, historical peak), due to the increasing amount of wind electricity, so nowadays the natural gas fleet operates about 12 % of the time (IEA, 2017a) and it is, hence, uneconomic. The subsidy has maintained this capacity as a reserve and prevented the DH heat price to soar.

The two subsidies (*Grundbeløb 1* and *Grundbeløb 2*) are production-independent support schemes for decentralized CHP plants, introduced to replace previous production-dependent subsidies. To receive the subsidies, a plant must be ready for use and available for most of the year. Therefore, these subsidies are a sort of capacity payments (Energinet.dk, 2014).

The amount of *Grundbeløb 1* varies from month to month, depending on the average price of electricity, so that a lower spot price gives a higher support and vice versa. In 2013 the average subsidy was 74,000 €/MW in East Denmark. This is just an indicative value, as there are differences in subsidies from plant to plant, and from East to West Denmark (due to the different electricity prices in the two areas) (Grøn Energi, 2017).

Grundbeløb 2 was introduced in 2013 and applies to decentralized CHP plants of less than 25 MW, running on natural gas and/or biogas. The amount of *Grundbeløb 2* is individually fixed for each plant. As a rough approximation, the average support per MW from *Grundbeløb 2* is about 2-3 times smaller than that from *Grundbeløb 1* (Energinet.dk, 2014).

Grundbeløb 1 and *Grundbeløb 2* expire at the end of 2018 and 2019 respectively (Energinet.dk, 2014). Then, many of the natural gas plant capacity will likely be decommissioned. According to the 2018 Energy Agreement, some measures are planned for the period 2019-2023, to mitigate the negative effects of the abolition of the *Grundbeløb* on DH companies and customers. These initiatives include pools for stranded costs, advice to companies and customers, financial support for individual heating solutions and to customers who will experience increased heating prices (Danish Government, 2018).

Electricity distribution grid

The DSOs in Denmark are regulated by the Danish Energy Regulatory Authority (DERA) under a revenue cap model, whereby revenues are fixed every year based on the “regulatory price” of electricity distribution. The cap is adjusted to allow for necessary new investments. In addition, DERA caps the allowed rate of return on grid assets (IEA, 2017a).

Starting in 2018, DERA should move to a new regulatory model developed by the Danish Energy Agency with input from the DSOs, DERA and consumers. While based on the revenue cap model, the new regulatory model should include an explicit incentive for efficiency improvements, a cap on returns from historical investments, future investments returns set according to a market-based weighted average cost of capital, and a reduction in the cap, if the “quality of supply” was to decline (e.g. a higher number of outages) (IEA, 2017a).

In addition, the possibility to apply time-of-use tariffs for all customers has been introduced. Initially this would only be based on expected demand, as real-time consumption data are not available. However, this may change, as smart meters become more common. Introduction of smart meters and flexible billing must be completed by 2020, according to EU regulation (IEA, 2017a).

The new model also includes an additional “availability” tariff for consumers who install distributed generation, e.g. PV. The purpose is that consumers pay for their share of the costs of the grid, even if they do not use it 100 % of the time. For large producers this tariff would be calculated on a case-by-case basis, but for households the tariff would be fixed and identical for everyone (IEA, 2017a).

2.2.7. Heating sector – District Heating

After the first installations the 1920s and ‘30s, DH in Denmark expanded considerably in the following decades and by the ‘70s, approximately 30 % of the Danish houses were connected to DH networks. The oil crises in the ‘70s and the discovery of natural gas in the North Sea gave a further push to the development of DH and of gas-fired CHP plants, whose surplus heat could be used to supply DH networks. The cogeneration agreement in 1986 made small CHP plants a major energy policy priority. Simultaneously, electric heating with electric panels was banned. A revised law on heating supply in 1990 promoted the conversion of existing coal and gas-fired DH plants to CHP plants, as well as the use of biomass. Additionally, new CHP plants were built to supply new DH networks installed in a number of larger towns (Danish Energy Agency, 2016c).

According to regulation, DH companies must be non-profit. In this way, the DH customers are protected from an otherwise possible abuse that might derive from the natural monopoly of a DH company.

Currently, DH supplies 63 % of all private buildings (Danish Energy Agency, 2016c). There are six large DH networks (in its largest cities) as well as approximately 400 small and medium-sized networks. In 2016, 67 % of the DH heat was produced in CHP plants, many of which are gas- and biomass-fired. Other DH networks use gas or biomass boilers, heat pumps and solar collectors. The current trend (and current policy incentives) is to replace fossil fuels with biomass, heat pumps and solar heating.

Forward and return temperatures are usually about 70-80 °C and 40-50 °C respectively, hence much lower than in many other countries. This makes the integration of solar heating in the DH systems feasible and efficient. It is, hence, no surprise that Denmark is the leader in the sector of large solar collector fields supplying DH systems.

The low temperatures also allow injecting excess heat from industry into the DH networks, either directly at the forward temperature (in case the excess heat is warm enough) or via a booster heat pump, which increases the temperature of the excess heat. The possibility for lowering the DH temperatures even further is being explored. This could include solutions such as ultra-low-temperature DH networks with operating temperatures between approx. 20 and 40 °C. Such grids would further increase the potential of using industrial excess heat.

Four DH plants equipped with a solar collector field also have a seasonal TES (water pit TES). The presence of the seasonal TES increases the solar fraction of the system above the 15 %-20 % value typical of systems without long-term storage. Additionally, in periods of high wind electricity production, hence, low electricity prices, TES can technically be used to balance the grid via heat pumps. Electricity can be converted into heat and stored in the TES, or used to run a heat pump to discharge the storage (Novo, Bayon, Castro-Fresno, & Rodriguez-Hernandez, 2010).

In systems where a large-scale TES is already present, the integration of the CHEST system could be easier and less costly, because the existing storage could be used as low-temperature TES for the CHEST system.

2.3. Germany

2.3.1. Political factors

In September 2010, the German government adopted the Energy Transition (*Energiewende* in German) as an elaboration of the national energy policy until 2050. The document is a comprehensive package containing policies for the electricity, heating and transport sectors, setting out measures and targets for the development of RES, transmission and distribution grids and energy efficiency. The Energy Transition is based on future scenarios elaborated by independent institutions and studies on how the energy and climate policy targets can be most efficiently achieved. Several policy goals are aimed at, such as securing energy supply, limiting climate change, promoting growth and competitiveness of the national industry, making Germany a leader in the fields of energy efficiency and environmental protection, maintaining competitive energy prices and a high level of prosperity (IEA, 2013).

The Energy Transition and the Climate Action Plan 2050 (passed in 2016) set targets for GHG emissions, RES and energy efficiency much more ambitious than those requested by the EU (Weiß et al., 2017). These self-imposed targets include:

- reduction of GHG emissions by 55 % by 2030, 70 % by 2040 and 80-95 % by 2050 compared to 1990 (the target of -40 % by 2020 will not be achieved, based on the current trend (AGEB, 2018));
- increase in the share of RES in the final energy consumption to 30 % by 2030, 45 % by 2040 and 60 % by 2050;
- reduction of primary energy consumption by 50 % by 2050 compared to 2008 (the target of -20 % by 2020 will not be achieved, based on the current trend (AGEB, 2018)).

To reach these goals, specific targets and measures have been set for every sector:

- Energy sector: expansion of RES and reduction in the use of fossil fuels. GHG emissions in the sector should decrease by about 62 % by 2030 compared to 1990.
- Heating sector: expansion of RES so that 14 % of the German heating demand (DH and individual heating) is supplied by RES in 2020 (this value was 12.9 % in 2017).
- Building sector: strict standards for new buildings, long-term refurbishment strategies and reduction of heating systems based on fossil fuels.
- Transport: promotion of alternative drives (especially based on electricity), public transportation, railways, cycling and interconnection of means of transport.
- Industry and commerce: energy efficiency measures, use of waste heat and a research and development program to reduce inevitable industrial process emissions.

To achieve the targeted GHG emission reduction, coal will have to be phased out. Although coal has decreased its share in the electricity mix over the last years (Figure 27), it still accounts for about 40 % of the gross power generation. The persistent use of coal and the yet undefined deadline for its phase-out are also motivated by the long tradition in mining of hard coal in the Ruhr region and of lignite in the Rhine region, in Central and Eastern Germany[1]. The phase-out of coal should be carried out without social and economic negative effects in the affected

[1] There are three large lignite mining areas in Germany: Ruhr area (Rheinisches Revier, Koeln, Aachen), central (Mitteldeutsches Revier, Leipzig, Halle) and east (Lausitzer Revier, Cottbus).

regions, while developing new industrial policy perspectives in a dialogue with stakeholders, regions and trade unions (Weiß et al., 2017).

Although nuclear power was assigned an important transition role in the 2010 Energy Transition, its role was reassessed after the Fukushima nuclear accident in 2011, and its phase-out was accelerated with latest deadline set for 2022, much earlier than originally decided. Of the 17 reactors in operation, 8 were shut down already in 2011 (IEA, 2013), decreasing the nuclear share in the electricity production from 25 % in 2010 to 17 % in 2012 (Fraunhofer ISE, 2018). The accelerated phase-out of nuclear power was offset by conventional power plants (mainly coal-fired) and required a fundamental reorganization of Germany's energy supply. A comprehensive package of legislation was approved, with measures regarding the increase of RES, upgrade of the electrical grid, energy efficiency, funding of the reforms and greater investment in R&D (IEA, 2013).

Gas-fired power plants and CHP plants are expected to play a key-role in the energy transition. In fact, modern, high-efficiency and quickly controllable gas plants can contribute to stabilizing the electricity market in the medium term. They can be used flexibly and produce much lower emissions than coal plants (Weiß et al., 2017). According to the regulation, the grid operator must connect CHP plants to the network and purchase any electricity they produce. Electricity from CHP receives either an agreed feed-in tariff plus a premium, or the premium only in the case of direct marketing, which is compulsory for new CHP plants (Hermeier & Spiekermann, 2017).

In the future, also EES systems may play a relevant role in the control of the electrical grid, especially in form of batteries, power-to-gas and hydrogen technologies (Brautigam, Rothacher, Staubitz, & Trost, 2017). Although the market is still rather small, it is increasing rapidly, as the installed capacity almost doubled from 2016 to 2017 (TenneT, 2018). The new government seems favourable to EES solutions and declared its intention to improve the regulatory framework for battery storage. Also, the German Environment Agency has given recommendations in this direction. Therefore, it is expected that the present taxation on EES will be reduced (currently EES is considered a consumer, thus, pays taxes accordingly).

2.3.2. Economic factors

General economic situation

Germany is a leading exporter of machinery, vehicles, chemicals and household equipment. Its economy grew by 2.2 % in 2017, mainly driven by exports, while domestic demand temporarily stagnated. The GDP is expected to grow by more than 2 % in both 2018 and 2019. The unemployment rate should further decline, after reaching a new low level of 3.5 % in February 2018. Scarcity in the labour market is expected to lead to an increase in wages, which, thanks to the moderate inflation (1.6-1.8 %), should entail a higher purchasing power. Equipment and housing investments are expected to grow in the coming years (European Commission, 2018).

Both imports and exports are expected to increase, but the higher importance of the latter should guarantee that the current account surplus remains high in 2018 and slightly decline in 2019. However, export's potential may be limited by geopolitical tensions and escalating protectionist agendas from commercial partners outside the EU (European Commission, 2018).

Energy-related industry

Investments in RES are of considerable importance for the German economy, since a large part of the added value is generated in the country itself. Since 2000, investment in RES installations has increased steadily, peaking at 28 G€ in 2010, then declining to 15 G€ in 2016. This decline was mainly due to the fall in PV prices in 2011-12 —while the installation rate remained the same— and the reduction in newly installed PV capacity since 2013. Thus, since 2013, wind energy (especially onshore) has collected the higher share of the investments (10 G€ in 2016, 66 % of the total). After installation, the operation and maintenance of the plants is a further economic factor. Personnel, electricity, replacement parts, fuel and other operating expenses incurred by the operator represent revenue for suppliers. The economic stimulus from the operation of RES installations has risen steadily, from 2 G€ in 2000 to 15.6 G€ in 2016 (German Ministry for Economic Affairs and Energy, 2017c).

The RES sector is also important in terms of creation of new jobs. In 2015 there were about 330,000 people employed in this sector (143,000 in the wind energy industry), against 117,000 people in the conventional power supply sector (Weiß et al., 2017).

Energy taxation

The main taxes on energy use in Germany are (OECD, 2018b):

- an energy tax which applies to oil products, natural gas, coal and coke products, at different rates depending on the use (transport, heat generation, industrial process, etc.). Fuels are untaxed when used for power generation in plants larger than 2 MW or when certain requirements for cogeneration of heat and power are fulfilled;
- a tax on electricity consumption of 20.5 €/MWh (but reduced rates and exemptions exist for specific types of consumption).

According to the EU directives, there is also a taxation on CO_2 emissions. Due to the currently low CO_2 tax, the German government lobbied at a European level for increased prices in the EU-ETS scheme (Weiß et al., 2017).

At the end of 2010, a tax of 145 € per gram of nuclear fuel was introduced, yielding about 6.3 G€ between 2011 and 2016. However, in 2017 the Constitutional Court declared the tax illegitimate and retroactively null (World Nuclear Association, 2018).

Electricity prices in Germany are among the highest (if not the highest) in Europe (Eurostat, 2017b). Although the wholesale electricity price is not particularly high, surcharges, taxes and fees increase the bill significantly. In 2018, politically-determined taxes represented 54 % of the electricity price for a household consumer (nearly 300 €/MWh, VAT included). Grid fees, metering and associated services accounted for 25 %, while the market electricity price just 21 %. The electricity price for industrial consumers is also amongst the highest in Europe (150 €/MWh in 2017, VAT excluded (Eurostat, 2017b)).

Subsidies for renewable energy sources

Support of renewable electricity was introduced by the Renewable Energy Sources Act (in German *Erneuerbare-Energien-Gesetz*, abbreviated EEG), adopted in 2000 and revised several times since. The EEG aimed at supporting new RES technologies by guaranteeing a fixed FIT and priority of feed-in. The 2012 edition of the EEG encouraged RES operators to sell their electricity on the market, receiving a market premium on top of the electricity market price, instead of the fixed FIT. The premium is calculated as the difference between the FIT and the monthly technology-weighted spot price (IEA, 2013).

Based on a 2014 amendment of EEG, the remuneration of large RES installations should be determined through competitive auctions, while FIT kept being granted only for small systems. Under the new auction scheme, the RES capacity which is to be built is announced, and investors offer a price at which they are willing to sell electricity from their planned projects. The lowest bids win the auction and have a guaranteed price for 20 years in form of a market premium, as explained before. Auctions for ground-mounted PV systems have been held since 2015, and were extended to roof-mounted PV, onshore and offshore wind, and certain biomass plants from 2017. The auction scheme has led to competition and lower costs (German Ministry for Economic Affairs and Energy, 2017c).

The financial resources to support RES electricity come from the EEG surcharge, which is applied to the consumers' bills. In the last years, the expansion of RES installation and the decrease of the electricity market price have caused an increase of the total financing needed for RES electricity. Hence, the EEG surcharge has constantly increased, reaching 6.88 c€/kWh in 2017 (it was 2.05 c€/kWh in 2010) and representing about 23 % of the electricity bill of a typical household consumer (German Ministry for Economic Affairs and Energy, 2017c).

Import and exports of electricity

Although Germany has been a net exporter of electricity since 2003, it was not until 2013 that the volume of exported electricity has become significant. In the period 2015-2017 net exports were about 50 TWh/year. The main importers of German electricity are Netherlands, Austria, Switzerland and Poland, while France is the net exporter to Germany (Fraunhofer ISE, 2018).

Wholesale market

Germany has an energy-only market of electricity. Electricity is traded either on the European Energy Exchange (EEX) or the European Power Exchange (EPEX). Besides allowing trading of several energy commodities and energy-related products, the EEX provides a spot market, a derivatives market and an over-the-counter (bilateral contract) market for electricity. The EPEX is the spot market (day-ahead and intraday) for Germany, Austria, France, the United Kingdom, Belgium, Luxemburg, the Netherlands and Switzerland (IEA, 2013).

The German/Austrian intraday market consists of two parts. Firstly, there is a daily intraday auction at 15.00 on the previous day which functions like the day-ahead market with the only difference being that 15-minute products are traded instead of hourly products. Secondly, there are two continuous intraday markets, one operated by EPEX and one operated by Nord Pool, both offering 15-minute, 30-minute and hourly products. The 15-minute products in the intraday market allow for a better approximation of the real demand and generation profiles, which is very important, as imbalance settlement are calculated on a 15-minute basis (TenneT, 2018).

Since 2015 the increasing renewable electricity production has caused a decrease of the electricity volume traded on the day-ahead market and an increase on the intraday market. As a result of forecasts of RES generation one day ahead are not so accurate, RES electricity is better traded close to delivery, when estimates on production are more accurate (TenneT, 2018).

Wholesale electricity price in Germany/Austria (single price zone) are among the lowest in Central Europe, followed closely by those in the Netherlands. Prices in Belgium and France are typically higher during winter (due to the use of electric heating), while they converge over summer (TenneT, 2018). However, the split between Germany and Austria price zone in October 2018 is expected to slightly lower the prices in Germany while increase them in Austria.

As the German electricity market is an energy-only market, there is no capacity market with explicit payment for capacity. Still, capacity reserve always guarantees the electricity supply, but this capacity is only used if —despite free price formation on the market and contrary to expectations—, the supply does not cover the demand at a particular time. This leads to price peaks, which cover not only the marginal cost of the reserve capacity, but also part of their fixed operating costs and capital costs. Hence, it is the customers who, through their demand and willingness to pay, determine the capacity level and pay for it through implicit payments for capacity on the electricity market. Additionally, reserve capacity can make profit through long-term contracts, which large users use to hedge against the risk of price volatility on the electricity market (German Ministry for Economic Affairs and Energy, 2015).

2.3.3. Social factors

Germany is a federal democracy divided into 16 regions (*Länder*), with an estimated population of 82.3 million and population growth rate of 0.22 % per year for 2016.

Aware of the importance of public commitment and of the limits to authoritative enforcement in the field of energy policy, the German government makes a continuous effort to inform and involve citizens in the Energy Transition policy, addressing them as consumers and entrepreneurs, conscious that the success of the transition depends also on individual investments and consumption changes. This is part of a consensus strategy, which consists also of extensive advertising of the Energy Transition as a national challenge and ethical responsibility; funding of research programs in the field to achieve economic growth, creation of jobs and a cost-efficient energy transition. Private citizens take also part in several of the advisory committees that the government turns to in the field of energy policy (Krick, 2018).

Nevertheless, most of citizen participation on more practical issues, such as grid extension and nuclear power, takes place at local level. For example, when the government resumed a nuclear-oriented policy at the end of 2010, large demonstrations took place in various parts of the country. Anti-nuclear opposition exploded after the nuclear accident in Fukushima in 2011, and under its pressure, the government announced the phase-out of nuclear power. More recently, local communities and environmental organizations, often backed up by local politicians, have opposed the extension of the transmission grid. To win public acceptance and accelerate the installation, the government decided that the planned north-south transmission lines would be mostly subterranean, despite the higher cost (Appunn, 2018).

Regarding RES projects, a 2017 survey showed a wide public acceptance with 95 % of the population supporting further expansion of RES. Lower acceptance rates were recorded, if the RES technology was to be installed near one's home (the so-called "not in my back yard" (NYMBY) phenomenon), with 72 % acceptance for solar parks and 57 % for wind farms. The rate rose to 94 % and 69 % respectively, when interviewed people had a RES plant already installed in their area (German Renewable Energies Agency, 2017). Another interesting survey on the public acceptance of different energy technologies and on the NIMBY phenomenon in Germany is presented in (Bertsch, Hall, Weinhardt, & Fichtner, 2016).

Besides the concerns about the environment, future generations and energy security (German Renewable Energies Agency, 2017), the public support also derives from the direct involvement of citizens in RES installations. In 2016, private citizens and farmers owned 42 % of the installed RES capacity (although 4 %-points less than in 2012), above energy companies (16 %), developers (14 %) or funds/banks (13 %). Private citizens and farmers owned 41 % of the onshore wind power capacity an 49 % of the PV capacity (German Renewable Energies Agency, 2018).

2.3.4. Technological factors

Current situation

The electricity production in Germany has traditionally been dominated by coal and nuclear, but these energy sources have declined since 2000, replaced by RES and natural gas. In 2016 the gross electricity production was 651 TWh (net 614 TWh), with a generation mix composed mainly of coal (40 %), RES (29 %), nuclear (13 %) and natural gas (12.5 %) (AGEB, 2018). Wind energy represented 42 % of the renewable electricity production, followed by biomass and waste (26 %), PV (20 %) and hydropower (11 %) (German Ministry for Economic Affairs and Energy, 2017c). In the same year the gross electricity consumption was 597 TWh (AGEB, 2018). The net generation capacity installed was 197 GW, against a peak demand of 87 GW. Of the installed capacity, wind turbines and coal plants account for 25 % each, followed by PV (21 %) and natural gas plants (15 %) (Fraunhofer ISE, 2018).

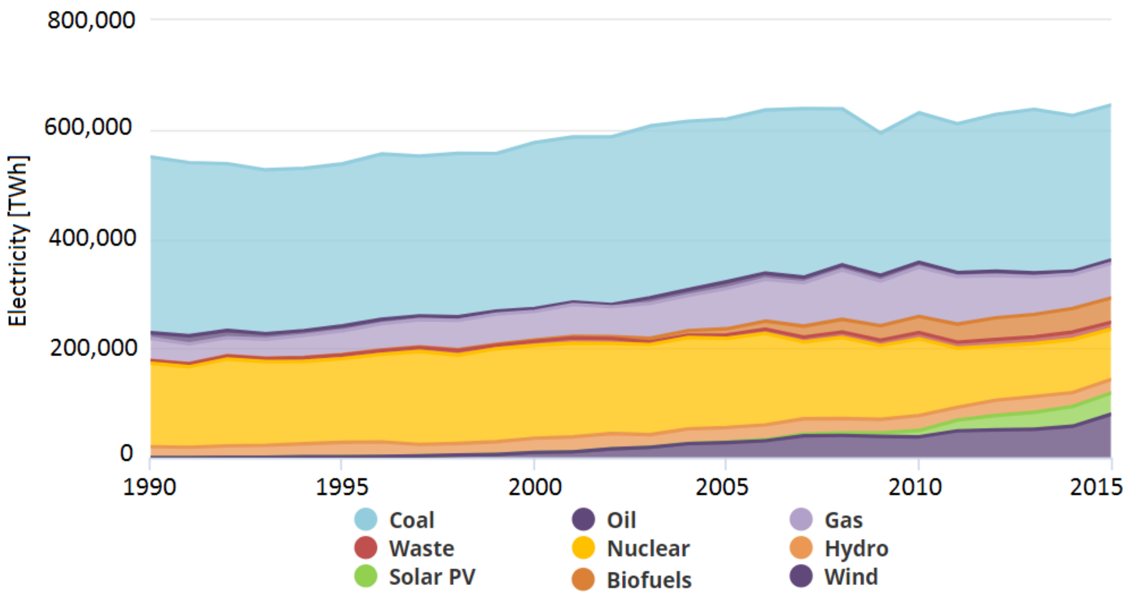

Figure 27: Gross electricity generation by source, 1990-2015 (IEA, 2018).

