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The State-of-Art of Sector Coupling in Europe
– a Literature Review

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Environmental Physics and Renewable Energy

Acknowledgements

This thesis was written in the spring of 2020 and marks the completion of my master's degree in Environmental Physics and Renewable Energy at Norwegian University of Life Sciences (NMBU). I am forever grateful for my classmates, friends and family who made both the highs and the lows of the last five years better.

I would like to thank my thesis advisors Sonja Monica Berlijn and Heidi Samuelsen Nygård for their knowledgeable expertise throughout the entire process, from infancy to finished product.

Working on this thesis has been an inspiring and educational process. It has given me increased confidence in sector coupling as a strategy for the energy transition. The thesis' theme is highly relevant for all involved in the current energy system; technical, political or otherwise. I hope Statnett and other stakeholders in the energy system find it serviceable.

Ås, 28.05.2020

Marthe K. D. Verbeeten

“I sell here, Sir, what all the world desires to have - POWER”

Matthew Boulton (1728 - 1809) - To James Boswell (biographer of Samuel Johnson), of his engineering works 1776.

Abstract

At the same time as climate change pushes us to move away from fossil fuels, increasing amounts of energy from variable renewable sources are entering the grid. This requires structural transitions, to bring more flexibility and agility into the grid. The Paris Agreement and The European Green Deal show political willingness to support such a transitions. The question remains, how should we approach these transitions? One possibility is sector coupling: a strategy to couple sectors such as power, gas, and transport to increase both flexibility and profitability. This is achieved through the integration of otherwise normally non-integrable power into the energy system, through demand side management or through the adaptation of loads to also act as power generators.

In this thesis, term origins and the working definitions of sector coupling have been examined. The technologies involved have been outlined and their readiness levels have been assessed. The focus has been on the coupling of the electric power sector with the heating/cooling sector, the mobility sector and the gas sector in addition to the engagement of storage options.

Two literature searches were undertaken. The first focused on sector coupling as a whole, and found 94 publications. The second was aimed at the technologies involved in sector coupling and resulted in 96 publications. Five publications, each describing one type of technology, were chosen for in-depth analysis, together with five related illustrative cases.

The analysis of the first search shows that this topic is attracting increasing interest and that most research is presently done in Germany.

In the technology search, five technologies emerged as prominent. These were: batteries; power-to-heat with thermal storage; district heating with heat pumps; vehicle-to-grid; and power-to-gas.

The analysis shows that much of the needed technology is already at a high level of readiness. This, together with political willingness, gives sector coupling a strong foundation for further development. What is lacking is the market model for the flexibility suppliers and smart control arrangements for all the coupled technologies.

Further research should include: the definition and quantification of the need for more flexibility in the grid; a definitive standardisation of flexibility as a term in use; and a market model for the changes implicit in the introduction of more flexibility.

Sammendrag

Global oppvarming tvinger oss til å gjøre et skifte fra fossile til fornybare energikilder. Dette medfører at økende andel variabel kraft blir tilført og som øker kraftnettets behov for fleksibilitet. Parisavtalen og European Green Deal viser at det er politisk villighet til å støtte dette skiftet, men det rår usikkerhet over er hvordan dette skal gjennomføres. En mulighet er sektorkobling, som er en strategi for å koble sektorene sånn som kraft, transport og gas for å øke både fleksibilitet og lønnsomhet. Dette oppnås ved å integrere ellers ikke-integrerbar kraft i energisystemet, ved styrt etterspørsel eller ved å tilpasse laster slik at de også kan fungere som strømkilder.

I denne masteroppgaven blir begrepsopprinnelsen og fungerende definisjoner studert. De involverte teknologiene blir kartlagt og hvor langt unna de er implementering blir vurdert. Oppgaven fokuserer på hvordan kraftsystemet kan kobles med oppvarming/kjøling, transport og gass-sektoren i tillegg til lagringsmuligheter for energi.

To litteratursøk ble gjennomført. Det første fokuserte på sektorkobling som en helhet, og resulterte i 94 publikasjoner. Det andre var rettet mot teknologier involvert i sektorkobling, og resulterte i 96 publikasjoner. Fem artikler ble valgt ut som fordypningslitteratur for fem forskjellige teknologier. Videre legges det frem illustrerende prosjekter som belyser de fem teknologiene i bruk.

Analysen av det første søket viser at det er økende interesse for temaet og at det er Tyskland som produserer mest på temaet.

Fem teknologier utpekte seg. Disse var: batterier, oppvarming med termisk lagring, fjernvarme fra varmepumper, «vehicle-to-grid» og gass produsert via elektrolyse.

Analysen viser at hoveddelen av den nødvendige teknologien er moden for implementering. Dette, sammen med den eksisterende politiske villigheten, lager er sterkt grunnlag for videre utvikling av sektorkobling. Det som mangler er en markedsmodell for tilbydere av fleksibilitet, samt IT-systemer til å styre tilkoblede laster.

Videre forskning bør inkludere: tallfesting og definisjon av behovet for fleksibilitet, standardisering av begrepet fleksibilitet bør utvikles, og en markedsmodell for fleksibilitet bør forhandles frem.

Abbreviations

CCS – Carbon Capture and Storage
CO_2 – Carbon Dioxide
DH – District Heating
DNV-