Coal is still the main energy source for electricity generation, but its relative importance is decreasing (from 53 % of the electricity production in 2000 to 40 % in 2016). Germany is self-sufficient with respect to brown coal (lignite), while it imports hard coal (54 Mton in 2016, mainly from Russia (IEA, 2017b)). Nuclear power (13 % of power generation in 2016) has also been declining (it was 31 % in 1997), especially after 2011, when eight plants were shut down.

In 2017, 15 % more electricity was generated by RES compared to 2016, mainly due to extremely favourable wind conditions and newly installed capacity of wind turbines. In fact, onshore wind turbine capacity increased by almost 5 GW, reaching a total of 50 GW. Offshore capacity increased by 1.3 GW, giving a total of 5.4 GW. PV systems supplied 5 % more electricity than in 2016. About 2 GW_p of new PV systems were installed in 2017, with a cumulated installed capacity of 43 GW_p. Electricity production from biomass was nearly unchanged compared to 2016 (AGEB, 2018).

Despite the high share of fluctuating RES, the German power grid has been very reliable so far (Danish Energy Agency, 2014). However, its upgrade and expansion now have a high priority, to cope with the increase in RES electricity and the future phase-out of nuclear and coal power.

Electrical grid

The 36,000 km of the super high-voltage (220-380 kV) transmission grid are owned and managed by four TSOs: 50Hertz, Amprion, TenneT and TransnetBW, overseen by the Federal Network Agency (Bayer, Matschoss, Thomas, & Marian, 2018). In Figure 28, the competence areas of the different TSOs are shown. The four TSOs are now legally unbundled entities, originally spun off from the four main conventional generators RWE, E.ON, EnBW and Vattenfall.

Until a decade ago, electricity in Germany was produced mainly at the highest concentration of consumption. This explains the multiple coal power plants built in the Ruhr region, and nuclear power plants in southern Germany. Although the electrical grid has been very reliable so far, the expansion of RES (especially wind power in North) and the phase-out of nuclear power plants require its upgrade. In 2015 and 2016 respectively, 4.95 % and 4.36 % of the wind electricity was curtailed due to network congestion, and the overall costs for congestion management has soared in the last decade peaking at over 1.1 G€ in 2015 (then 850 M€ in 2016) (Joos & Staffell, 2018). The deployment of PV (mainly in the south) and interconnections with pumped hydro storage in Austria have partly mitigated the situation, but the potential to increase this form of storage is now very limited (IEA, 2013).

Unscheduled transfer flows and power loop flows have become more frequent. Power loop flows occur when, due to insufficient internal transmission capacity, power produced in Germany is diverted through neighbouring countries' grids and then back into Germany. This has created significant difficulties in Central Europe, especially in Poland and Czech Republic, which have consequently seen their transmission capacity reduced (IEA, 2013). In 2017, the European Commission pushed for splitting Germany into two price zones (North and South Germany), but the government objected, because this would have increased electricity prices in the south. A compromise was reached with a split in price zones along the German-Austrian border from October 2018 (K. Porter, 2017).

The distribution grid —divided in low (400 V), medium (20 kV) and high (110 kV) voltage— is operated by 883 DSOs (Bayer et al., 2018). As 98 % of the RES capacity is connected to the distribution grid, this also requires an upgrade to cope with the increasingly bi-directional flows from prosumers, e.g. households with PV that both feed in and draw electricity from the grid. The upgrade includes smart meters, local distribution substations, accurate weather forecasting equipment and a range of new software to make the grid controllable from afar (Appunn & Russell, 2018).

Future scenarios

By 2022, Germany's nuclear power plants will be shut down and other fossil fuel power plants will also be decommissioned. At the same time the share of renewable electricity will increase. These changes affect the electrical grid: it is expected that more than 7,500 km of transmission lines will need to be upgraded or built in the next years. A major role will be played by high-voltage DC transmission lines, such as SuedLink and SuedOstLink, connecting the north and the south of the country. The upgrading of the interconnectors to the neighbouring countries is also considered important, as it would allow e.g. to connect the hydroelectric reservoir in Scandinavia and in the Alpine countries to the wind farms and PV fields in Germany (German Ministry for Economic Affairs and Energy, 2017a). An overview of the existing transmission grid, the ongoing and planned expansion projects is given in Figure 28. The map was retrieved from (German Ministry for Economic Affairs and Energy, 2017b) and updated to the status at 15 August 2018, according to the interactive and continuously updated map available on the website of the Federal Network Agency (German Federal Network Agency, 2018).

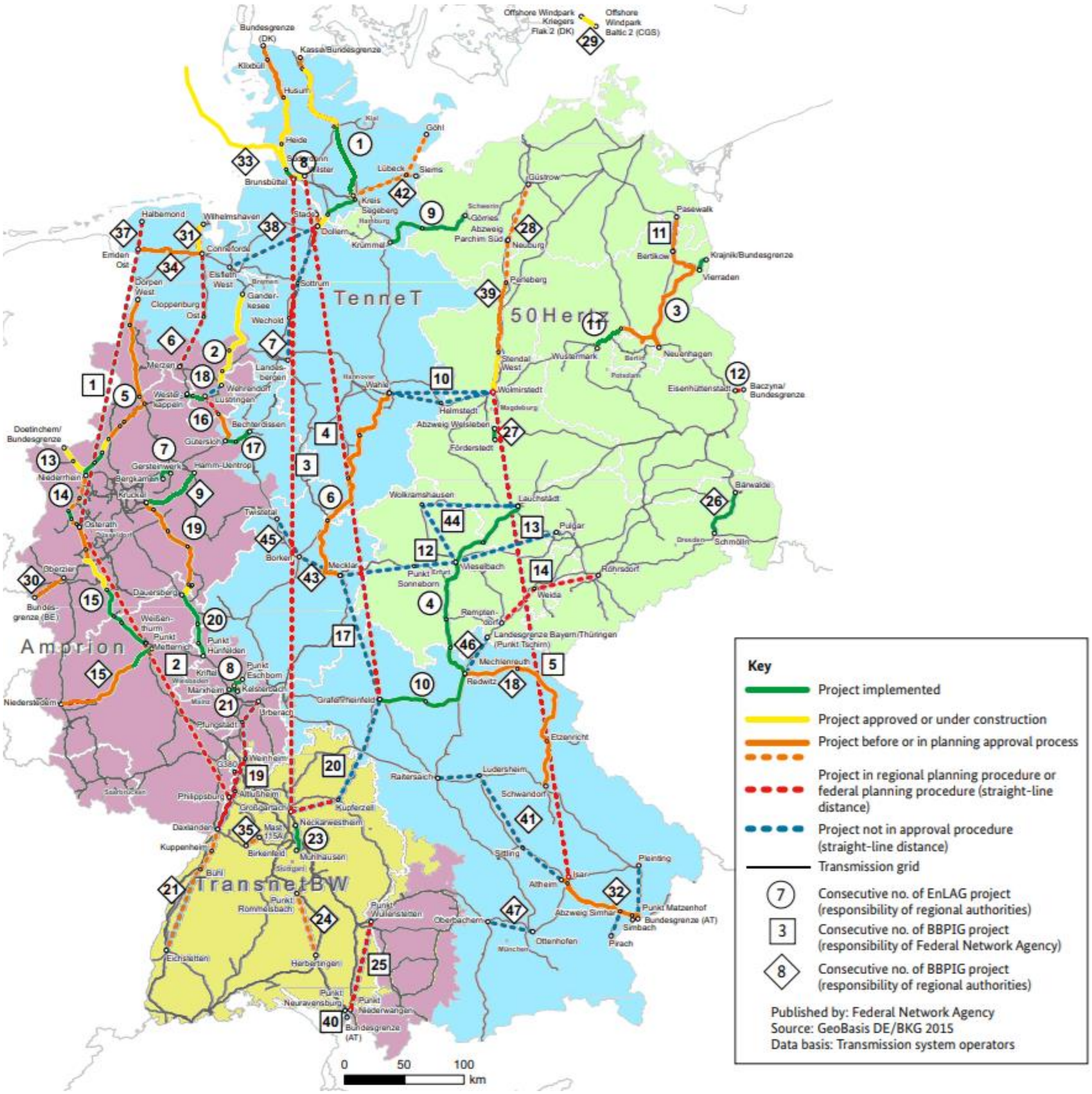

Figure 28: Existing transmission grid and future expansions projects.

Driven by the relatively low installed capacity of primary reserves and the new political agenda, EES projects —in particular in form of batteries— have recently attracted increasing interest. Some examples are a 48 MW/50 MWh lithium-ion battery installed in Jardelund (the largest battery in Europe) (Colthorpe, 2018b), a 7.5 MW/2.5 MWh lithium-ion battery combined with a 4.4 MW/20 MWh sodium-sulfur battery in Varel (Buchmann, 2018) and a 22 MW lithium-ion battery in Cremzow (Colthorpe, 2018a).

2.3.5. Environmental factors

In 2016, the total GHGs emissions in Germany were 906 Mton of CO_2-eq, with the main contributors being energy sector (38 %), industry (20 %) and transport (18 %) (Figure 29). Compared to 2006, the total emissions have decreased by 8 %. Carbon dioxide is the main GHG and represents 88 % of the total CO_2-eq emissions (Weiß et al., 2017).

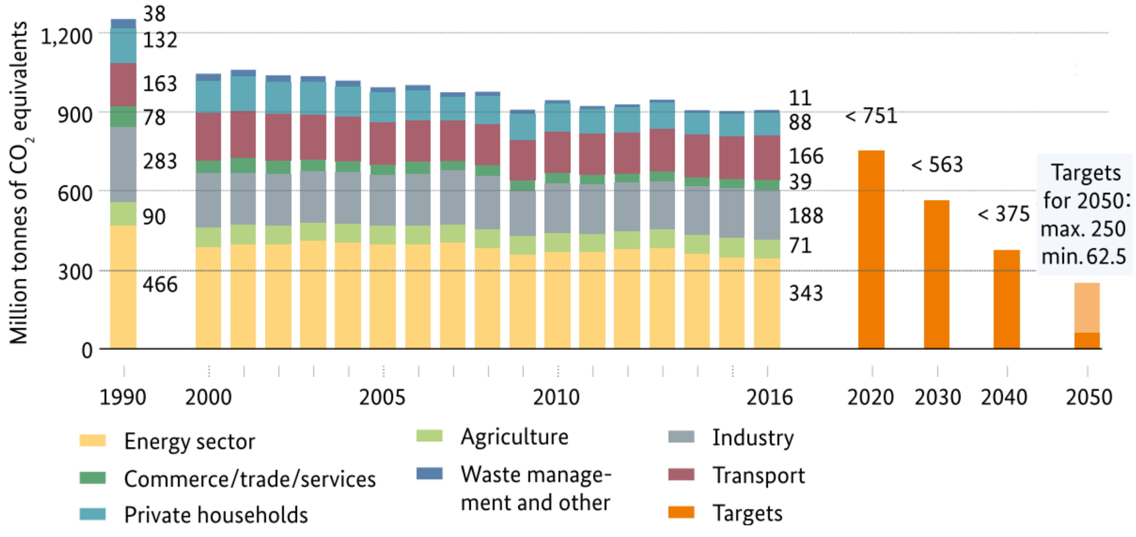

Figure 29: Historical GHGs emission development by sector and future targets.

In the energy sector, almost 80 % of the emissions come from the combustion of coal. Expansion of RES and promotion of energy efficiency have already caused an estimated 26 % reduction compared to 1990 (Weiß et al., 2017). Modernisation of the energy and industry sector in former East Germany gave a key contribution. However, the German power and heat production is still characterized by a very high CO_2 intensity, about 430 g/kWh in 2017 (AGEB, 2018).

Germany's GDP has increased over time, while the required primary energy consumption and CO_2 emissions have decreased. Consequently, the ratio between CO_2 emissions and GDP (PPP) decreased by 19 % in the period 2005-2015, from 0.35 to 0.28 kg_{CO2}/(2010-€) (IEA, 2018).

2.3.6. Legal factors

As a member of EU, Germany has implemented the relevant directives in the electricity sector. Accordingly, the legal framework provides for a regulated third-party access system for transmission and distribution networks. The liberalized electricity market allows industrial and private consumers to freely choose their electricity provider.

Institutions

The Ministry for Economic Affairs and Energy is responsible for the formulation and implementation of the energy policy, while market adoption and research in the field of RES are overseen by the Ministry for the Environment, Nature Conservation and Nuclear Safety. This Ministry also manages the EEG and is responsible for the environmental regulation that applies to the energy sector (e.g. regulations on pollution abatement, climate change mitigation, nuclear safety and radiation protection).

The Federal Network Agency acts as network regulator and aims at facilitating the development of the market, by liberalization and deregulation (IEA, 2013).

Revenue cap model for DSOs and TSOs

The Federal Network Agency determines revenue caps for each TSO and DSO, i.e. the maximum that a network operator can earn from grid fees. The revenue cap is based on a review of each operator's costs in a reference year and an efficiency benchmark of all operators, which determine the efficiency of each operator compared to the most efficient one(s). All operators must gradually increase their efficiency level during the five-year regulatory period for which the revenue caps are set. Hence, the network operators are encouraged to outperform their set targets, so to keep the additional difference between costs and fixed revenues (Scholz & Ante, 2018). To increase the generation of electricity from RES and CHP plants, network operators are obliged to offer a connection to the grid, unless it is technically impossible or economically unreasonable. In case of RES installations, the lower voltage level entails that mostly DSOs are concerned.

Future development of RES capacity

To pace the development of RES installations and give time to the electrical grid to be upgraded accordingly, the 2017 revision of the EEG limited the RES auction volumes as follows:

- 2,800 MW/year of onshore wind for 2017-2019 and 2,900 MW/year from 2020;
- 600 MW/year of PV systems;
- 150 MW/year of biomass for 2017-2019 and 200 MW/year for 2020-2022;
- auction volumes for offshore wind shall be compatible to reach 6.5 GW by 2020 and 15 GW by 2030;
- 400 MW/year of technology-neutral auctions for onshore wind and solar power together for 2018-2020.

Legislation on power generators and EES

Regarding power generators, there is no energy law-based authorisation required to operate a plant. The German Energy Act only refers to technical safety regulations set by industry associations, and the construction of the plant must follow the general construction and environmental standards.

Regarding the EES, the required type of permit depends on the type of EES. A battery EES requires a building permit, so it must comply with the relevant planning and building law. Power to gas/liquid EES usually require a permit under the Emission Control Act. To participate in the reserve control market, the EES must pass a prequalification procedure carried out by the TSO. Currently, this is not easy, because of minimum size requirements (1 MW for primary reserve, 5 MW for both secondary and manual reserves (German Ministry for Economic Affairs and Energy, 2015)) as well as other criteria for the primary frequency response market, which are also challenging for larger battery storage. According to the EEG 2017, electricity stored in an EES receive a feed-in premium, when it is fed into the grid. However, EES are treated as consumers, so the stored electricity is subject to several levies and taxes which are imposed on the consumption of electricity. Because the final consumer of the electricity fed by an EES pays the levies and taxes again, the stored electricity is taxed twice (Norton Rose Fulbright, 2017). However, EES are exempted from paying grid tariffs and EEG surcharge, when the electricity withdrawn from the network is only re-fed with a delay into the same network, provided that metering requirements are complied with and subject to limitations if only part of the electricity is fed back into the public grid (Janzen & Wippich, 2016; Norton Rose Fulbright, 2017). There is an ongoing discussion at a political level on how to favour the integration of EES into the electrical system.

2.3.7. Heating sector – District Heating[2]

Currently in Germany DH supplies about 5.7 million households, which correspond to about 14 % of the total number of households. Every year, the number of households supplied by a DH network increases by about 75,000.

About 83 % of the heat for DH comes from CHP plants. Thermal plants provide about 15 % of the heat fed into DH networks, while the remaining 2 % comes from industrial waste heat. The use of RES in DH systems is still rather small. In 2015, the main energy sources for DH systems were natural gas (36 %), hard coal (34 %), lignite (13 %), biomass (5 %), waste and others (12 %).

The development of DH has been fairly slow in the last two decades. Since 2000, the total length of DH networks increased by 17 %, from 18,326 km to 21,521 km in 2016, while the installed heat capacity remained almost constant at around 50,000 MW. In order to achieve the target of 14 % of RES in the heating sector by 2020, incentive payments have been introduced for DH systems, especially when RESs are used. First, the German Act for the support of RES in the heat sector includes financial support for solar thermal, biomass, geothermal, TES and DH networks. Secondly, the German Act for the conservation, modernisation and expansion of combined heat and power (KWKG) ensures payments for the electricity generated by CHP plants, but it also supports new and expanded DH networks and TES. The market incentive program (MAP) is another measure to support RES, but also DH networks and TES. There are different funding conditions for private applicants, companies and municipalities. Financial support can be in the form of direct payment of a share of the investment costs or in the form of a loan with reduced interest rate. Finally, there are also possibilities for support through programs at regional or municipal level.

[2] This section is an extract from deliverable 2.1 of the CHESTER project (Section 2.5.5 – District Heating).

2.4. Belgium

2.4.1. Political factors

The political framework in Belgium for the energy sector is strongly influenced by the European Union energy policy objectives. They define many aspects of the political factors, from the structure of electricity and gas market to long-term renewable energy resources deployment or the GHG emissions reduction.

As a federal state, composed of three regions (Flanders, Wallonia and Brussels-Capital), the implementation of these objectives is shared between the federal administration and the regional administration. Each administration has its own entity responsible for the electricity market affairs as well as its own electricity market regulator. Besides this, several coordination entities among regions and federal government exist, which yields a somewhat complex partition of competences among the different administrative institutions in the country.

The hampering of the energy policy in Belgium by this administrative complexity is shown by the lack of a common long-term vision for the energy sector in the country. This long-term vision is in debate since 2003, when the government established the phase-out of nuclear power, which should be implemented by what is known as the Energy Pact. This pact has been negotiated and concluded by the four ministers of energy but is not yet enforced.

Although the Energy Pact is not enforced, it incorporates the political agreement to phase out nuclear power by 2025. This point has been the main driver of the political debate for the electricity sector, since nuclear power is a fundamental element of the energy system, accounting for 53 % of the electricity production in 2016. The Energy Pact establishes four lines to reach its objectives in 2050 from this scenario (Partners, 2018):

- electricity consumption reduction by means of energy efficiency;
- definition of a new energy mix focused on renewable energy;
- flexibilization of the energy vectors and encouraging storage;
- increased transmission flexibility by deployment of further transnational connections.

Besides the political commitment to avoid nuclear power in the electricity mix, the stress that such measures pose on the security of supply has so far avoided the application of the schedule to turn off the nuclear reactors as they reach their expected 40 years of technological life. This schedule appeared in the 2003 law, but it has been reviewed in 2013, when the plan for secure energy supply (known as the Wathelet plan) was introduced. This plan, besides the commitment of adding new gas-fired base-load plants, extended the operational lifetime of the Tihange 1 nuclear reactor. The following revision of the schedule in 2015 provided the ten-year extension of the operating license for the country’s two oldest reactors, Doel 1 and Doel 2 until 2025 (Nucleaire, 2017) (according to a 2013 law, they should have been turned off by 2015).

Given the relevance of the nuclear energy in the national energy mix, these decisions have had a huge impact on the base-load energy mix. Together with relatively low prices for energy, and the difficulties in establishing a long-term energy vision by the political sector, generates an uncertainty that has hampered the investments in new base-load capacity by the stakeholders during the Eurozone crisis period. This resulted in recent years in the system’s inability to supply the required capacity under winter peak demands, which forced the government to establish a mechanism of reserve capacity to ensure the electricity supply. This reserve relies technically on two mechanisms; on one side it maintains in operation some out-of-date thermal power plants (the state finances maintaining them in reserve), and on the other side, a peak demand management system, by the aggregation of voluntary flexible consumers, who can offer a limitation of their demands as a network service, in exchange of economic revenues. The TSO Elia is responsible for operating the reserve capacity. In November 2018, an electric energy storage system of 18 MW based on electrical batteries has been added to the Reserve Capacity pool. Elia also operates this system.

2.4.2. Economic factors

General economic situation

After having contracted in 2013, the Belgian GDP grew by 1.3 %-1.4 % in the period 2014-2016 (EU data). However, the growth remains modest, partly as a result of the remaining structural challenges, high labour costs, a low labour force participation rate and high-income tax. The public deficit reached 3 % of GDP in 2016, while the debt ratio is expected to stand at 107 % of GDP in 2017. Belgium has notably established a wage freeze and a reduction of employers' social contributions. The Government has also adopted a labour market reform in the attempt to moderate the high cost of the labour force (Market Research Reports, 2017).

Energy-related industry

The liberalisation of the Belgian electricity market was completed in 2007. The only TSO operator is a nationally held company, Elia. The electricity sector is strongly concentrated, with Electrabel, the historical national supplier of Belgium, holding 66 % of the country's installed capacity, including most of the nuclear capacity. However, its dominant position is slowly declining, as in 2007 it controlled 85 % of the country's capacity. Electrabel is a subsidiary of Engie (former GDF). Luminus, a subsidiary of EDF, holds 12 % of the total capacity and E.On is the third biggest actor with 7 % of the total capacity. Overall, these three transnational companies control 85 % of the country's capacity, as well as 91 % of the energy production in 2014 (Technopolis Group, 2016).

The renewable energy sector has benefited in recent years from the favourable scenario motivated by the long-term objectives of Belgium within the European policy. The recent years have seen a huge increase in investments in renewable energy capacity, with a total increase of 229 % of the electricity capacity installed from 2005 to 2014 (IEA, 2016a). The current context of the electricity system and the legal factors ensures that the growth is going to extend in the coming years: according to the European project Repap2020, it is estimated that to meet the efficiency and renewable energy objectives of Belgium, the investment associated with new renewable electricity capacity should reach 3.3 G€ in 2020, and an additional 956 M€ are necessary for thermal renewable capacity (Edora, 2010).

Energy taxation

Energy and carbon taxes in Belgium are levied within the framework of the 2003 EU Energy Tax Directive, which sets minimum rates for the taxation of energy products in member states (OECD, 2018a). Within this framework, the main taxes on energy use in Belgium are the following:

- An energy tax applies to oil products, natural gas, coal and coke consumption, including fuel oil and coal and coke used for electricity generation;
- Electricity output is taxed (per MWh).

Besides, Belgium participates in the European Union emissions trading system (ETS). The rates at which these taxes apply differ for fuels and users, with the transport sector being the one with a highest rate of taxation.

For the electricity sector, the taxation has seen a notable increase in the share of the electricity costs for final users in all consumption bands. This is due to an increase in the electricity VAT from 6 % to 21 % in 2015, but also to the supporting mechanisms for PV systems. In 2016, the share of taxes on the electricity prices for domestic users was 33.9 % of the average cost; that was 27.44 c€/kWh (Figure 30).

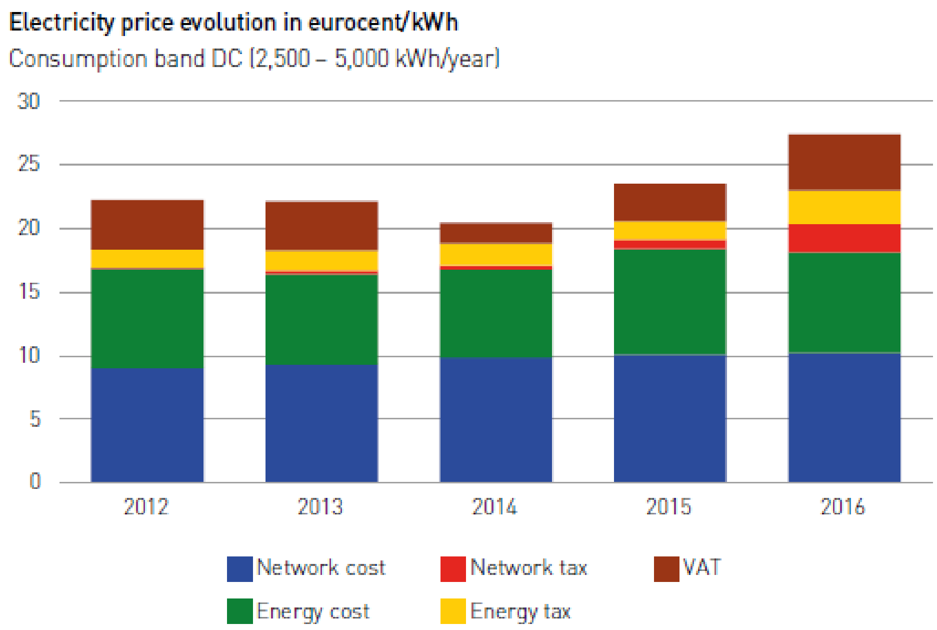

Figure 30: Electricity price evolution in Belgium (Federal Public Service Economy, 2017).

Subsidies for renewable energy sources

In Belgium, renewable electricity is promoted by means of a quota system together with a green certificate system; the electricity suppliers have to reach a certain quota of renewable energy in their production mix, and if not able to do so, they must buy green certificates in the market to cover their mandatory quota. The green certificate itself is a transferable asset that demonstrate a certain energy saving by the owner, who always has the right to sell it to the DSO at a minimum guaranteed price (KPMG, 2015).

The green certificate values granted to renewable electricity production are updated annually to incorporate the constantly reducing costs and are set specifically considering specific internal rate of return (IRR) objectives for the investor. Since the promotion of renewable energy is in the competency of the regional authorities, three different systems are in place (one for each region). Each region establishes the quotas applicable in their territory and runs its own certificate market.

The targeted return on investment differs by region and technology, as shown in Figure 31. In the Flemish region, the system aims at a guaranteed return on investment of 5 % for solar, 8 % for wind and 12 % for biomass and biogas. In the Walloon region, the targeted rates are 7 % for solar, wind and hydro, 8 % for less than 1.5 MW biomass and 9 % for 1.5 MW or more biogas and biomass. In the Brussels-Capital region, a payback time of seven years (roughly equalling a return of 10 % per year) is targeted. In Flanders, the system of green certificates has been

discontinued for installations of less than 10 kW_p and certified after June 2015. Net metering, otherwise, has been guaranteed for the next 25 years for the newer installations.
For offshore wind power, which is in the competency of the federal authorities, the certificates generated are not tradable, but the TSO has an obligation to purchase green certificates from the producers at a minimum price set by the legislation, which is renewed every three years. This operates in practice as a feed-in-tariff mechanism.

	Federal level	Flemish region	Walloon region	Brussels-Capital
Based on	MWh generated	MWh generated	CO_2 avoided	CO_2 avoided
Quota 2014, %	-	15.5	23.1	3.8
Quota 2017, %	-	19	33.0	5.8
Quota 2020, %	-	20.5	37.9	8.0
Minimum price/ certificate. Purchasing entity	EUR 90 to 107 or LCOE (maximum EUR 138)	Price varies by technology. DSOs	EUR 65. TSO	-
Duration, years	20	10 (15 for wind and solar PV)	15 (10 for solar PV)	10
Fine, EUR/ certificate not submitted	-	100	100	100
Certificates accepted	No tradability	Flemish only	Walloon only	Brussels-Capital and Walloon

Figure 31: Summary of green certificate systems operating in Belgium (IEA, 2016a).

Import and export of electricity

Belgium is part of the Central Western European region, and is well interconnected with France, the Netherlands and Luxembourg. The flow of electricity between countries is set by specific cross-border market mechanisms, but it is limited by the available interconnections. This cross-border market mechanism establishes the rules to allocate the available interconnection power capacity to electricity producers in order to allow them to participate in a neighbour market (either day-ahead or intraday). They are specific for each interconnection; for instance, the France-Belgium interconnection has an explicit allocation procedure, where capacity is allocated on an hourly basis in a "first come, first served" model, while the Netherlands-Belgium connection is factored within a common day-ahead market for both countries. Current interconnection capacity is 3500 MW, of which 2100 MW are connections with France (IEA, 2016a).

The cross-border capacity has increased in the last years, due to its central position within the European Energy Policy. Belgium, which has seen supply problems with their generation capacity (nuclear power) in the last years, has a special interest in promoting the deployment of new interconnections. Currently, there are five new connections under development with France, UK, Germany, the Netherlands and Luxembourg, with a total capacity of 4700 MW. All should be commissioned between 2018 and 2023 (IEA, 2016a).

This cross-border capacity has been fundamental for ensuring the supply of the Belgian electrical grid. This was especially true in 2015, when unplanned incidents in two nuclear power plants drastically reduced the available capacity in the country. This scenario repeated itself in 2018, because of unplanned maintenance requirements to two nuclear reactors. Only one out of seven existing reactors was in operation in November 2018, and the market price evolved with abnormally high prices during autumn 2018 (Figure 31).

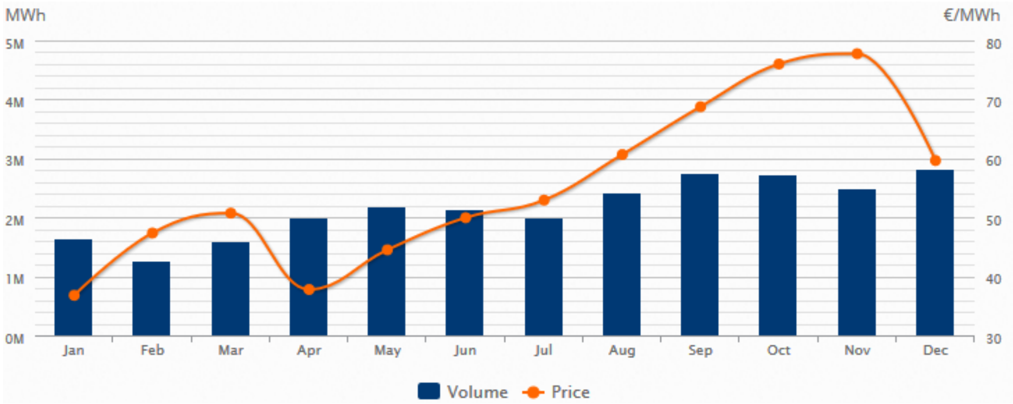

Figure 32: Electricity market price in Belgium in 2018.

Import capacity is restricted because a part of the German electricity transported from north to south Germany is rerouted via the Netherlands and Belgium, thus occupying a large part of the available interconnection capacity.

Figure 33 shows the evolution of generation, load and imports for the electrical grid in the period 2007-2016; as can be seen, imports of electricity represented 26 % of the total load in 2015, when the availability of the nuclear capacity in the country was scarce. The high weight of specific reactors over the total national capacity implies that when they —due to technical reasons— are temporarily unavailable, the security of supply is compromised. This situation could worsen as the nuclear plants age. The electricity imports have been reliable, avoiding problems from the reduced available capacity, and are now seen as a fundamental component in the energy mix while the nuclear phase-out takes place.

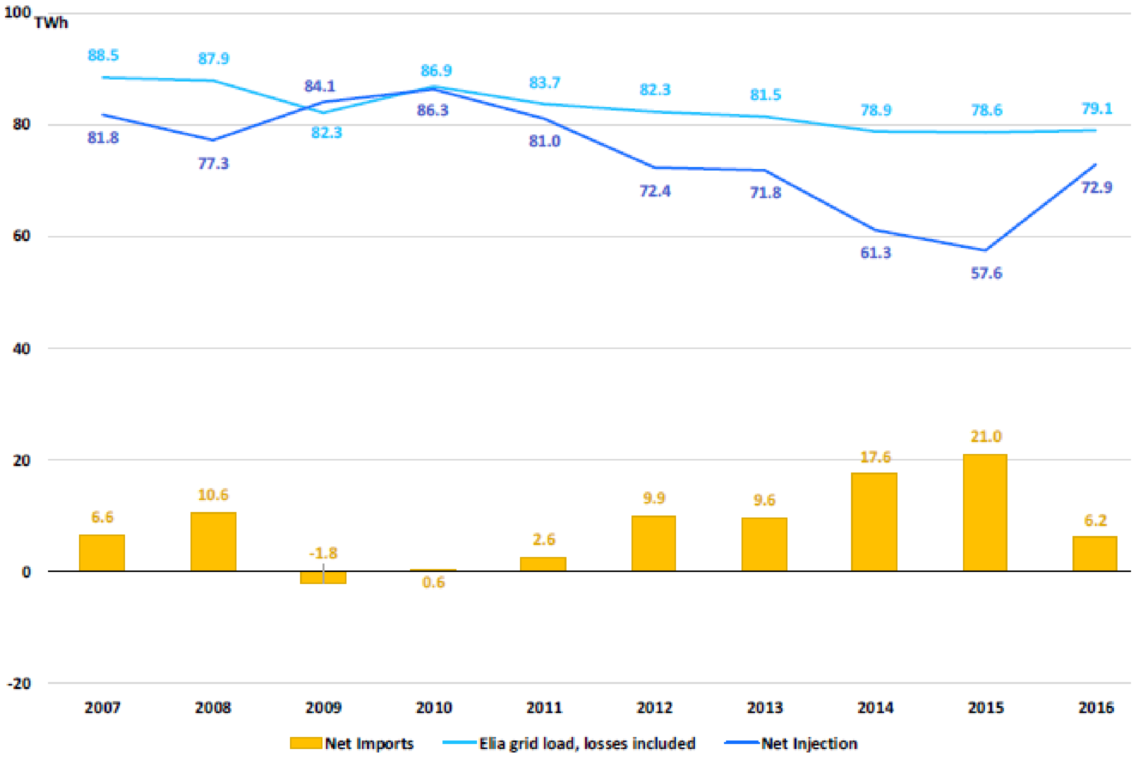

Figure 33: Generation and imports in the Elia electrical grid 2007-2016 (CREG, 2017).

Wholesale market

The Belgian electricity spot market is part of EPEX, which includes France, the Netherlands, Luxembourg and Germany. It is composed of a day-ahead market and an intraday market. This market, Belpex NV, is coupled with most of Europe by the multi-regional market developed at the European level.

Although the Central Western Europe (CWE) market is in concept a price-coupled area, the prices show significant differences among the countries involved due to a limited interconnection capacity. Belgium is consistently in the upper end of the CWE region: in 2014, the average day-ahead market price in Belgium was 40.79 €/MWh, while other countries of the CWE region such as France or Germany had 34.67 €/MWh and 32.78 €/MWh respectively (IEA, 2016a).

2.4.3. Social factors

Climate and energy are two topics very present in the public debate. Two interrelated topics, in particular, have been the object of public debate: the phase-out of the nuclear power and the security of supply. The current nuclear phase-out schedule, which has been repeatedly updated to capacity shortages, is a frequent debate in the media, as well as the potential electricity black-out consequence of the capacity shortage. Although the energy sources are not a main concern of the citizens, in comparison to the energy price and the security of supply, there is a message carried by cooperatives, civil society associations and other alternative actors in favour of a new way to control the economy. This message has an influence on the public opinion and pushes in favour of renewable energies. This is reflected in the public consultation organised in 2017 as a support tool recovering the ambitions of the citizens in regard to the National Energy Pact. Among the topics to be addressed by the pact, according to the citizen voting, three are the most repeated: nuclear phase-out, price and affordability of energy and renewable energy. Regarding the technologies to be considered in the energy mix, more than 85 % of the votes were in favour of renewable energy sources, and the second most voted source was storage and flexibility, with 40 % of participants including it in the mix. Nuclear power was a valid option only for 25 % of the voters, and fossil fuels stood even worse, with 23 % of the votes (Concere, 2017).

As an indication of the public's willingness to invest in renewable energy, it is worth noting that by the end of 2017, there were 453,000 small PV systems online, out of a total 4,828,000 households in Belgium. In other words, nearly one out of 10 homes in Belgium owns a PV system (Maisch, 2018).

2.4.4. Technological factors

Current situation

The backbone of the country's installed capacity relies on 7 units in two nuclear plants (Doel and Tihange), that together have almost 6,000 MW, roughly 30 % of the national capacity. Fossil-fuel plants with different technologies, mostly burning natural gas, account for another 35 %, and the rest is shared mainly by solar PV and wind energy.

Belgium's electricity generation was 71.5 TWh in 2014, 13 % less than in 2013. The peak generation in 2010 reached 93.8 TWh and has been falling since. From 2010 to 2014, electricity generation fell by 24 %, primarily because of long and extensive outages at the country's nuclear power plants; the cross-border electricity imports have covered the missing national generation.

In 2014, nuclear power as the primary source (Figure 34) of electricity in Belgium accounted for 47 % of total generation (its share was stable during the 2000s at around 55 %). Since 2011, the share has fallen from 54 % to 47 %, as the total nuclear power generation declined by 30 % over the same period because of the long outages. Natural gas accounted for 27 % of the total generation in 2014 (19.3 TWh). Electricity produced using natural gas grew for decades to peak at 31.4 TWh in 2010 (33.5 % of the total) (IEA, 2016a). Since then, gas use in electricity generation has fallen by 39 %, as imports from cheaper sources and wind and solar power have gained ground. RESs represent 19 % of the electricity production, made up of biofuels and waste (7.9 %), wind (6.5 %), solar (4 %) and hydropower (0.4 %). The share of RES in generation was 2.9 % in 2004. On average, biofuels and waste grew by 11 % per annum over ten years. Driven by subsidies and starting from a low absolute level, solar grew by 122 % per year and wind by 42 % (IEA, 2016a).

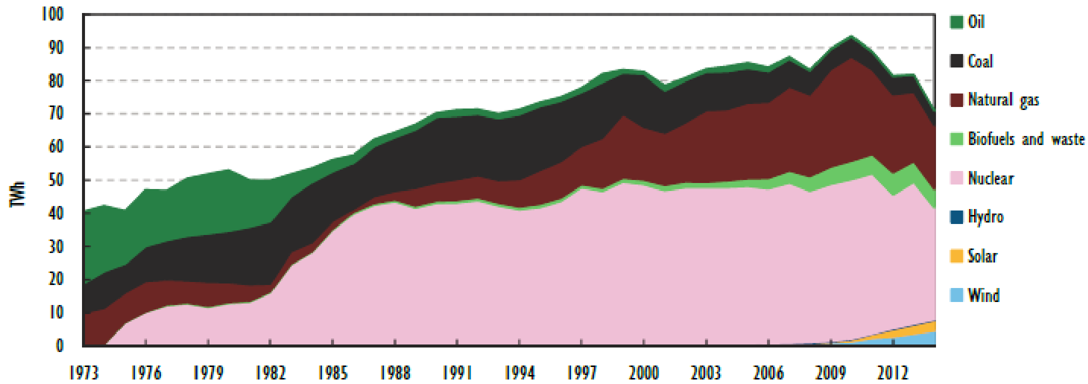

Figure 34:Gross electricity generation by source, 1990-2015 (IEA, 2018).

By October 2018, according to TSO Elia up-to-date numbers, nuclear installed capacity reduced to 40 %, while wind energy capacity reached a new 8.7 % level of total generating capacity.

Electrical grid

The Belgian high-voltage electricity network is owned and operated by the TSO Elia. In 2015, the transmission system had a total length of 3,655 km, of which 891 km operate at 380 kV, 302 km at 220 kV and 2,462 km at 150 kV. Elia is 45 % owned by Publi T, a company representing Belgian municipalities and inter-municipal companies, 2.5 % is owned by Publipart, while the rest is free floating on the Brussels stock exchange (IEA, 2016a).

The investments planned by Elia for voltages over 70 kV are set in the Federal Development Plan 2015-2025. Investments for 70 kV or less voltage are set in regional investment plans. Elia estimates that its investment needs will total more than 2 G€ for the next decade (IEA, 2016a). Investments focus on interconnections with neighbouring countries and on grid upgrades, necessary to connect decentralised and renewable generation. Finally, substantial replacement investments must also be made in order to address grid ageing. Transmission tariffs are collected from grid users to finance these investments. The tariffs are set by CREG (Commission for Regulation of Electricity and Gas, the national energy regulator) and they also include costs of public service obligations, such as reduced rates for low-income consumers (IEA, 2016a).

Future scenarios

The long-term goal for 2050 is a 100 % renewable energy supply, but there is a shorter-term goal for 2025 in which all the nuclear energy in the country should be phased out. In the short term, a key role will be played by the development of interconnectors, to ensure supply, but this will not be enough and new investments in natural gas plants must be activated to compensate the phase-out of nuclear power. It is likely to be difficult for the country to keep the path of emission reductions while substituting nuclear power by natural gas power plants.

Due to the favourable legal conditions, renewable energy deployment shall proceed at a good rate, as has been the case in the last years, reaching a 40 % share of the electricity mix by 2040 and 100 % in 2050. Other measures, such as demand side management and storage, should achieve installed capacities of 1.5 GW and 3.5 GW respectively by 2030.

An important element to consider are the mobility policies, in particular the plan to extensively deploy electric vehicles to reduce transport related emissions. According to CREG, (CREG, 2017), a massive deployment of electric vehicles (1 million as mentioned in the report) will not decrease the security of supply on the condition that electric cars are charged in due time (off-peak hours). In addition, a 100,000-electric vehicle deployment should add more than 50 % of the actual storage capacity. Considering that nowadays there are 5.6 million vehicles in Belgium and only 4,368 are electric, this is not a short-term problem.

2.4.5. Environmental factors

Belgium's GHG targets are derived from the European Union's 2020 targets. Because of the effort-sharing of the Union's target for reducing GHG emissions by 20 % from 2005 to 2020, the country will have to reduce emissions from the sectors outside the Emissions Trading Scheme (ETS) by 15 % (by 2020 compared with 2005). For this, it can use international flexibility mechanisms, also known as Kyoto Mechanisms, which include Clean Development Mechanisms, Joint Implementation and Emissions Trading (UNFCCC, n.d.), to cover an amount equalling 1 % of its total GHG emissions in 2005. The sectors covered by the ETS in the European Union as a whole will have to cut emissions by 21 % below 2005 levels by 2020 (IEA, 2016a).

Energy-related CO_2 emissions (Figure 35) from fuel combustion were 89.1 Mton in 2013, which was 16 % lower than the 106.2 Mton in 1990 and 24 % lower than the 117 Mton in 1996. Compared to 2003, CO_2 emissions declined by 21 %. The sector emitting the highest volumes of CO_2 in Belgium is transportation, representing 27 % of the total. Power generation accounts for 20 % and households for 20 %, while manufacturing industries and construction together emit 15.5 %. The commercial and public services sectors (including agriculture, forestry and fishing) emit 10.5 % of the total and other energy industries (including refining) account for the remaining 6.3 % (IEA, 2016a). The decline in overall carbon emissions since 1990 is mainly due to a reduction of emissions in the power sector (25.9 Mton to 18.1 Mton, a decrease of 30 %) and in the manufacturing and construction sector (28.1 Mton to 13.8 Mton, a decrease of 50.8 %). Both sectors have experienced some volatility in emissions over the 1990-2013 period because of variations in output. The share of power generation in total emissions has fallen by 24.4 % compared to 1990, while that of the industry sector has fallen by 26.5 % (IEA, 2016a).

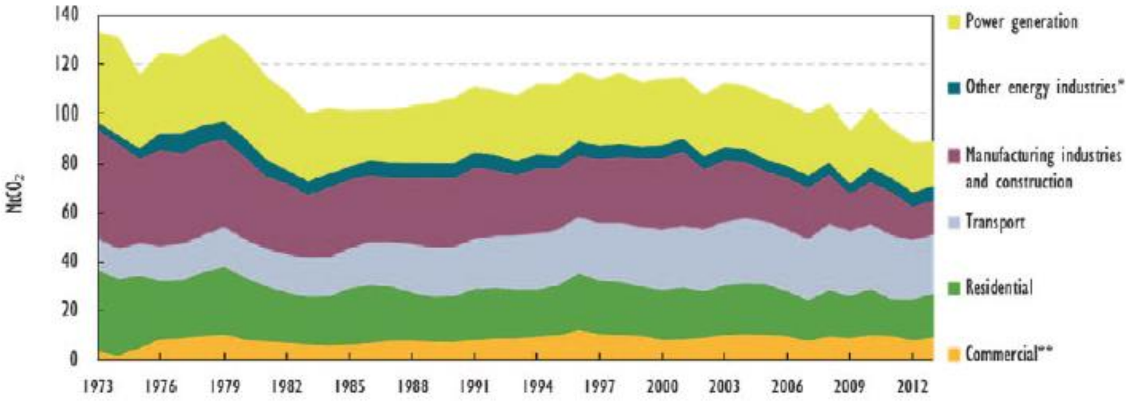

Figure 35: CO_2 emissions by sector.

2.4.6. Legal factors

European dimension

The EU regulatory framework influence has shaped the national legal framework decisively. Some of the most relevant examples are:

- The Directive on Energy Markets established the liberalisation of the energy markets, and functional independence among generation, distribution and supply activities. The first directive was transposed in the Energy Act of 1999 and has been amended often to incorporate new requisites set at European level. This defined the structure of the current Belgian electricity market.
- The development of an Internal Electricity Market for Europe has a political priority. This has established the mechanisms to operate interconnected network systems and, in particular, a common wholesale electricity market. Also, it opened the possibility to incorporate the national system cross-border power capacity, strongly affecting energy mix and prices.
- The EU objectives related to carbon emissions abatement state that the contribution of renewable energy to the energy mix in Belgium must reach 13 % of the total primary energy consumption. Since 2010, the National Renewable Energy Plan 2011-2020 defines the policies and measures to meet this objective.

National dimension

The federal regulator of the energy sector, the CREG (Commission for Regulation of Electricity and Gas) was responsible of establishing tariffs at the national level until 2014. Afterwards it transferred this responsibility to the federal regulators (Brugel in the Brussels region, CWaPE in Wallonia, and VREG in Flanders). The federal regulators are also responsible for maintaining transparency and competitiveness in their respective retail markets, while the national regulator monitors the wholesale market at national level.

The TSO Elia is responsible for operating and maintaining the high voltage network (over 70 kV), under supervision of the CREG, who establishes transmission taxes and exemptions. DSOs operate and maintain the network under 70 kV, with supervision of the competent regional regulators. Each regulator is responsible for establishing the distribution tariffs within its territory and these are used to cover any system expenses, such as the financing of regional renewable energy policies, tax exemption for protected customers, distribution charges, etc. Elia as the TSO is allowed by the Electricity Act to operate electrical storage devices, as long as it does not prevent the competitive operation of the market. In 2018, a battery storage system with 18 MW was deployed in Terhills, and it will be operated by Elia as part of the Reserve Capacity system.

2.4.7. Heating sector

Natural gas as a primary source dominates the heating sector in Belgium. There is a trend for expanding the gas distribution network and the progressive replacement of oil boilers. An important issue is the reliance on the low-calorific gas (L-gas) from the depleting Groningen field in the Netherlands. Consequently, there is a need to shift to high-calorific gas because the L-gas network will be phased out by 2029. This problem could become an opportunity for RES at a local level.

In the Brussels region, the share of natural gas in space heating of buildings rose from 65 % in 2001 to 72 % in 2012. Similarly, for the Wallonia region there was an increase of 25 % in the number of residential gas customers from 2011 to 2015 (IEA, 2016a).

The district heating sector is poorly developed in Belgium, which is surprising since both the climatic conditions and the high population density (among the highest in Europe) seem to favour the deployment of the technology.

However, many support policies for renewable heat promotion —which considers also district heating— exist at the regional level, as local authorities hold the competencies for renewable heat policies. For instance, in the Flemish region, there have been direct subsidies for investment in renewable heat projects since 2013, with special interest in projects promoting integration of renewable or waste heat into district heating networks. Additionally, in this same region, since 2014, there has been an obligation for new buildings to incorporate a share of renewable energy capacity. Each year the share of renewable energy for new buildings is increased in order to reach, by the end of 2020, the NZEB obligation. Among the eligible technologies for new buildings to fulfil the share of renewable energy mentioned before there appears, among others, a district heating connection (IEA, 2016a).

2.5. The Netherlands

2.5.1. Political factors

The Netherlands has had a varied history with respect to energy policy. At times, it has been a frontrunner in sustainable development, while at other times it has seen this leading position disappear. An important factor has been the very large natural gas resources which, starting in the 1960s, have had a great impact on both the Dutch energy infrastructure and the Dutch economy. Figure 36 shows that gas revenues have constituted a very significant part of government revenues since the 1960s.

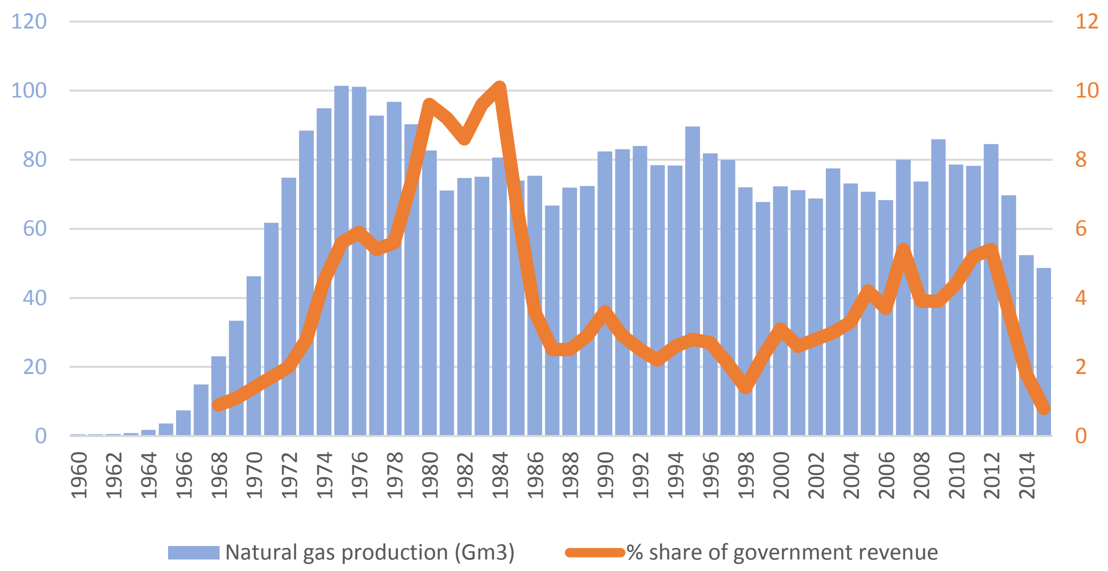

Figure 36: Natural gas in the Netherlands.

The abundance of natural gas has had a dampening effect on large scale investments in renewable energy and energy efficiency. This is evidenced by Figure 37, which shows that the Netherlands have been lagging behind most of the EU's countries in terms of renewable energy consumption.

More focus was given to these topics starting from around 2000 with various subsidy programmes. However, the policies did not always match the market development and sometimes were prematurely withdrawn.

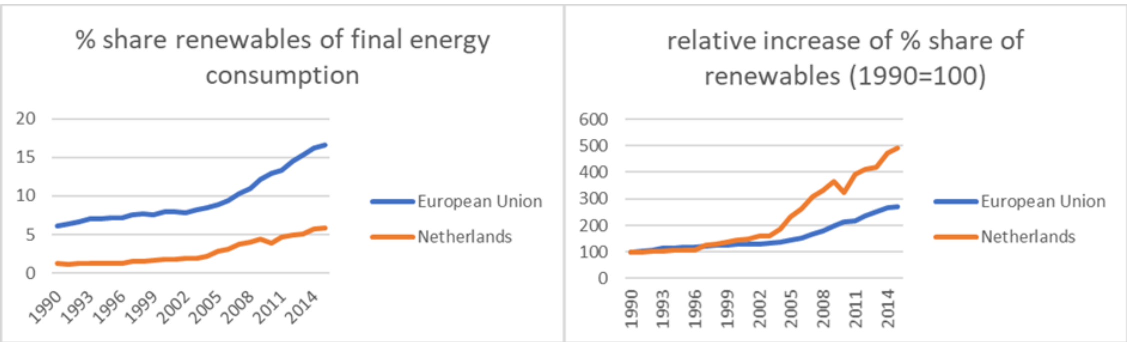

Figure 37: Evolution of percentage share of renewables in the Netherlands.

From the 2010s onward, a more consistent policy was put in place with respect to climate and energy. In 2011, a climate agenda for municipalities and provinces was published. In 2013, the publication of the Energy Accord for Sustainable Growth set a 16 % target for renewables by 2023 as well as the Climate Agenda with a 40 % CO_2-emission reduction target by 2030. The Netherlands were part of the Paris accord in 2015 and updated their CO_2-targets with an 80-95 % reduction target by 2050. In 2017, the energy intensive industry agreed on a 9 PJ reduction by 2020. In 2018, a ban on coal-powered electricity production by 2030 was put in place, with the aim for the two oldest plants to close by 2025.

During the run-up to national elections in 2017, sustainability was a topic of low importance. However, the winning Green Party expressed a great focus on sustainability unlike the other parties, such as the Liberal party. The government currently consists of the Liberal party (VVD), the Christian-democrat party (CDA), the Centre-democrat party (D66) and the Christian-social party (ChristenUnie).

Following the elections in 2018, both a climate law and a climate accord were drafted. The former concretises mid- to long-term climate policy, while the latter attaches concrete measures, targets and obligations (Van 't Lam en Vos 2018). At the time of writing, both documents have not yet been finalised, however, certain pertinent aspects can already be ascertained:

- **CO2 reduction:** 49 % CO_2 emissions reduction target by 2030;
- **Renewable electricity**: five-fold increase by 2030: from 17 to 84 TWh, with 49 TWh covered by offshore wind and the remainder by onshore renewables like wind and solar;
- **Cost and pricing**: the goal is to eliminate subsidies after 2025 and to implement robust CO_2 pricing. Expected major shift in energy taxation: 75 % increase for natural gas, 50 % reduction for electricity, to stimulate electrification;
- **Industry**: focus on electrification, hydrogen and carbon capture, utilisation and storage;
- **Flexibility and integration**: focus on demand control, storage, international interconnection, power-to-heat and power-to-X and hydrogen;
- **Participation and public support**: tailored regional strategies and focus on efficient use of space.

2.5.2. Economic factors

General economic situation

Gross Domestic Product (GDP) in the Netherlands grew by 3.2 % in 2017 and is expected to grow by 3.0 % and 2.6 % in 2018 and 2019, mainly driven by domestic demand. The current economic boom is attributed to the favourable international economic situation, low interest rates, expansive government policy and a strong housing market. Consumer spending is up by 2.2 %; the unemployment rate was 4.9 % in 2017 and is expected to go down to 3.5 % in 2019 (it was 7.4 % in 2014). Wages went up by 1.9 % in 2017 and are expected to increase by 2.7% and 3.3% in 2018 and 2019. Export growth was 6.1 % in 2017, resulting in a trade surplus of more than 10 % of GDP.

Companies have seen record profits. The sector that has seen greatest growth is professional services with 5.7 %. The construction and trade sectors also performed well, both with 5.6 % growth. Industry has grown by 4.4 %, mainly driven by the production of machinery, equipment and transportation and by the chemical industry. Mining has decreased significantly, mainly due to tightened production limits on natural gas. Bankruptcies were at the lowest point since 2001.

The Government budget had a surplus of 1.1 % of GDP in 2017. It has met the European norm of at most a 3 % deficit since 2013. In 2017, Government's debt has dropped below the European 60 % norm for the first time since 2010 due to a record decrease of 18 G€.

Energy related industry

The conventional energy sector in the Netherlands employs around 170,000 FTE (Full-Time Employee). Of these, the renewable energy sector employs 52,000 FTE, or 0.7 % of the total employment in the Netherlands. The benefit to the economy of this sector is 0.8 %, which shows that the sector is relatively labour extensive. The large majority (94 %) of these jobs are due to investments, 57 % of which are in energy efficiency activities. The remaining 6 % are due to energy exploitation activities. The solar and wind sectors represent 13,000 FTE (both exploitation and jobs from investments)(CBS, n.d.).

The contribution of various aspects of the energy sector to the Dutch economy is presented in Figure 38. As can be seen, the Netherlands is a net importer of energy. Production is very significant, which is mostly due to natural gas production. The contribution of energy related activities to the Dutch economy, shown Figure 39, is going down strongly in recent years, primarily due to the reduced natural gas production and a stronger focus on RE/EE. This is also reflected in Figure 40, which shows that investments in conventional energy are declining significantly, whereas investments in RE, EE and infrastructure are increasing.

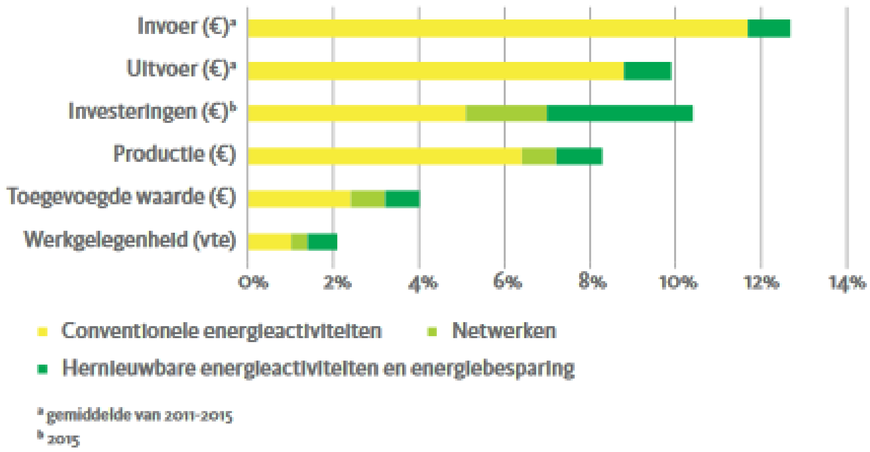

Figure 38: contribution of energy related activities to the Dutch economy for various indicators in 2016. "Invoer" = import; "uitvoer" = export; "investeringen" = investments; "productie" = production; "toegevoegde waarde" = added value; "werkgelegenheid (vte)" = employment (FTE).

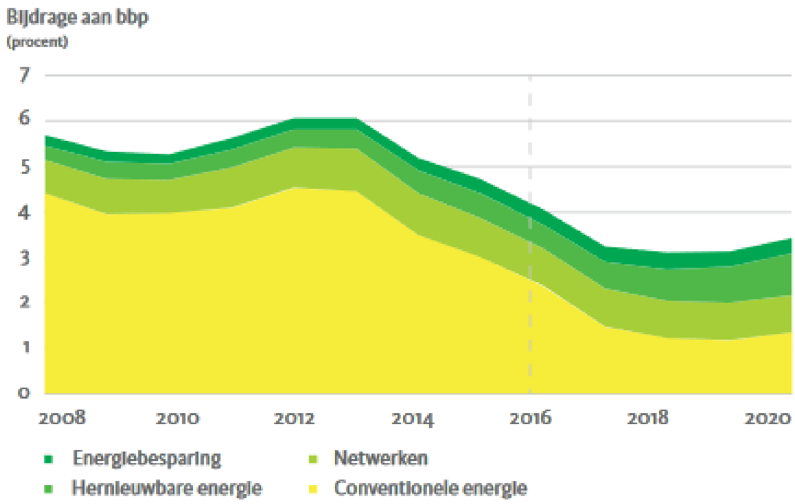

Figure 39: Contribution of various energy related activities to the Dutch GDP ("Energiebesparing" = energy savings/efficiency; "hernieuwbare energie" = renewable energy; "netwerken" = networks; "conventionele energie" = conventional energy).

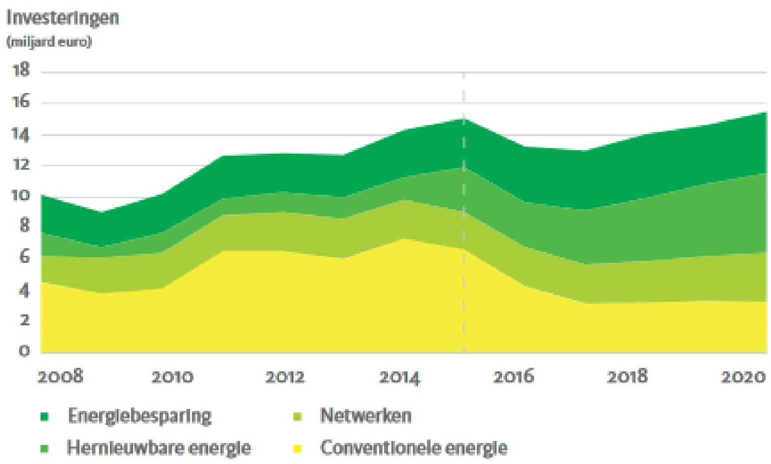

Figure 40: investments in energy related areas ("Energiebesparing" = energy savings/efficiency; "hernieuwbare energie" = renewable energy; "netwerken" = networks; "conventionele energie" = conventional energy).

Energy taxation

Dutch energy taxes fall under the umbrella of environmental taxes, which cover also areas like tap water and waste (Table 2). Taxes vary by energy carrier (e.g. electricity or natural gas) and are tiered based on consumption. There are two main components to energy taxes:

- Regular tax
- *Opslag Duurzame Energy* (ODE - surcharge renewable energy)

The latter is used to stimulate renewable energy investments. The SDE+ program (see below) is funded from the revenues of this tax. 21 % VAT is charged over the total amount the end user pays, i.e. the sum of energy price and taxes. The rates for 2018 are given below. Several refunds or lower tariffs exist for e.g. energy intensive industry and horticulture. In addition, several exemptions exist, e.g. to industrial parties whose electricity is completely produced from renewable sources (PwC, 2017).

A CO_2 tax is topic of discussion, but currently only the ETS as a direct CO_2 instrument is applied.

Table 2: Taxation on energy in the Netherlands.

Natural gas						
Consumption [m^3]	0-5,000	5,001-170,000	170,001-1,000,000	1,000,001-10,000,000	10,000,000+ (private)	10,000,000+ (commercial)
Regular tax per m3	€ 0,26001	€ 0,26001	€ 0,06464	€ 0,02355	€ 0,01265	€ 0,01265
ODE per m3	€ 0,0285	€ 0,0285	€ 0,0106	€ 0,0039	€ 0,0021	€ 0,0021
Electricity						
Consumption kWh	0-10,000	10,001-50,000	50,001-10,000,000	10,000,000+ (private)	10,000,000+ (commercial)	
Regular tax per kWh	€ 0,10458	€ 0,05274	€ 0,01404	€ 0,00116	€ 0,00057	
ODE per kWh	€ 0,013200	€ 0,018000	€ 0,004800	€ 0,000194	€ 0,000194	

Subsidies for renewable energy sources

The main instrument the government uses to stimulate renewable energy investments is the *Stimuleringsregeling Duurzame Energieproductie*, or SDE+. This subsidy program provides a semi-annual budget for investment projects. The subsidy is awarded to parties with the smallest claim on a long-term feed-in tariff. This way, scale and innovation are awarded because these are expected to drive down the kWh-price.

Different renewable technologies compete for the same budget. Some technologies are more “expensive” for the subsidy provider, i.e. in terms of the claim that is expected to compensate for the unprofitable portion of an investment. To still allow the more expensive technologies like photovoltaics or geothermal to also have a chance of receiving a subsidy, the claim per kWh is capped for the “cheaper” technologies through a tiered application system. In some years this has resulted in significant subsidies for e.g. photovoltaic projects, whereas in other years the budget was fully claimed by the cheaper technologies like biomass and wind.

The actual subsidy per year is corrected for changes in market energy prices. The subsidy is granted for a period of 12-15 years, depending on the technology.

In 2017, the SDE+ budget consisted of 12 G€ divided in two rounds and it was fully claimed. In 2018, the spring round of 6 G€ was not fully exhausted. This was thought to be caused mainly by a decrease in large-scale biomass and wind projects. The budget for the fall round of 2018 is again expected to not be fully claimed.

The Energy Investment Credit (EIA, *Energie Investerings Aftrek*) is a fiscal incentive available to companies in the form of a tax credit on a wide range of RES/EE investments. A percentage of the investment amount may be subtracted from the company’s profit, resulting in lower taxes paid. In 2018, this percentage was 54.5 %. At a corporation tax rate of 25 %, the net benefit in avoided taxes is 54.5 % x 25 % = 13.6 % of the total investment.

Innovation subsidies are available for a wide range of RE/EE topics such as offshore wind, geothermal, hydrogen, urban environment, CCUS (Carbon Capture, Use and Storage), green gas and energy in industry, covering the topics of the TKI’s (see above) and adjacent areas of interest. Subsidies are available for collaboration projects for R&D, pilot and demonstration and vary between €50 thousand and €6 million. Figure 41 shows the total amount of subsidies for energy related R&D in the Netherlands by theme.

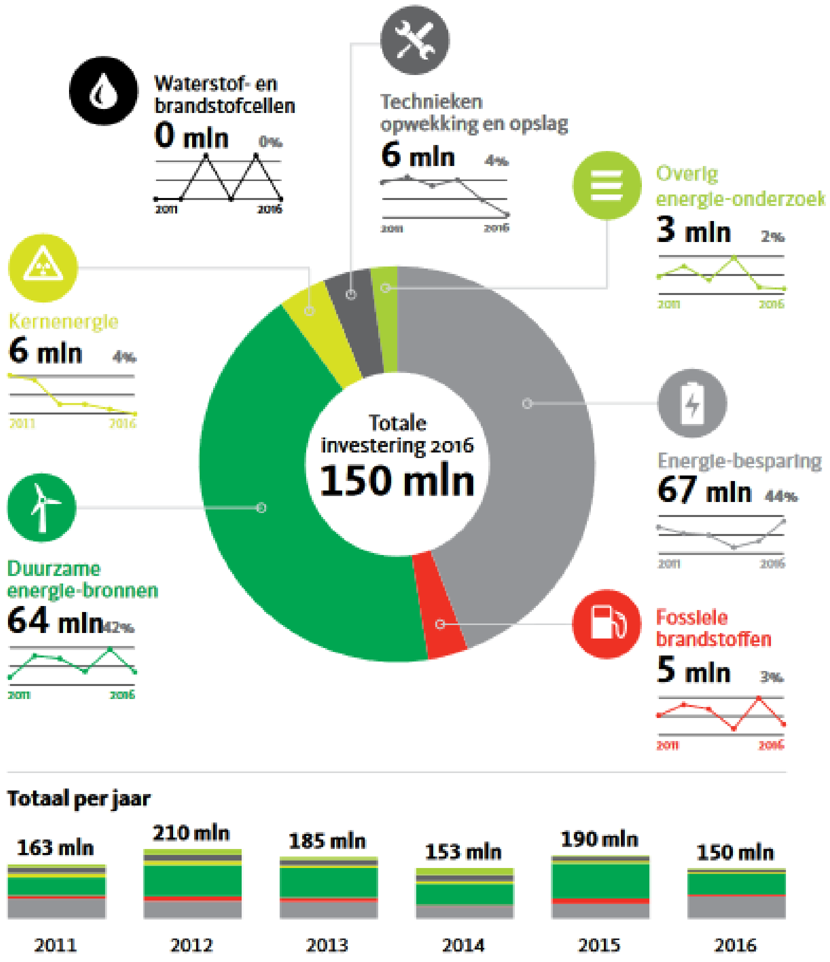

Figure 41: Energy related R&D subsidies by theme. Dutch terms, clockwise from top left: "waterstof- en brandstofcellen" = hydrogen and fuel cells; "technieken opwekking en opslag" = techniques for storage and generation; "overig energie-onderzoek" = other energy research; "energiebesparing" = energy saving/efficiency; "fossiele brandstoffen" = fossil fuels; "duurzame energiebronnen" = renewable energy sources; "kernenergy" = nuclear energy. Center: "totale investering" = total investment.

Import and export of electricity

The Dutch energy market is strongly integrated with the North-western European market. The Netherlands is therefore in large part dependent on developments in neighbouring countries in areas like renewable energy production (capacity), import/export, and electricity prices. Both energy prices and investments are tightly connected with the developments in neighbouring countries. Current and projected interconnections are shown in Figure 42. The Netherlands is a net importer of electricity, as is shown in Figure 43.

	Huidig	2020	2025	2030
NL-DE	2450	4250	5000	5000
NL-BE (BE-NL)[a]	1400	1400 (2400)	3400	3400
NL-DK	0	700	700	700
NL-UK	1000	1000	1000	1000
NL-NO	700	700	700	700

Figure 42: Current ("huidig") and projected international interconnection capacity in MW.

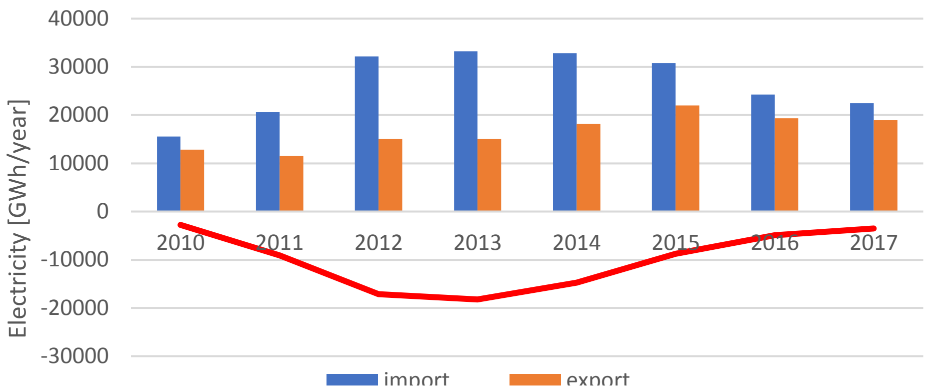

Figure 43: Electricity import vs export in the Netherlands in recent years (source: CBS).

Wholesale market

The Netherlands has an energy-only market of electricity. Proponents of a capacity market are becoming more numerous, but this has not yet materialised. Steps in that direction are being taken through aggregators, but a formal capacity market has not been established.

Figure 44: Dutch electricity markets as a function of the time between trade and use.

Electricity is traded on several platforms (OTC – month/quarter/year, APX – day-ahead, intraday). In 2018, the use of the European Cross Border Intraday (XBID) platform was greenlighted. Figure 44 shows the different electricity markets.

2.5.3. Social factors

Employment

Employment in the conventional energy sector has decreased significantly in recent years, from 83,000 FTE in 2014 to 73,000 in 2016. The decrease is mainly caused by lower investment activities in the oil and gas industry. In the same period, the number of jobs in renewable energy related fields grew from 46,000 FTE to 52,000. This increase is expected to continue due to continuously increasing demand. Job growth is expected mainly in the construction and installation sectors, which is seeing rapidly increasing shortages of skilled workers. A shortage of 15,000 workers is expected in the near future. Industry associations are starting initiatives to attract and train new employees. DSOs are also experiencing shortages of workers.

Another issue is the fact that relatively many employees involved in the energy transition are over 45 years old and that relatively few educational programs specifically targeting the energy transition exist. The sector is heavily tilted toward a male workforce.

General expectations as to needed skills and knowledge are that the average required education level will go up and that work will get more highly specialized. This also changes the nature of collaboration, which in turn will increase the importance of social innovation within organisations (Sociaal Economische Raad, 2018).

Public support and perception

Public support for the energy transition is largely positive, with 75 % of the population in favour of supporting renewables and only 2 % against. The majority expects developments to result in larger energy independence and an improved and more competitive economic position.

The Dutch population in 2015 overestimated the progress being made in the transition. They estimate that 50 % of energy came from fossil fuels (actually 90 %) and that more than a third was renewable (actually 6 %). This overestimation may weaken the sense of urgency and pose an obstacle toward reaching sustainability targets.

Only a minority think the attention for sustainability is overblown. The wish for an increase in the share of renewables is prevalent, although only 20 % put energy in their top-5 of most pressing societal problems (Motivaction, 2016).

An important aspect of generating public support is ensuring the burdens and benefits are shared equally. A 2017 study identifies several topics which may cause division among varying groups in society along dimensions of income, employment, geographical location and mobility (ECN, 2017). Some examples:

- Investments in solar energy are quite profitable, but low-income households generally are unlikely to invest.
- The forced abolishment of natural gas disproportionally affects poor home owners who generally live in lower-quality homes and cannot invest in alternative RE/EE measures.
- Large scale solar and wind parks are most feasible in areas with low urbanisation, disproportionally impacting the living environment in rural areas.

2.5.4. Technological factors

Current situation

The Dutch energy system is characterized by a high reliance on fossil fuels, mainly natural gas and coal. Renewable energy represented 6 % of total energy consumption. An overview of the Dutch energy system in terms of import, export, production, conversion and consumption is provided in Figure 45. A translation table for the Dutch terms is included.

Electrical grid

The Netherlands has one TSO (TenneT) responsible for the high voltage infrastructure, which consists of transmission lines at various voltages (380, 220, 150 and 110 kV) and connections between these (Figure 46). In addition, TenneT is responsible for correcting for imbalance on the national level by buying or selling energy on the “imbalance market”. The transmission net consists of around 20,000 km of circuit, 443 substations, 36 million end users and 67 GW of installed capacity. TenneT aims to make the Netherlands one of the central hubs for the Northwestern European electricity system. This involves significant upgrades to international connections to the UK, Norway and Denmark.

The distribution network is operated by 8 DSOs, connected to the transport network at the substation level. These are responsible for the low voltage distribution infrastructure and the connections to the end users. By law, these are prohibited from performing supply activities (see 2.5.6). This role is provided by energy suppliers who trade energy over the distribution grid, irrespective of geographical location.

The Dutch grid provides a high degree of electricity security with a large surplus of generating capacity with reserve margins of over 40%. This is in part due to the small share of (intermittent) renewable production, which means that even under the most ambitious medium-term renewable expansion, margins are still expected to be more than sufficient. However, this is not taking into account the possible premature closing of gas or coal fired power plants due to reduced gas production, changing political climate and public perception (IEA, 2014).

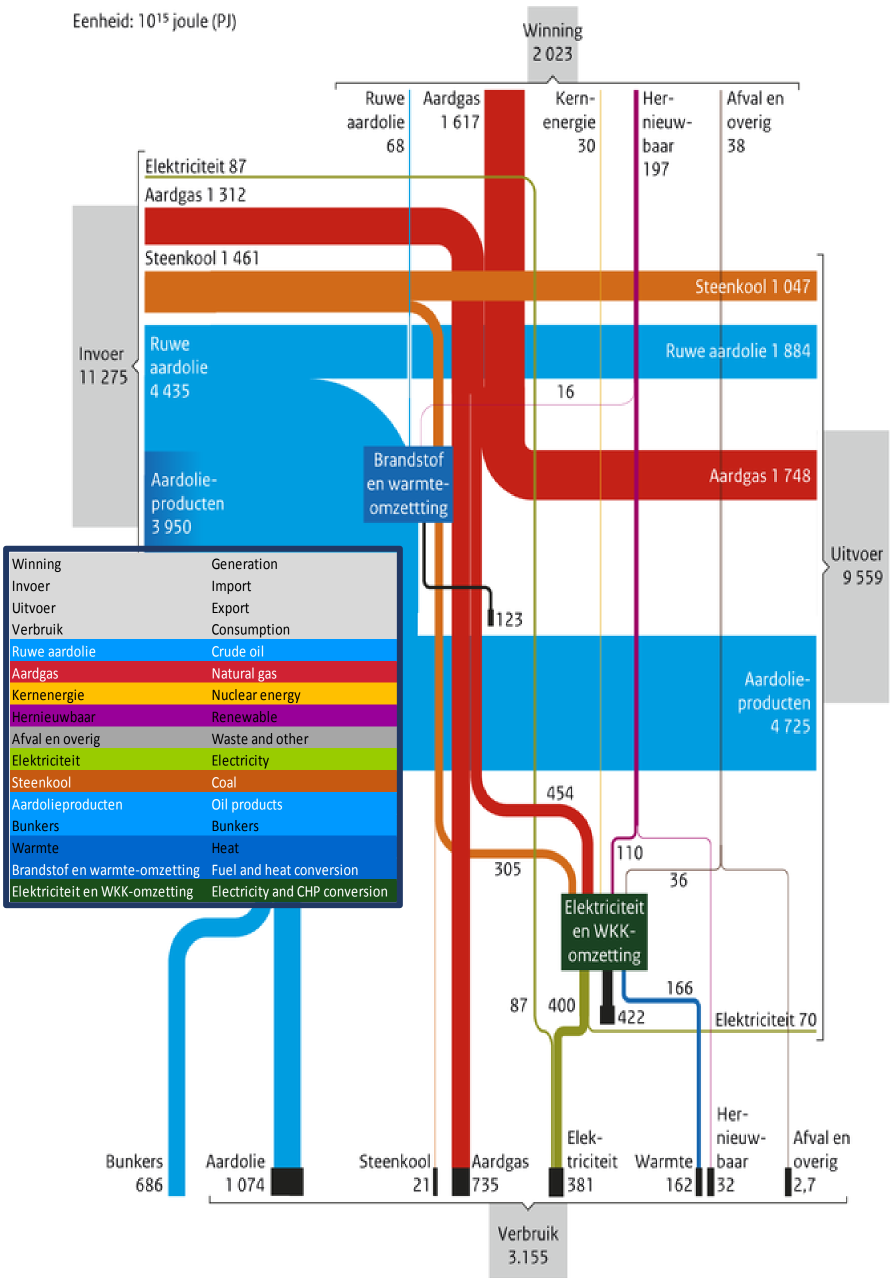

Figure 45: Sankey diagram of the Dutch energy system with translation table for Dutch terms. Size of energy streams is indicated by the numbers (PJ) as well as the width of the bands.

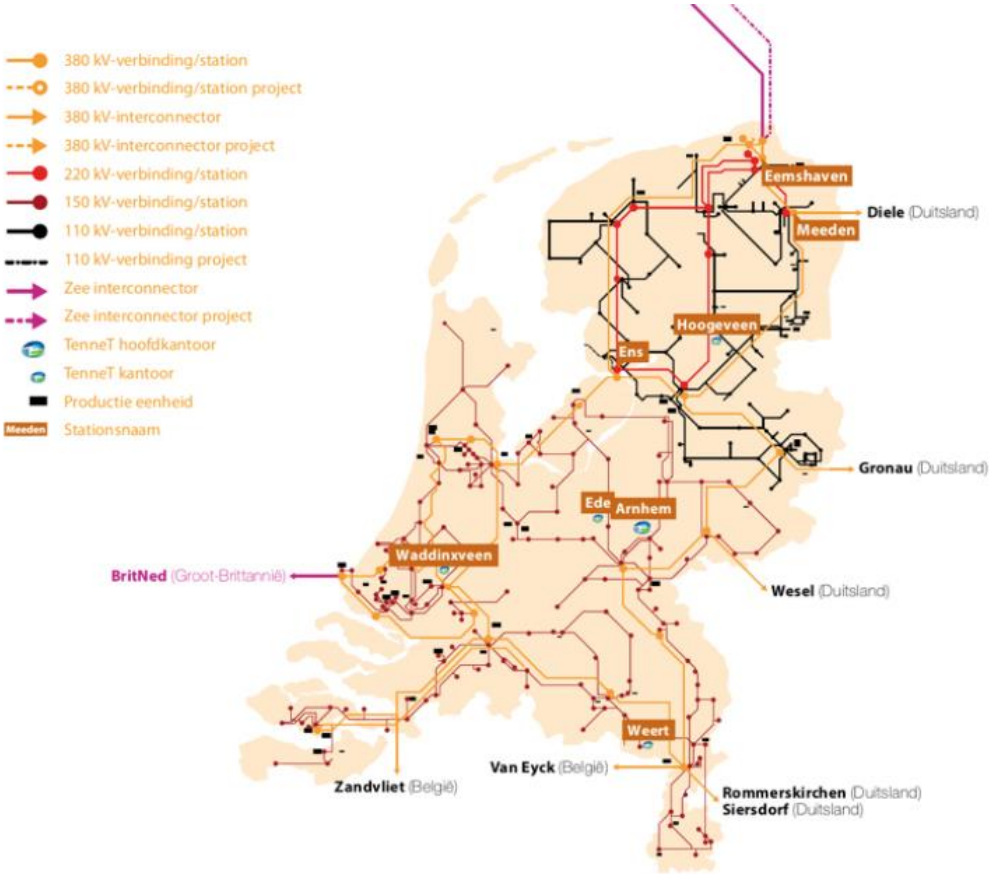

Figure 46: Dutch high voltage infrastructure including international interconnections.

Future scenarios

In 2018, the national government committed to more ambitious CO_2 emission reduction targets, notably a 49 % reduction by 2030. This will require major investments in many aspects of the energy system. Scenarios were evaluated by the *Planbureau voor de Leefomgeving (PBL)* on cost versus effectiveness in achieving the goals at two main levels of ambition.

1. **Static cost optimal**. Measures are selected in order of decreasing cost effectiveness (cheapest first). Measures already agreed on in the coalition accord were included, most importantly the closing of coal-fired power plants. Realizable potential was used as a criterion (versus technical potential, which does not consider possible practical obstacles like currently missing legislation or instruments). EU policy is adhered to. Import/export effects of electricity are kept at minimum.
2. **Transition.** This takes scenario 1 as a basis, but instead of aiming to reach only the 2030 target, it aims to reach that target *and* be optimally positioned by that time to reach the 95 % reduction target by 2050. This means that other, more expensive choices than in scenario 1 to reach the 2030 target might be made initially, in order to eventually arrive at the 2050 targets (which might not be feasible building on the choices made in scenario 1). Backcasting is used determine which measures must be prepared for.

These scenarios show that the added costs of the new 49 % target will be between 2.1 and 3.4 G€ per year (Planbureau voor de Leefomgeving 2018). Table 3 lists the most cost-effective measures per sector, giving an indication of which measures have a higher chance of implementation.

Table 3: RES measures considered for the future development of the Dutch energy system.

Measure	Emission reduction (Mton)	Cost effectiveness (€/ton)
Electricity production		
8 GW extra-large scale PV	3.2	-20
5.4 GW extra onshore wind	5.7	-20
1.6 GW extra nuclear	4.5	20
5.3 GW extra offshore wind	8.3	20
Industry		
Recycling	2.2	-140
Process efficiency (low cost)	3.3	-120
CSS industrial process emissions	1.5	40
Urban environment		
A+++ equipment in homes	0.5	-20
Residential PV	4.9	110
Insulation existing homes	3.3	290
Transportation		
Efficient tyres (potential)	0.6	-300
CO2 norm freighting 2% increase by 2021	0.6	-260
CO2 norm freighting 2.8% increase by 2021	0.9	-240
Agriculture and land use		
Geothermal horticulture	1.1	-20
Methane oxidation manure	0.6	10
Greenhouse as energy source	1.9	70

2.5.5. Environmental factors

Greenhouse gas emissions were almost 200 MTon of CO_2 equivalents in 2017. The Netherlands ranks 24 in the EU in terms of emissions per capita and 26 in terms of the share of renewables (annual generation). Figure 47 shows the emissions per sector over time. Although the trend is downward, recent years have seen an increase in emissions again, mainly due to the improved economic situation causing e.g. more road traffic.

Progress is being made recently, with a 3 % reduction between 2017 and 2018. This was mainly caused by the closing of coal-fired power plants. Energy consumption in e.g. transportation, agriculture and construction has gone up, however, indicating that a society-wide transition is still challenging.

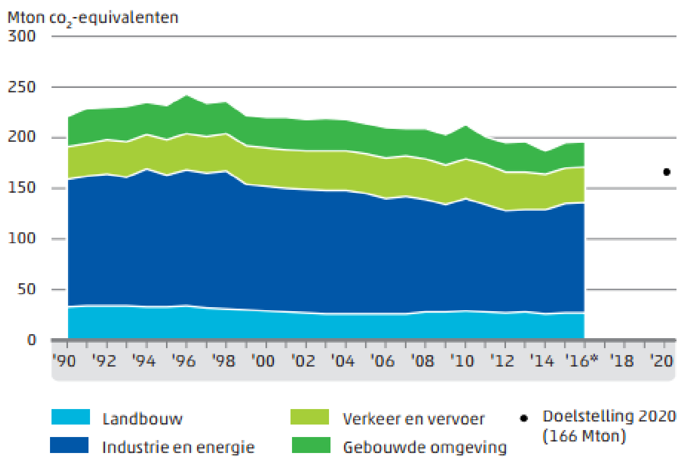

Figure 47: Greenhouse gas emissions per sector.

2.5.6. Legal factors

Roles and institutions

The Ministry of Economic Affairs and Climate Policy is responsible for energy and climate policy in the Netherlands, with certain areas also covered by the Ministry of Infrastructure and Water Management.

The Netherlands Authority for Consumers and Markets (ACM) is the independent regulator of the energy market.

The TSO TenneT has a lawful monopoly on the Dutch high voltage infrastructure. It is wholly owned by the Dutch government and its activities are regulated. Its fees are controlled by the ACM.

Up to 2004, energy companies performed both energy supply and DSO roles. However, in 2004, the energy market was opened up through the forced separation of energy companies into energy providers and DSOs. Both types of companies are privately owned, but their roles are regulated by the ACM. The two tasks of the DSOs are to maintain the infrastructure and to facilitate the functioning of the energy market. DSOs are prohibited to take on other roles, which causes friction when they might want to introduce new concepts or technologies that cross the boundary between the playing fields of DSOs and energy companies. An example is smart charging of electric vehicles. DSOs would benefit from managing the infrastructure before and after the charging station, since this allows them to manage flexibility on the grid, reducing the need for large grid capacity investments. However, currently they cannot play a role or invest on the user side of the charging station. Exemptions can be given to experiment with new models.

Energy providers buy energy from energy producing parties such as power plants or solar parks. They sell this energy to end users, using the distribution network of DSOs to deliver the energy. Their activities are regulated by the ACM. For instance, they are required to provide reliable service and to charge reasonable fees.

Measurement companies are independent of the energy providers or DSOs and are responsible to accurately determine energy consumption by end users.

Aggregators are a relatively new type of player which tries to match supply and demand by combining available energy production from various sources and offering this to consumers who need flexibility.

Laws and regulations

There are distinct laws for different areas of the energy system in the Netherlands:

- Electricity law
- Gas law
- Heat law

The overarching environmental law is called *Wet Milieubeheer* (“law for environmental conservation”), which provides the legal tools to protect the environment and which translates European policy and directives to the Dutch situation. From this law, several energy related regulations have sprung:

- EED (European Energy Efficiency Directive) – mandatory 4-yearly audit for energy use and efficiency measures)
- "Activiteitenbesluit" - EE measures with payback period < 5 years are mandatory
- MJA3 - voluntary commitment to 2 % energy reduction per year
- MEE - similar to MJA3, but for companies covered by the ETS
- EPBD (Energy Performance in Buildings Directive)
    - Mandatory energy label C or better for all office buildings (2023)
    - Mandatory energy label A for all office buildings (2030)

For district heating, laws and regulations apply at various levels of government. At the municipal level, environmental and building permits are obtained so are the concessions for operators of heat nets. The provinces supply environmental permits in case of groundwater extraction for geothermal energy. The national government provides permits related to flora, fauna and soil quality. All levels of government are responsible for their own inspection and enforcement.

Storage and flexibility

The legal status of energy storage is unclear and covered by a multitude of laws and regulations (electricity law, system code electricity, tariff code electricity, EU directive 2016/631, heat law, etc.). This has several unwanted consequences, among others:

- Energy tax is charged twice: when charging and at the end user after discharging.
- Due to taxation, purchase of electricity is more expensive than sale, which makes the price of storing a kWh of electricity more expensive than it should be, dampening the adoption of storage for flexibility.
- Small prosumers (e.g. homes with solar panels) can currently offset their entire energy costs including taxes through their own production, removing any incentive for local storage.
- Time-of-use is not currently a variable in electricity prices for small consumers, removing the incentive for them to store locally generated electricity.

2.5.7. Heating sector – District Heating

District heating in the Netherlands plays a relatively small role, mainly due to the highly developed and fine-grained natural gas network. A typical energy technology in the large majority of residential and commercial buildings is a gas-powered heater. Of the 7.7 million homes in the Netherlands, around 400,000 (5 %) are estimated to be connected to a district heating system. Another 500,000 (6.5 %) homes are connected to a block heating system (ECN, 2017).

A rough classification into large heat nets, small nets and block heating can be made. The distribution of connections and consumption over these categories is presented in Table 4.

Table 4: Connections and heat consumption for large and small heat nets and block heating.

		number of connections	heat consumption (PJ/year)
Large heat nets (>150 TJ/year)	small users (<100 kW)	294000	8
	large users (>100 kW)	5000	11.6
	TOTAL	**299000**	**19.6**

Small heat nets (<150 TJ/year)	**TOTAL**	**45249**	**1.5**
Block heating	**TOTAL**	**496227**	**16**
TOTAL		**1184725**	**37.1**

The distribution of energy sources for small and large nets is listed in Table 5.

Table 5: Nature and size of energy sources for small and large heat networks.

	Consumption (PJ/year)		
	Large nets	**small nets**	**TOTAL**
CHP	13.0	0.9	**13.9**
gas-powered boiler	1.4	0.1	**1.5**
biomass	2.9	0.2	**3.1**
Other (a.o. non-biogenic waste)	3.1	0.0	**3.1**
heat-cold storage	0.0	0.2	**0.2**
TOTAL	**20.3**	**1.4**	**21.7**

A recent study on the future of heat networks in the Netherlands anticipates that in the long-term, two thirds of the low temperature heat demand could be supplied by climate neutral heat networks fed by renewable sources. In this scenario, geothermal energy would be the main contributor (Planbureau voor de Leefomgeving, 2017).

Development of district heating projects, especially using renewable energy in the form of e.g. geothermal or waste heat, can vary greatly depending on circumstances like location, public and private parties involved and scale. Often municipalities, provinces and the national government will provide financial support to get projects off the ground. Several Green Deals (see 2.5.2) have been developed around heat networks.

3. Porter's Five Forces Analysis

3.1. Introduction

Porter's five forces model (M. E. Porter, 1979) can be used to explain the competitiveness within a sector. It is the result of five forces (Figure 48), which are briefly described in the sections 3.1.1—3.1.5, after which the five forces for CHESTER is analysed:

1. threat of new competitors,
2. power of suppliers,
3. power of customers,
4. threat of substitutes,
5. industry rivalry.

Awareness of Porter's five forces can help a company understand the structure of the sector in which it operates and its profitability over the medium/long term. At the same time, it provides a reference framework through which the company can anticipate and influence the competition and profitability of the sector over time, thereby determining a lasting competitive advantage.

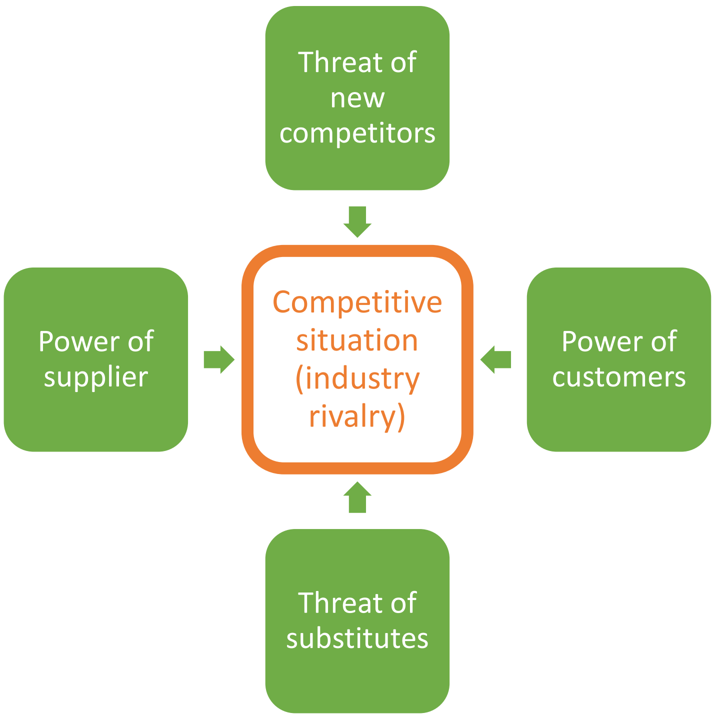

Figure 48: Porter's Five Forces.

3.1.1. Threat of new competitors

The threat of new competitors entering a certain sector can limit the profit potential of the companies already operating in the sector. A lower threat of new competitors is for example caused by higher barriers to entry. These barriers may be of different natures. Some examples are:

- Legislative barriers: e.g. the existence of patents, rights, government policy, etc.

- Start-up cost and economies of scale: high start-up costs and cost structures characterized by large fixed cost and low operating cost represent a barrier to entry, because a new player must face a large upfront investment and then be able to become sufficiently large to make profit.
- Restricted/limited access to distribution channels.
- Customer loyalty: customers may be loyal to a brand, and therefore unlikely to change supplier, even when offered a product with equivalent or better quality-to-price ratio.
- Switching costs: customers may be unwilling to change from one supplier to another because of high costs incurred through switching suppliers.
- Profitability: the lower the industry profitability, the lower the threat of new entries.
- Expertise: sectors characterized by steep learning curves may be unattractive to new players, which may struggle to compete against experienced companies.

3.1.2. Power of suppliers

The bargaining power of the suppliers may contribute in reducing profit margins in a certain sector, by raising the prices or reducing the quality of the supplied goods and services.

The bargaining power of suppliers depends, among other things, on the size of the company with respect to suppliers, the presence and differentiation of substitute input products that can be purchased by the company, the costs for switching to another supplier, supplier competition (i.e., the ability of the supplier to forward-integrate and cut out the buyer). Additionally, it is important to consider the sensitivity of the overall cost, quality and differentiation of the final product/service on the cost and quality of the input product.

3.1.3. Power of customers

Customers can exercise their bargaining power and capture greater value by forcing lower prices, demanding higher quality or better services, and generally forcing companies within a sector to fight against each other. The power of customers is influenced by different factors: size of purchases (the larger the volume purchased by a customer, the larger the contractual power), number of customers (the fewer the customers, the larger their bargaining power), possible backward-integration, switching costs, availability of existing substitute products.

3.1.4. Threat of substitutes

Substitutes are products technologically different from that proposed by the company treated in the Porter’s analysis, but which satisfy an identical or similar need of the customer. How much of a threat a substitute product represents is influenced by several factors, such as buyer's switching costs, buyer propensity and ease to substitute, price and quality performance of the substitute. Rapid technological development can dramatically change a sector by creating completely new substitutes.

3.1.5. Industry rivalry

The level of profit in a sector is determined by the degree of competition between the existing companies. Several factors affect the degree of competition: concentration of the sector, differentiation of the product, excess production capacity, barriers to exit, economies of scale and cost structure.

3.2. Porter's Analysis of the CHEST system

Electrical energy storage (EES) technologies are those where electricity is transformed from one form to another —the latter being suitable to be stored—, which is then converted back to electricity as per requirement. The stored energy can be used in periods of high demand, high generation costs and/or low energy production.

Several factors are expected to boost the global market for EES. These include:

- a steady increase in the electricity demand worldwide,
- higher share of RES (often fluctuating) in the electricity generation mix,
- an increase in renewable energy curtailment,
- requirements for reliability of the electrical grid,
- need to increase energy efficiency and reduce CO_2 emissions,
- coupling of different energy sectors, such as electricity, heating, cooling and transport.

As of mid-2017 the estimated EES capacity installed worldwide was approximately 4.7 TWh in terms of energy and 176 GW in terms of power capacity (International Renewable Energy Agency, 2017), which was about 2 % of the world's total generation capacity. This percentage is recommended to be about 8 %, solely for peak shaving and daily charge/discharge cycles (Du & Lu, 2014). If fluctuating RES are to increase their share in the generation mix, the required capacity of EES should be even higher. According to (Bloomberg, 2017), the global market for EES would double six times from 2017 to 2030, reaching a deployment of 125 GW/year, equivalent to 300 GWh/year (Figure 49). About 90 G€ are expected to be invested in EES over that period. Moreover, the IEA estimates that limiting global warming to 2 °C would require the global installed EES capacity to increase to 450 GW by 2050 (Bardajií et al., 2017).

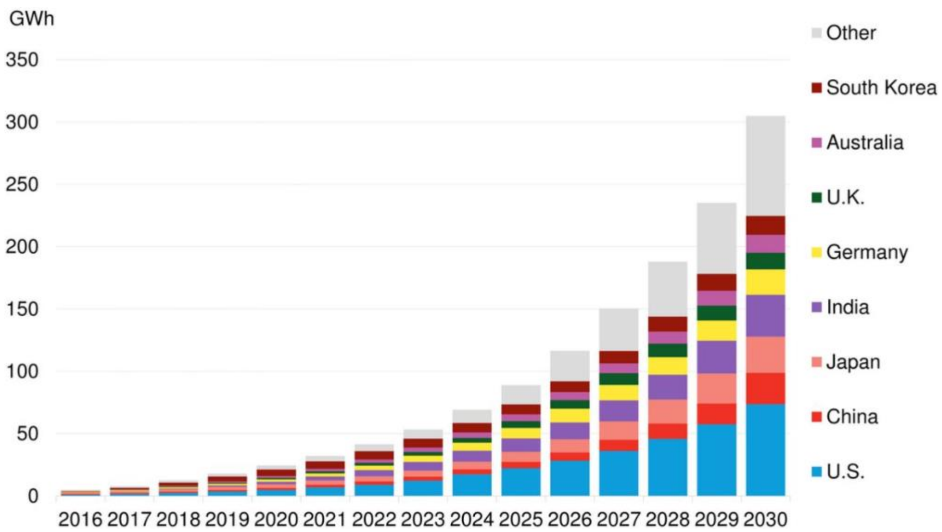

Figure 49: Forecast of EES deployment worldwide until 2030 by country (Bloomberg, 2017).

3.2.1. Threat of new competitors

The strong growth of the EES market which is expected in coming years (Figure 49) and the strategic importance which is recognized to the sector is likely to favour the profitability of the EES industry. This may push new players to enter the market either as new suppliers of existing technologies or with completely new solutions. The CHEST system itself is proposed as a new potential competitor in the field of EES.

The sector of EES has been extremely dynamic in the last years. After a century, during which the sector only had pumped hydro as a player, the last decades have seen the birth and development of new technologies. In this respect electrochemical EES (batteries) deserves a notable mention, as this is the technology which has grown more rapidly in the last years.

Although a variety of well-established chemistries already exists (e.g. lead-acid, lithium-ion, etc. in subsection “Batteries” in Section 3.2.4), the development is non-stopping. New chemistries, which currently are just in the research phase, are claimed to have the potential to replace present batteries within the next one or two decades. These chemistries include metal-air, sodium-ion, lithium-sulphur and sodium nickel chloride (Bardajií et al., 2017).

With respect to hydrogen, the well-established alkaline electrolysis (subsection “Chemical storage” in Section 3.2.4), could be replaced by proton exchange membrane cells, characterized by higher power density and efficiency (Bardajií et al., 2017).

Despite the ongoing developments and rapid changes in the EES sector, different barriers in different countries may currently limit the growth of the stationary EES market worldwide. The barriers include (Eller & Dexter Gauntlett, 2017):

- lack of familiarity with EES among utilities, regulators and financiers;
- high upfront costs. Although the cost composition changes from one EES technology to another, all of them are characterized by high investment costs and relatively low operation costs;
- need for skilled and experienced technicians to maintain and operate the systems;
- regulations preventing third-party or customer ownership of certain distributed energy resources;
- regulations preventing EES from competing in energy, ancillary service or capacity markets.

If a new competitor plans to enter the market offering well-established technologies, the threat toward existing players seems fairly weak, mainly because of the high upfront costs which must be faced and the required expertise. Another factor that limits the threat of new competitors is represented by the high switching costs. EES systems have generally fairly long technical lifetimes (except for some battery chemistries) and high investment costs (Table 7), so decommissioning an EES to install a new one before the end of its lifetime may be very costly. Furthermore, the market for EES is expected to grow so much in the near future, that new technologies could find opportunities for entering the market, focusing on new capacity to be installed, rather than replacing operating EES.

A potential competitor entering the EES sector with a new technology may rapidly conquer a large share of the market, because there is currently no EES solution which is applicable in all contexts. To be competitive and possibly disruptive, new EES technologies should be efficient, reliable, cost-effective over a long lifetime, site-independent, environmentally and socially acceptable.

3.2.2. Power of suppliers

Although the main components of the CHEST system are existing technologies, such as HP and ORC, the technical characteristics required from these components make them very customized. The HP shall for example work with unusually high temperatures and temperature differences, which limits the number of refrigerants that can be used, force mechanical components to their limits or implies a heat pump configuration with multiple heating stages. The heat-engine pump is currently in a prototype phase, so it is not a standard component. Also, the components of the ORC as well as the high temperature latent heat storage system will be manufactured specifically based on the requirements of the CHESTER project. Therefore, it can be expected that the number of potential suppliers of the different components will be very limited, especially in the first period of the CHEST technology. This will give the suppliers a strong bargaining power and the possibility to drive the prices up.

However, if the technology proves to be promising and competitive, other suppliers of HP, ORC and TES components would be interested in entering this new market, making their offers to supply relevant components for the CHEST system. If suppliers spot a good potential in the CHEST system, they would be keen on favouring its development, by applying reasonable pricing and providing assistance, for example in R&D.

Heat pump

For the HP, the critical component that will certainly limit the access to this technology is the compressor. The development of a dedicated high-temperature compressor suitable for the CHEST system is something considered out of reach of the CHESTER project. Thus, a complete dependency on the suppliers is expected for this technology.

The development of commercially available low- to medium-sized high-temperature HP (<2 MW_{th}) is in its initial phases, reaching for the moment temperatures at around 165 °C with few manufacturers that could reach temperatures above 110 °C (Kobelco, Viking Heat Engines, Ochsner, Hybrid Energy AS, Mayekawa, Oilon, etc. see Figure 50). However, this market sector seems very active, mainly due to the recent interest in introducing this technology in industrial processes (mainly in waste heat recovery and drying processes), so a fast introduction of new competitors and products may occur in the following years.

Whereas for large-scale high-temperature HP (>2-3 MW_{th}), there are no known manufacturers that can provide a HP operating at temperatures higher than 90 °C, and the market in this application range seems to be controlled by a few large corporations (Johnson Controls, GEA, Carrier, Friotherm, etc. see Figure 51). For this capacity range, it is less likely that a fast introduction of new high-temperature models could take place in the next years, and the presence of new manufacturers is not likely.

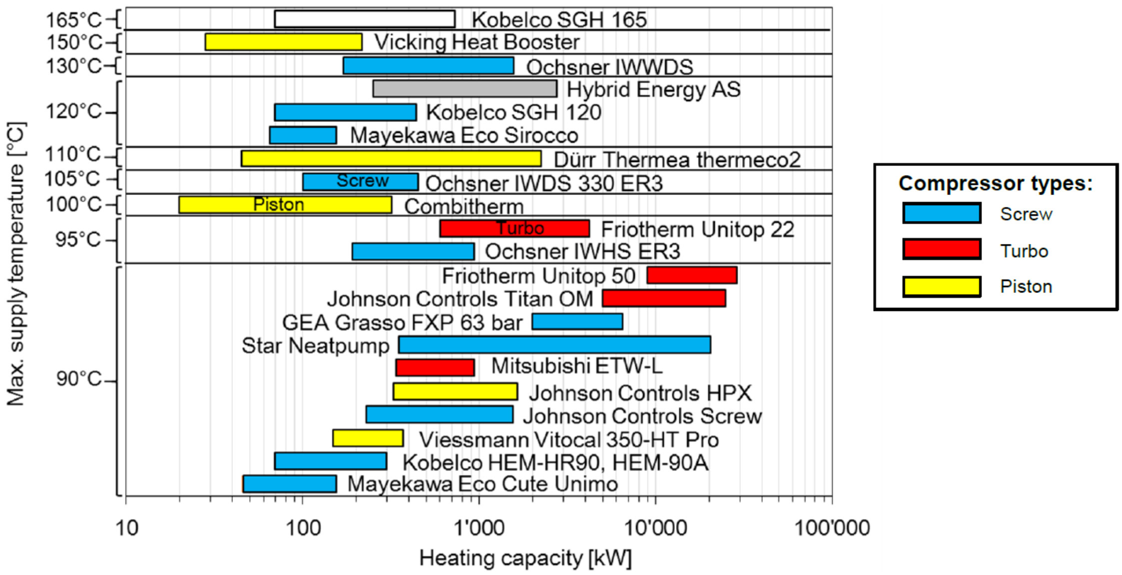

Figure 50: Commercially available industrial HT-HPs C (Arpagaus, Bless, Schiffmann, & Bertsch, 2017).

Manufacturer	Product	Refrigerant	Max. supply temperature	Heating capacity	Compressor type	Reference
Kobe Steel (Kobelco Steam Grow Heat Pump)	SGH 165 SGH 120 HEM-HR90,-90A	R134a/R245fa R245fa R134a/R245fa	165°C 120°C 90°C	70 – 660 kW 70 – 370 kW 70 – 230 kW	Double screw	(IEA, 2014a; Kaida et al., 2015; Kuromaki, 2012; Watanabe, 2013)
Vicking Heating Engines AS	HeatBooster S4	R1336mzz(Z) R245fa	150°C	28 – 188 kW	Piston	(Nilsson, 2017; Nilsson et al., 2017; Viking Heat Engines AS, 2017)
Ochsner	IWWDSS R2R3b IWWDS ER3b IWWHS ER3b	R134a/ÖKO1 ÖKO (R245fa) ÖKO (R245fa)	130°C 130°C 95°C	170 – 750 kW 170 – 750 kW 60 – 850 kW	Screw (twin unit 1.5 MW)	(Ochsner, 2017a, 2017b, 2015; Zauner, 2016)
Hybrid Energy	Hybrid Heat Pump	R717 (NH_3)	120°C	0.25 – 2.5 MW	Piston	(Hybrid Energy SA, 2017; Jensen et al., 2015a, 2015b)
Mayekawa	Eco Sirocco Eco Cute Unimo	R744 (CO_2) R744 (CO_2)	120°C 90°C	65 – 90 kW 45 – 110 kW	Screw	(IEA, 2014a; Mayekawa, 2010; Watanabe, 2013)
Dürr Thermea	thermeco$_2$	R744 (CO_2)	110°C	45 – 2'200 kW	Piston (up to 8 in parallel)	(Dürr thermea GmbH, 2017; IEA, 2014a; Thermea, 2012)
Combitherm	Customized design	R245fa	100°C	20 – 300 kW	Piston	(Blesl et al., 2014; Wolf et al., 2014)
Friotherm	Unitop 22 Unitop 50	R1234ze(E) R134a	95°C 90°C	0.6 – 3.6 MW 9 – 20 MW	Turbo (two-stage)	(Friotherm AG, 2005; Wojtan, 2016)
Star Refrigeration	Neatpump	R717 (NH_3)	90°C	0.35 – 15 MW	Screw (Vilter VSSH 76 bar)	(EMERSON, 2012)
GEA Refrigeration	GEA Grasso FX P 63 bar	R717 (NH_3)	90°C	2 – 4.5 MW	Double screw (63 bar)	(Dietrich and Fredrich, 2012)
Johnson Controls	HeatPAC HPX HeatPAC Screw Titan OM	R717 (NH_3) R717 (NH_3) R134a	90°C 90°C 90°C	326 – 1'324 kW 230 – 1'315 kW 5 – 20 MW	Piston (60 bar) Screw Turbo	(Johnson Controls, 2017)
Mitsubishi	ETW-L	R134a	90°C	340 – 600 kW	Turbo (two-stage)	(IEA, 2014a; Watanabe, 2013)
Viessmann	Vitocal 350-HT Pro	R1234ze(E)	90°C	148 – 390 kW	Piston (2-3 in parallel)	(Viessmann, 2016)

Figure 51: Industrial HT-HPs with temperatures above 90 °C (Arpagaus et al., 2017).

Organic Rankine Cycle

The ORC is considered a mature low-temperature heat-to-power technology. Its application is found in various fields including geothermal energy, biomass and industrial heat recovery. The chart in Figure 52 shows the percentage market share of these applications. Geothermal power shows the largest market share (76%) followed by industrial heat recovery (13%) and biomass (11%). Each of these niche fields relate to specific temperature levels and capacities.

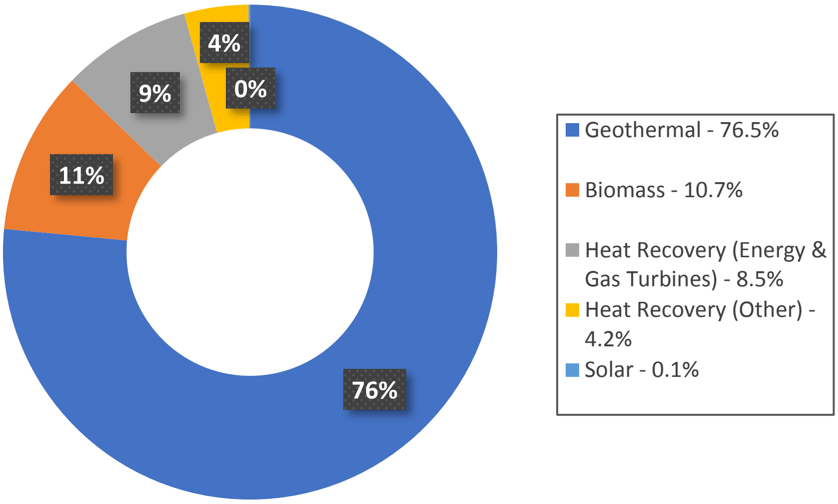

Figure 52: Percentage market share of the ORC market (Tartière & Astolfi, 2017).

Because of the applicability and incentives derived from its usage, a fairly large number of companies have come forward in the manufacturing, design, analysis and testing of ORC systems. Typically, each company focuses on a single specific field. Figure 53 lists the main ORC manufacturers and their share in the total installed capacity of these systems. The manufacturer ORMAT, which focuses on geothermal applications, is the major player with an installed capacity of 1701 MW with a total of 1102 ORC units installed (all data collected until 2016).

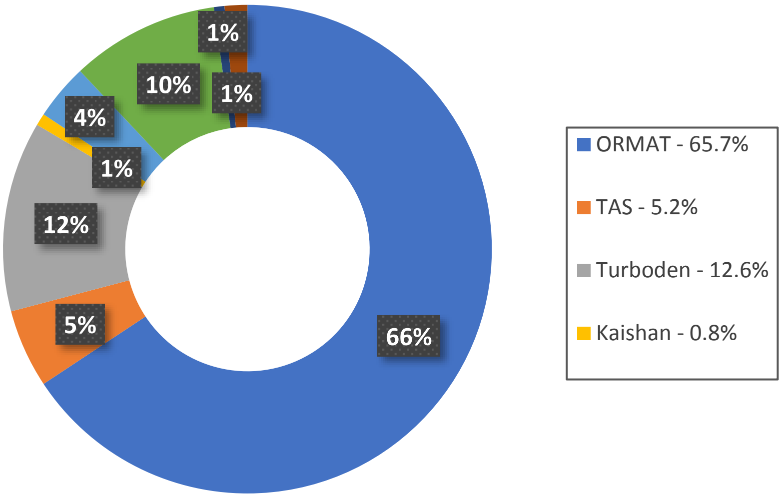

Figure 53: Share in installed capacity of difference ORC manufacturers (Tartière & Astolfi, 2017).

Based on the boundary conditions defined within the CHESTER project, the manufacturers that may have the experience, interest and required specifications needed to meet the project goals are listed in Table 6.

The main difference among the different manufacturers is the expander design. The expander dictates the performance, temperature levels, capacity and the part-load operation. Especially for the CHESTER project, the part-load performance will be significant, as the load can vary depending on the grid conditions. Furthermore, the temperature levels at the condenser side are variable depending on whether the condensing heat is used for DH or dissipated to the environment. The few manufacturers (Viking Heat Engines, Exoes) that focus on this topic are working on waste heat recovery for vehicles where the dynamics are large. Upscaling of this technology and further modifying it for the CHESTER project will thus be crucial.

Table 6: ORC specifications supplied by the manufacturers.

Manufacturer	Temperature source	Capacity	Reference
ABB	T > 200°C	500 kW	ABB
Viking Heat Engines	80 to 215°C	15.5 kW	
BEP E-Rational	85 to 115°C	500 kW	E-Rational Low Temp ORC
Calnetix	T > 110°C	125 kW	Access Energy ORC System
Enertime	150 to 200°C	300 to 3000 kW	Enertime ORC Module
Enogia	80 to 120°C	5 to 100 kW	Enogia ORC Module
Exergy	80 to 350 °C	100 to 50 MW	Exergy ORC Technology
Electratherm	77 to 122°C	35 to 110 kW	Electratherm Power+Generator
Exoes	T < 300°C	4 kW	Exoes EVE
GE Power	T > 155°C	50 - 140 kW	Clean Cycle II R-Series
ORMAT	T > 126°C	≥45 MW	ORMAT ORC
TMEIC	T > 125°C	250 kW	TMEIC ORC
Turboden	-	2 to 10 MW	Turboden Waste Heat Recovery
gT – Energy Technologies	T > 108°C	170 kW	gTET ORC generator

High-temperature thermal energy storage

For the HT-TES, one must analyse the power of suppliers separately from the passive and active storage concept perspective. From a manufacturing perspective, a passive latent TES system is essentially an adapted heat exchanger. Its design for manufacturing can be developed and optimized by companies that build heat exchangers. The thermal design is more critical, though with the development of design tools and experience gained from research in the integration and limits of the technology, this can also be adopted by companies interested in developing and optimizing the technology. Active latent heat storage systems, on the other hand, are in an earlier stage of development from the system design perspective, as these concepts have been developed specifically for heat transfer and storage and not as much experience has been gained to this date.

In the context of CHEST technology, it can be expected that the forward integration threat will not assume remarkable dimensions. The complexity of the CHEST system, which makes use of several non-standards components, reduces the risk that the supplier of a specific component has interest in and/or the possibility of supplying the entire system as a turnkey solution.

3.2.3. Power of customers

The bargaining power of buyers in the market of EES can be assumed to be fairly strong. Energy (and, hence, energy storage) is a commodity, so no brand or technology loyalty can be expected. Much more relevant aspects for customers are reliability of the technology, quality, flexibility, prices (in terms of €/MW, €/MWh and €/MWh/cycle) and warranty.

The relatively small number and large size of customers in the large-scale EES market (industry, power plants, DSOs, TSOs, large entities operating in the electric market) and fairly large variety of EES technologies (see Section 3.2.4) increases the impact of losing (or not acquiring) a customer, thereby strengthening the power of the customers.

For example, let us assume that a customer is considering an investment in an EES to increase the share of fluctuating renewable electricity (the transmission capacity to/from nearby areas is limited, hence the supply and demand need to match locally). A variety of EES technologies exists (see Section 3.2.4), but some of them —such as pumped hydro and compressed air EES— may be immediately excluded due to geographical/topological/geological and environmental reasons, as they require very specific conditions to be implemented in a cost-effective way. If the customer looks for EES technologies suitable for supply-demand balancing with a usage time of several hours or a few days, the choice could be limited to batteries and a CHEST system. Supposing that all these technologies are mature and can meet the quality/reliability requirements of the costumer, the investment and operation cost of each single technology would have a key role in the final choice of the customer, who could, hence, take advantage of this to ask for better offers from different suppliers.

Assuming that the technical lifetime of the CHEST system can be expected to be twice as long as the lifetime of battery systems (about 40 years against e.g. 20 years for vanadium redox batteries), then the CHEST system could be up to twice as expensive (in €/kWh) than the battery systems and still remain price-competitive.

Obviously, if a customer has stricter and more specific requirements (e.g. with respect to the environment, safety, response time, space limitations, etc.) the number of feasible solutions decreases and so does the bargaining power.

Finally, the backward integration threat can be expected to be low. The complexity of the CHEST system reduces the risk that final customers could have the competences and would be willing to take the risk of implementing the system themselves, after purchasing several non-standards components from different manufacturers.

3.2.4. Threat of substitutes

The CHEST system would be a new type of EES, which would enter a very dynamic market, characterized by many different technologies.

On the one hand, according to the form in which electricity is transformed and stored, EES technologies can be categorized in mechanical storages (pumped hydro, compressed air, flywheels), electrochemical storages (batteries), chemical storages (fuels, such as hydrogen and methane) and electromagnetic storages (supercapacitors and super magnetic storages). Besides storing electricity, many of these technologies can also provide ancillary services to the grid, such as reserve capacity and frequency regulation (Sveinbjörnsson, Trier, Hansen, & Mathiesen, 2018).

On the other hand, the CHEST system is a form of thermal energy storage (TES), as electricity is used to run a HP, whose condensing heat is stored in a high temperature TES. Other TES technologies for power generation (such as molten salt, steam, crashed rocks/pebble stones storages usually connected to solar power plants) exist, but these are not treated in this deliverable. In fact, although the stored energy can be used to drive a steam cycle and so produce electricity, the original energy form that is converted and stored is not electricity, hence these technologies do not comply with the definition of EES given above.

Pumped Hydro Storage (PHS)

In a PHS, electricity is converted and stored in the form of gravitational potential energy, given by height differences in water levels. It is the most common form of EES, currently representing more than 97 % of the EES capacity. In 2014, there are about 250 plants, with a total capacity of 120 GW (Du & Lu, 2014). Updated estimates range between 118 and 132 GW (International Renewable Energy Agency, 2018; Nordling, Englund, Hembjer, & Mannberg, 2016).

The popularity of PHS comes from many factors, such as high efficiency (65-85 %), large power capacity (100-1000 MW), large storage capacity (1-24+ hours), long storage period, long lifetime (30-60 years) and low cycle cost (0.1-1.3 €/kWh/cycle). PHS is generally limited to high-power applications due to its high investment costs (500-1700 €/kW), environmental damages from flooding large areas of land and long project lead time (Du & Lu, 2014). PHS has a short response time, thus, it can be used for voltage and frequency control, spinning/non-spinning reserve, system capacity support and black start (Bardajií et al., 2017; Nordling et al., 2016).

Compressed Air Energy Storage (CAES)

A CAES system uses an underground site, such as a cavern or a mine, to store a compressed gas at approximately 4-8 MPa. Currently, CAES shows the highest potential for large-scale EES, after PHS. It is characterized by large power capacity (50-300 MW), large storage capacity (2-50+ hours), long storage period (over a year), quick start up (10 minutes), long lifetime, low investment cost (350-700 €/kW) and almost no environmental impact (Du & Lu, 2014). On the contrary, it has a low efficiency (42-54 %) and requires specific geological conditions, i.e. the presence of a suitable underground storage.

Although only two CAES exist, these have shown high reliability and economic feasibility. These are the 290 MW plant in Huntorf (Germany) from 1978, and the 110 MW plant in McIntosh (USA) from 1991 (Crotogino, Mohmeyer, & Scharf, 2001). In both plants, cheap off-peak electricity is used to compress air, which is stored in a cavern. When needed, the compressed air is released, natural gas is burnt together with it and then expands in a gas turbine generating electricity. The natural gas is added to counter the cooling effect generated by the decompression.

Besides time-shifting, load levelling and peak shaving, CAES can provide system services such as inertial response, reserve (primary, secondary and tertiary), fast frequency response, dynamic reactive response and steady state reactive power (Bardajií et al., 2017).

Several new CAES projects have been investigated, especially in the USA and in Europe. For Europe it is worth mentioning the research projects ADELE-ING (Zunft et al., 2017) and RICAS (Montanuniversität Leoben, 2018), investigating the feasibility of adiabatic CAES, which should increase the round-trip efficiency of the system by recycling the heat developed in the compression phase, minimizing/avoiding the use of natural gas in the expansion phase.

Batteries

Batteries are electrochemical energy conversion and storage devices. Many types of batteries exist, and more are under development. Although in 2016 batteries represented only 1 % of the 171 GW of installed EES capacity worldwide, they are the EES technology which has been developing fastest in the last years (Bardajií et al., 2017). This has been caused by increased performance and falling costs, which are further expected to decrease in the future: the cost per unit energy of most battery technologies (lead acid, sodium-sulphur, zinc-bromine, vanadium redox and lithium-ion) in 2030 is estimated to be 50 %-66 % lower compared to 2016 (International Renewable Energy Agency, 2017).

Batteries can be divided in “conventional” batteries and “flow batteries”. In conventional batteries, the electrochemical cell acts as both energy conversion and storage devices. The charge/discharge power and the energy storage capacity depend on the size of the cell and cannot be varied independently of each other. In flow batteries, the energy conversion occurs in the cell, while storage takes place in special electrolyte tanks. Hence, the charge/discharge power depends on the size of the cell, while the storage capacity depends only on the size of the electrolyte tanks.

Lead-acid (Pb) batteries. More than 130 years old, lead-acid batteries are widely used as small-medium scale EES, such as vehicles (70 % of the total market), communication and solar PV systems. They are relatively cheap (100-400 €/kWh), reliable, efficient (65-80 %), hence, are suitable for uninterruptible power supply, power quality and spinning reserves. Nevertheless, they are characterized by short lifetime (500 cycles, 3-4 years), low depth of discharge (20 %) and low energy density (30-50 Wh/kg) (Du & Lu, 2014; Nordling et al., 2016). More recently, advanced lead-acid batteries have shown better properties, such as 2800 cycles, 50 % discharge depth and a life of 17 years (Nordling et al., 2016).

The largest lead-acid battery (10 MW/40 MWh) was installed in 1988 in California for load levelling (Du & Lu, 2014).

Nickel-Cadmium (NiCd) batteries. NiCd batteries are characterized by higher energy density (50-75 Wh/kg), longer lifetime (2000-2500 cycles), but also higher cost compared to lead-acid batteries. Their application in connection with RES is strongly limited by the so-called memory effect. If a battery is not completely discharged before being charged, its capacity will degrade. In the last decades the use of NiCd batteries has decreased, also due to the stricter rules on the use of toxic cadmium (such as EU directive 2006/66/EC). The largest NiCd battery is installed in Alaska, has a nominal power of 27 MW and is used as spinning reserve (Du & Lu, 2014).

Sodium-Sulfur (NaS) batteries. NaS batteries are a mature technology, which has increased dramatically in the last years (from 10 MW in 1998 to 305 MW in 2008). The reasons for this success are: long lifetime (1500-4500 cycles, 15 years), high efficiency (80-90 %), intermediate energy density (60 Wh/kg) and recyclable components. However, drawbacks are the high operating temperature (300-350 °C), high investment cost (500 €/kWh) and highly corrosive sodium sulphides (Du & Lu, 2014; Nordling et al., 2016). Additionally, sodium burns in contact with air, thus the battery must be vacuum-insulated. The largest NaS battery is a 50 MW 300 MWh system, which was installed in Japan in 2016 to balance the grid frequency, when connected to RES (Ohki, 2016).

Lithium-ion (Li-ion) batteries. Commercialized in 1991, Li-ion batteries have spread massively in several markets, especially that of portable devices and electric vehicles, thanks to the high efficiency (>90 %), good lifetime (1000-5000 cycles), high energy density (150-200 Wh/kg) and high power density (250-340 W/kg) (Du & Lu, 2014). Their cost, around 850 €/kWh in 2010, has been continuously falling in the last years (170 €/kWh in 2016 (Zart, 2017)). Concerns for large scale application of Li-ion batteries are their flammability and the fairly centralized supply of key materials, such as lithium and cobalt. The largest Li-ion battery is a 100 MW 129 MWh system, which was installed in 2017 in South Australia, to store fluctuating electricity generated by Hornsdale's wind farm (Ayre, 2017).

Zinc-Bromine batteries. These batteries are flow batteries characterized by 75 % efficiency, 75-85 Wh/kg, long lifetime, no self-discharging and no negative effects from deep-discharge. In 2009 (Du & Lu, 2014). The high cell voltage and highly oxidative bromine set specific requirements to the electrodes, membranes and fluid handling components, which increase the cost. Zinc is a limited resource (Du & Lu, 2014), while bromine is a highly toxic and measures must be taken to guarantee system safety (Energy Storage Association, 2018).

Vanadium Redox Flow (VRF) Batteries. These flow batteries are a proven technology, which has been installed in various locations, mainly for load levelling, stabilization of energy supply from RES, uninterruptible power supply, back-up power and power quality. VRF batteries are characterized by 75-85 % efficiency, long lifetime when properly maintained (up to 12,000 cycles at 100 % depth discharge with no degradation of the electrolytes), but low energy density (16-33 Wh/l) (Du & Lu, 2014; Nordling et al., 2016). The largest VRF battery (200 MW 800 MWh) is under construction in China, and will help balance supply and demand in the province's power grid and avoid curtailment of wind electricity production (Lombardo, 2016).

Chemical storage

In chemical EES, electrical energy is used for producing chemical fuels (gaseous or liquid). The fuels can be stored and later converted again to electrical energy. Hydrogen (H_2) (and oxygen) is produced through electrolysis of water by introducing an electric current. Hydrogen can then be stored in chemical or physical storages, or converted to methane (CH_4) adding carbon dioxide (Sabatier reaction). When needed, hydrogen is used to run a fuel cell or a combustion engine, producing electricity. Currently, hydrogen storage is characterized by high investment costs (650-1000 €/kW), low storage conversion efficiency and low volumetric energy density, which requires compression between 200 and 700 bar or liquefaction (Bardajií et al., 2017). However, examples of this technology in connection with wind electricity storage exist in Norway and Denmark. More than in the energy sector, hydrogen might become relevant in the transport sector as an alternative to conventional fuels (Du & Lu, 2014; Nordling et al., 2016).

Flywheels

A flywheel is a mechanical EES consisting of a rotating mass. A flywheel stores/retrieves energy by changing its angular velocity, with the amount of stored energy being proportional to the square of the velocity. Flywheels are characterized by a long lifetime (20 years), high efficiency (90-95 %), fast response, high energy density, but also high capital cost (850-4300 €/kWh). Additionally, the high self-discharge rate (up to 100 %/day) makes them only suitable for short-term storage.

Electromagnetic EES

Electromagnetic EES include capacitors and superconducting magnetic energy storage (SMES). These can provide high power only for a very short time, therefore are not usable for energy storage. Capacitors and supercapacitors can provide power-factor correction, voltage and reactive power support (Du & Lu, 2014; Sveinbjörnsson et al., 2018).

The main characteristics of the above-mentioned EES technologies are listed in Table 7**¡Error! No se encuentra el origen de la referencia.**, based on the information retrieved from (Du & Lu, 2014; International Renewable Energy Agency, 2015; Nordling et al., 2016). Figure 54 shows the

Levelized Cost of Storage (LCOS) for some of the above-listed EES technologies, for 100 MW/400 MWh system with 365 cycles per year and assuming an electricity price of 3 c€/kWh. For the purpose of this report, the LCOS can be seen as the ratio between the sum of investment cost and the operation cost of the EES over its lifetime, and the total amount of electricity released by the EES over its lifetime. (for the exact definition of the LCOS, the reader should refer to (Jülch, 2016)).

Table 7: Main characteristics of different EES technologies.

	Capacity	Usage time	Efficiency	Start-up time	Energy density	Losses	Lifetime (y=years, c.=cycles)
Pumped hydro	<5 GW	1–24 h	65-85 %	s-min	0.13-1.12 kWh/m³	0-0.5 %/day	50-100 y
Compressed air	MW-GW	1–24 h	42-54 % (normal) 70 % (adiabatic)	min	0.5-0.8 kWh/m³	0-10 %/day	25-40 y
Power to H_2	kW-GW	s–months	62-82 %	s-min	3 kWh/Nm³	0-1 %/day	10 y
Power to CH_4	kW-GW	s–months	49-56 %	min-h	9.8 kWh/Nm³	0-1 %/day	20 y
Flywheels	2 kW-20 MW	s–min	95 %	s-min	200 Wh/kg	100 %/day	20 y
Supermagnetic EES	1 kW-10 MW	s	90 %	ms	40-60 Wh/kg	10-15 %/day	50,000 c.
Supercapacitors	10-1000 kW	ms–s	95 %	m	1-30 Wh/kg	5-40 %/day	10-25 y, 10^6 c.
Batteries							
Lead-based	1 kW-50 MW	s–3 h	65-80 %	-	30-50 Wh/kg	5 %/month	3-4 y, 500 c.
Sodium-Sulfur	0.5-50 MW	s–h	80-90 %	-	60 Wh/kg	small	15 y, 1500-4500 c.
Lithium-based	kW-MW	min–h	85-99 %	ms	150-200 Wh/kg	5 %/day, then 2 %/month	1000-5000 c.
Zinc-bromide	0.05-2 MW	s–10 h	70-75 %	ms	75-85 Wh/kg	small	>2000 c.
Vanadium redox	0.03-7 MW	s–10 h	75-85 %	ms	16-33 Wh/l	5 %/month	20 y, 12000 c.

Additionally, a database of EES installations throughout the world can be found online (Sandia National Laboratories, 2018).

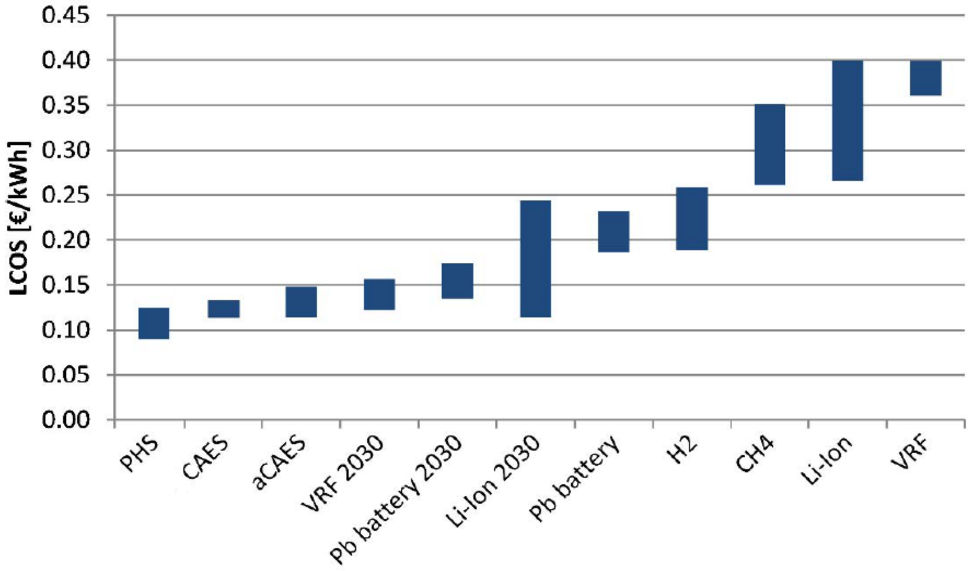

Figure 54: Comparison of the LCOS of different EES technologies (Smallbone, Jülch, Wardle, & Roskilly, 2017).

Comparison of substitutes to CHEST

Different EES have different applications in the energy system. Capacity, cost, energy density, efficiency, and technical and economic lifetime determine which type of EES is more suitable for a given application. Therefore, PHS and CAES are suitable for energy balancing; batteries are best suited as reserve power, for over-generation and off-grid systems, while flywheels, supercapacitors and super magnetic energy storages can be used for electricity quality and stability.

Due to its potentially large power output capacity, large storage capacity and a start-up time in the order of minutes, the CHEST system would more directly compete with PHS and CAES technologies. However, it should be mentioned that battery systems grow increasingly larger and are now used not only for uninterruptible power supply, but also for balancing supply and demand on a local and regional scale (Ayre, 2017; Lombardo, 2016)

Compared to the above-mentioned alternatives, the CHEST system offers several advantages.

First, the CHEST system is site-independent, not requiring specific geographical/topographical and/or geological conditions, unlike PHS and CAES systems, which are currently the main types of EES for large-scale application. Even in locations where PHS would be technically and economically feasible, environmental and social considerations —such as destruction of flora, fauna and landscape; flooding of vast land areas that could otherwise be used; negative effect on tourism; etc. — may prevent its deployment. On the other hand, the CHEST system has a minimum interaction with the environment, so it does not pose environmental and/or social issues. Additionally, if run on renewable electricity, it is completely emission free, unlike the existing CAES technology, which uses natural gas.

Among the different battery technologies, those expected to dominate the market in the near future are sodium-sulphur batteries, lithium-ion batteries and vanadium redox batteries (Lee, Kim, Yeom, & Kim, 2017; Nordling et al., 2016). Compared to the conventional sodium-sulphur and lithium-ion batteries, the CHEST system promises to be cyclically stable and have a much longer lifetime (about 40 years), which gives this system a competitive advantage in a life cycle analysis perspective.

Regarding safety consideration, it should be noted that the PCM planned to be used in the CHEST system is a mixture of lithium and potassium nitrate. These materials are oxidizers, so a certain amount of care is due when handling them. However, also many battery chemistries contain hazardous materials, e.g. lead, sulphuric acid, sodium and lithium. The CHEST system does not require limited resources during construction and operation, whereas with the mentioned battery technologies, there are concerns on the cost, safety and relative difficulty in obtaining cobalt (a key component of many Li-ion batteries), and on the availability of vanadium (International Renewable Energy Agency, 2015).

Compared to any other EES technology described above, the CHEST system would be able to take advantage of the availability of the low/intermediate temperature heat, so creating an interconnection among the electricity sector and other sectors, such as DH and industrial heat. In fact, low/intermediate temperature heat can be used as a heat source for the heat pump (HP) of the CHEST system during the charging of the high temperature thermal energy storage (HT-TES), thereby improving its COP. Relevant heat sources could be excess heat from industrial processes, solar heat, a seasonal TES or a DH network. Furthermore, because a heat sink is needed on the condenser side of the ORC, a CHEST system would also provide heat in output, its temperature depending on whether priority is given to the electricity or heat production. Relevant heat sinks could be the external environment (ambient air, rivers, lakes, sea, etc.), a seasonal TES or a DH network. The presence of two different temperature levels in the CHEST concept theoretically compensates for any irreversibility within the energy conversion and gives the possibility of achieving a power ratio (power out/power in) of 100 % or higher. An overview of the different operation modes of the CHEST system with respect to heat source and heat sink is shown in Figure 55.

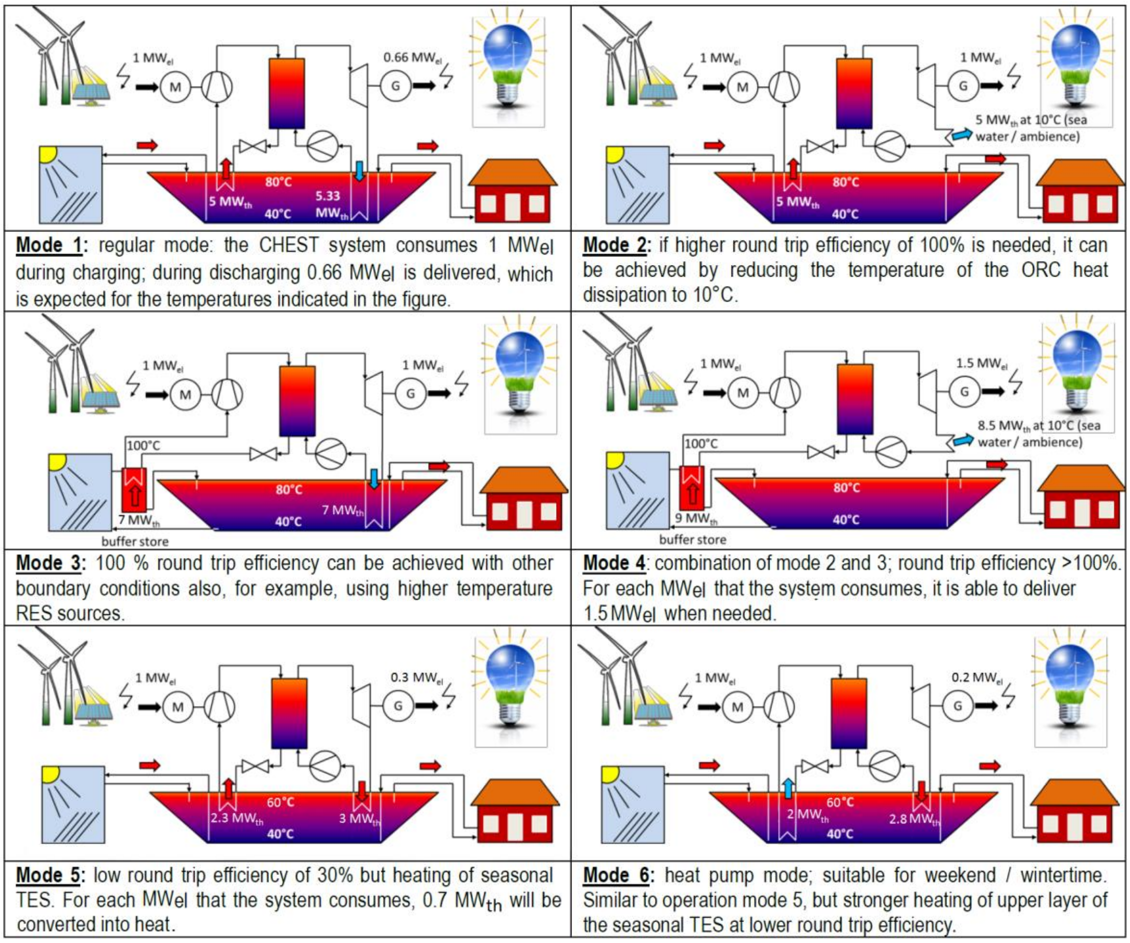

Figure 55: Different operation modes of the CHEST system with respect to heat source and heat sink.

3.2.5. Industry rivalry

In general, many factors are likely to influence the rivalry within an industry. In the case of EES, this can vary strongly from country to country according to specific key factors which characterize that specific market. However, some general considerations independent of the country can be made.

The rivalry between completely different EES technologies is likely to be limited, as the specific boundary conditions will mainly determine which technology is the most economically feasible in a certain location, rather than the prices and add-on services offered by the technology suppliers. On the contrary, the competitive rivalry within the same technology (PHS, CAES, batteries, etc.) is high because of the low product differentiation, no brand loyalty, importance of the offered add-on services and bundling options (e.g. maintenance and decommissioning of the EES). Additionally, the specialized assets needed to produce EES technologies represent a very high exit barrier, which may force companies to remain in the market and compete even at low profit margins.

Consequently, as seen in the subsection "Comparison of substitutes to CHEST" in Section 3.2.4, a CHEST system offers the additional ability of interacting with the heating sector, which could make it preferable under specific boundary conditions, e.g. in combination with DH systems, solar heat, excess heat. A CHEST system could therefore limit curtailment of solar thermal output in sunny periods, avoid the dissipation to the environment of low temperature excess heat and add flexibility to a DH network.

Finally, the expected growth in the EES market in the future (Figure 49) will likely reduce industry rivalry for acquiring larger market shares. If, for example, the supply of battery EES is not able to follow the pace of the growing demand, e.g. due to limited production capacity or availability of raw materials, there would then be space for new technologies, as soon as they prove their technical feasibility and reliability. Hence, it is of key importance that within the CHESTER project both a prototype and a full-scale CHEST system are developed.

The Porter's Five Forces diagram for the CHEST system is shown in Figure 56. This summarizes the main points presented in the previous sections and rates the strength of each of the five forces.

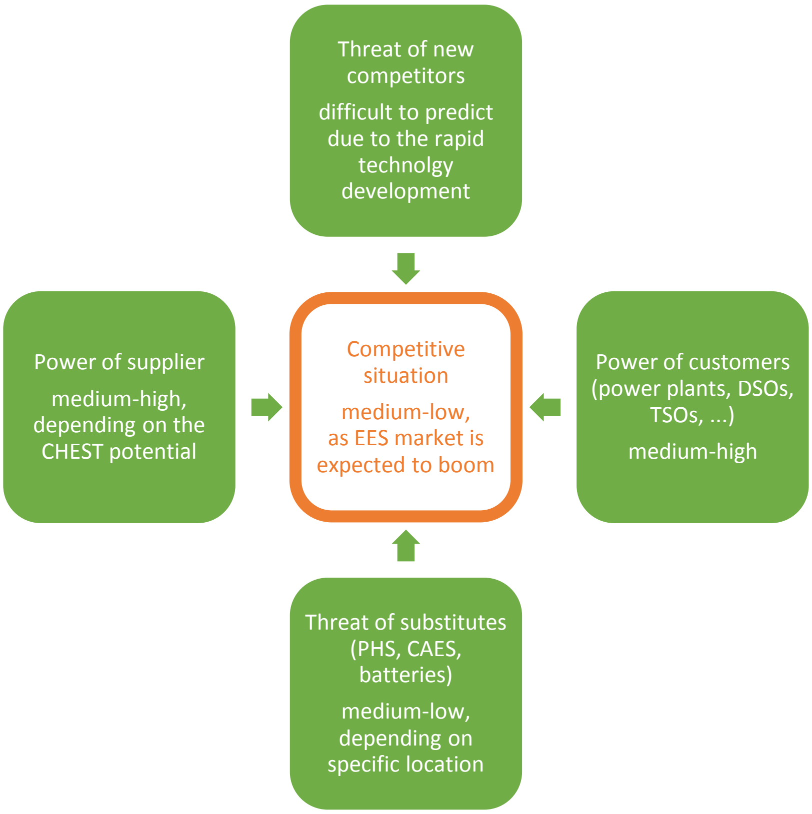

Figure 56: Porter's Five Forces for CHEST system in the EES market.

3.3. Country-specific conditions

3.3.1. Spain

If we neglect the transport sector, in which Spain has a strong dependence on fossil fuels and CHESTER cannot play a role, we can identify some interesting scenarios in view of the trends that occur in the country.

The electricity sector presents an energy mix that is highly technologically diversified. RESs has reached a share of around 35-45 % in recent years with the consequent need of curtailing renewable electricity, especially wind farms, particularly windy nights when the TSO is forced to shut down wind farms across the country. To cope with this situation, two scenarios (not necessarily mutually exclusive) can be foreseen:

- An energy policy that supports an increased amount of interconnection capacity with other countries (France in particular), so that surpluses may be used by other countries.

- Developing other solutions such as CHESTER in which the surpluses will be consumed closer to the producer sites.

One weakness of the second scenario is that most of the wind farm sites are not close to urban centres, where they can take advantage of the thermal development of the CHESTER solution. In this scenario, the storage in 'electric' mode for its re-discharge to the network is not fully deployed normatively and the current battery systems have been oriented to aspects of protection of facilities for other purposes. A possible improvement in the €/MWh cost would allow a direct use.

The recently approved Royal Decree-Law 20/2018 on urgent measures to boost economic competitiveness in the industry and commerce sector in Spain (Ecológica, 2018) allows closed networks to be developed in industrial zones. This opens up opportunities for the implementation of generation integration solutions with consumption, so that different technologies and sources can be exchanged. These are, for example, surplus heat from industries and renewable electric sources (PV, wind), allowing local production, reducing losses of the networks, reducing supply costs (electric pool) and defining new business models, with aggregations of demand and medium-scale generation.

Spain has few DH networks compared to other countries, especially in northern Europe. This situation represents a loss of opportunity to massively integrate CHESTER solutions taking advantage of existing heat sources and complementing with new renewable electrical installations that increase the presence of renewable generation. However, existing networks can be suitable test benches for the deployment of technology and the promotion of thermal and electrical solutions based on renewables in other areas.

The regulation of the electricity sector is very restrictive. However, recent political changes have included new royal decrees: one from October 2018 (which, in addition to reducing administrative burdens, allows several owners to consume from the same generation point nearby) and another from December 2018 (for the creation of closed networks in industrial areas). Although they are waiting for their regulatory deployment, these measures open the possibility of deployments of renewable production mainly in the sector of industry and industrial estates.

In the building and urban planning sector, the developed model of building concentration does not allow the large deployment based on the CHESTER solution for large urban areas, but the use-scenarios based on neighbourhood communities that had infrastructures, as silos for fuel tanks in the 60s-70s and now use natural gas, could be analysed. The integration of renewables in buildings to reduce their demand may allow for the expansion of smaller CHESTER modules in these facilities.

The acceptance of the public will be determined by the global cost of acquisition of energy (€/MWh). Thus, the public administrations, should act as promoters, enabling that industrial networks together with the current existing DHs, can be niche markets (ENGERATI, 2017). Besides, the relaxation of the regulations in electrical production and consumption will be crucial to be able to integrate the two sources and allow for increasing initial integration of the CHESTER technology.

3.3.2. Denmark

The general trend seen in Denmark regarding the progressive phase-out of fossil fuel plants, high and increasing share of fluctuating RES electricity, spreading use of DH, and the electrification of the heating and transport sector seems favourable to EES solutions and demand response management.

According to the Danish TSO, the primary measures identified as the most suitable to guarantee power system balancing and integration of more RES electricity are the following: expansion of the interconnectors (especially towards the Norwegian PHS plants), reinforcement of the grid, electrification of the DH sector (through electric boilers and heat pumps) and of the transport sector, and downward regulation aided by low spot prices. Electricity storage would be a secondary/later option, possibly in form of chemical storage, CAES, batteries (Energinet.dk, 2010). More recent studies have highlighted the importance of EES in the Danish energy system (Allan Schrøder Pedersen et al., 2014; Sorknæs et al., 2014). Simulations on the possible future energy mix —with high shares of wind electricity— have shown that EES would likely be required (especially in West Denmark), even when considering the electrification of the heating sector and unlimited transmission capacity to Germany (Sorknæs et al., 2014).

In this respect, the CHEST technology may prove to be an attractive EES option, offering large capacities both in terms of energy and power. In fact, the Danish morphology prevents PHS from being an option, while large-scale battery storage seems still a very expensive option at the moment. Another advantage that the CHEST system could benefit from in the Danish context is the spread availability of DH at relatively low supply and return temperatures, which could be used respectively as a heat source and heat sink for the CHEST system.

However, the current taxation on stored electricity needs to be changed to favour EES technologies. In fact, stored electricity is taxed twice (when purchased and when resold), which is a barrier to a wider use of EES and reduces opportunities for demand-side flexibility in the power system (IEA, 2017a).

3.3.3. Germany

The ambitious environmental and energy-related targets set by the German government will entail a strong reduction in the use of fossil-fuel and an increase in the electricity production from RES (especially wind and solar). Although fast-response gas-fired CHP plants are expected to balance the fluctuating wind electricity production, the decarbonization and denuclearization of the energy system seems favourable to EES solutions. Additionally, at a political and legislative level there is the intention of improving the regulatory framework for EES.

Although Austria has large PHS systems, the interconnection capacity between the two countries is limited and the PHS capacity is finite. Additionally, the transmission lines between northern Germany (where most of the RES electricity is produced) and southern Germany (where most of the electricity demand occurs) have proven insufficient and are currently under expansion, which is not always welcomed by the local communities. In this respect, locally-based and site-independent EES solutions may be very attractive, limiting the need for strengthening and expanding the grid, as well as reducing transmission losses.

The EES technologies that have attracted more attention so far are batteries, power-to-gas and hydrogen, and their combined market (although still rather small) is increasing rapidly. The CHEST concept may find its space in this growing market, also taking advantage of the interaction it can offer with the DH sector.

Regarding power-to-heat-to-power EES, it is relevant to mention the proof-of-system EES facility which is currently close to being completed in Hamburg-Altenwerder. The concept of the project, developed by the company Siemens-Gamesa and funded by the German Ministry for Economic Affairs and Energy, differs from the CHEST principle in several aspects (such as temperature levels, components, working fluid, storage material), but both concepts are examples of power-to-heat-to-power EES. Hence, this proof-of-system facility and the plan of the Siemens Games to provide commercial solutions by 2021 are very encouraging for the concept of this type of EES altogether (Siemens Gamesa, 2018).

3.3.4. Belgium

The situation of Belgium in relation to the possibilities offered by CHESTER are ambivalent. Opportunities and challenges intersect equally.

The first aspect to consider is the strong nuclear dependence of the country. This dependence is, in turn, at odds with the need to reduce the country's CO_2 emissions. The phase out plans for the Belgian nuclear power plants imply an increasing dependence on interconnections with neighbouring countries. Likewise, the low availability of nuclear power plants in the most necessary moments leads to an increase in the use of natural gas plants. Finally, the TSO must manage demand peaks from the consumption side, complicating the management processes.

In this context, the CHESTER technology would allow for a reduction of the electrical and/or thermal demand and be a support element to the TSO, from small to large scale. In the small scale, it could allow for a reduction of the total electricity demand of the country and, on a large scale, be able to act as peak demand management systems.

The need to increase interconnections reduces the country's investment capacity in other energy aspects. The country's high dependence on L-gas from Groningen must be considered and it will involve modifying infrastructures for the use of networks in H-gas mode. It is an opportunity to drive investments to more distributed projects where the combination of DH and CHESTER can go hand in hand.

In this sense, the obligations of NZEB buildings by the end of 2020 is another challenge and opportunity to promote renewable energies. DH is developed very sparsely in the country, but it has a great potential. The support of local regions, such as the Flemish, for these technologies is an aspect to be emphasized. In this regard, important steps have been taken by the country for the massive deployment of small-scale RES.

Finally, public surveys on the energy topic indicate a large support to RES and a fairly high concern about the need of demand management and storage. Therefore, a social substrate would support the deployment of the CHESTER technology.

3.3.5. The Netherlands

The Dutch energy system is tightly connected to, and strongly dependent on, neighbouring countries. With a clear trend towards the increased use of intermittent, decentralized electricity generation, as well as electrification, there exists an increasing need for flexibility, hence EES. Several beneficial aspects of large-scale energy storage within the Dutch system can be identified.

On sunny summer days, the wholesale electricity price is negative due to large-scale solar electricity generation, both domestically and in e.g. Germany. Storing this electricity is beneficial for ensuring that the business case for solar remains positive. Analogously, curtailment of wind energy from the wind farms in the North Sea can be reduced or avoided altogether. Seasonal variations are expected to increase, although it is not expected that seasonal storage will become economically feasible soon.

The application of EES for balancing and backup purposes appears attractive, in addition to, or as replacement for, conventional gas-powered plants that are prevalent in the Netherlands. The expected strong increase in the use of electric vehicles will help this application further. However, the fact that the Dutch market is currently not capacity-based dampens this development.

The current regulations and system of taxations do not properly value flexibility, as expressed for instance by the fact that electricity is taxed more heavily than gas. The current government plans to reverse this in the near future, however, improving the outlook for EES because of the expected increased electrification, which is also one of the pillars of the 2018 energy accord. The current system of offsetting residential consumption with production also strongly removes any incentives for local storage. This system is also expected to end in the near future.

Uncertainty about the future economic viability of EES can pose a problem, created by e.g. uneven government policies over the past 15 years, uncertain cost price development and uncertainty about the balance between EES and possible choices for alternatives like demand response (TU Delft 2015).

3.4. Discussion

The countries considered in this report have different levels of penetration of RES in the electricity generation mix: the Netherlands (12 %), Belgium (19 %), Germany (29%), Spain (34 %) and Denmark (63 %). With respect to the CHEST technology, it is more relevant, however, to consider the contribution to the energy production given by the non-dispatchable RES, such as wind and solar. If only this type of RES is considered, the contribution to the electricity production decreases, varying from 4 % in the case of the Netherlands to 45 % in the case of Denmark.

According to the energy agendas, these countries have a common goal of decarbonization, denuclearization of their electricity sectors and to considerably increase (up to 100 %) the contribution of RES in the generation mix, although the timeline and methodology differs from country to country. It can therefore be expected that the curtailment of RES electricity, strengthening of the electric grid, EES and demand-side management will become increasingly hot topics with the increase of the RES contribution to electricity generation.

Already, curtailment of non-dispatchable RES electricity has been increasingly adopted in these countries, in times when the electricity production exceeds the demand and cannot be transferred elsewhere due to bottlenecks in the electricity grid. A solution which can be adopted to address this issue is the extension and reinforcement of the distribution and transmission grid, as well as of the interconnectors with neighbouring countries. Currently, all the above-mentioned countries are implementing and/or planning grid extensions.

Grid extensions are very expensive and may not be able to provide a definitive solution in the long run, if most of the European countries increase the share of non-dispatchable renewable electricity in their generation mix. This is probably why EES is currently a hot topic in the agendas of several countries. Although the implementation of EES remains limited at the moment, mainly due to economic and technical reasons, this is expected to rapidly increase in the coming years. In this context, an EES technology such as CHEST may be a very interesting solution, as it promises to be cost-effective and with a long lifetime (unlike many battery chemistries), site-independent (unlike PHS and CAES), and environmentally and socially acceptable (unlike PHS).

An important aspect which should be addressed to favour the deployment of EES technologies are the regulations that currently apply to these systems. The legal framework on how EES can operate in the electricity market is often unclear, when not unfavourable. For example, EES is currently seen as a consumer in the considered countries, hence, the stored electricity is taxed twice: when absorbed by the EES and when used by the end-user. Additionally, due to energy taxations and grid fees, the price of the electricity is higher when purchased by the operator of the EES, compared to its price when the same electricity is sold. Therefore, the arbitrage model (charging the EES when prices are low, and then discharging when prices are higher) appear to be inadequate. The participation of EES in the reserve market seems more economically viable, but in this case, obstacles also exist due to stringent requirements that the EES systems must meet to operate in these markets, e.g. minimum capacity and response time.

Among the listed countries, Germany seems the country that is more oriented toward EES, having invested significantly in R&D and implementation of EES technologies, such as power-to-gas, power-to-hydrogen, batteries and even an EES system similar in principle to the CHEST concept. Also, at a political level, there is willingness to change the current regulation on EES, which at the moment does not favour its development. Already now, EES are exempted from paying grid tariffs and the EEG surcharge, when the electricity withdrawn from the network is only re-fed with a delay into the same network.

Moreover, other countries, such as Denmark, Belgium and the Netherlands, have declared their willingness to change legislation with respect to EES to favour their deployment. For example, the Dutch government plans increase the taxation on natural gas and decrease that on electricity in the near future, to improve the business models for EES solutions.

Of the considered countries, Denmark is that with the highest share of non-dispatchable RES in the electricity generation mix, with almost 42 % of the electricity being produced by wind farms. Additionally, the contribution of wind energy is expected to increase further in the coming years, as new wind farms will be installed. Denmark plans to produce 100 % of its electricity from RES by 2030. To cope with this increasing share of fluctuating RES generation, Denmark is investing in the upgrade of its electricity grid and in new interconnectors. Although EES is mentioned in the political agenda as a topic of interest, so far, no examples have been implemented. Demand side management (central electric boilers, central and individual heat pumps), interconnection to the Norwegian and Swedish PHS, and energy storage in electric vehicles are given a higher priority, compared to large-scale inland EES.

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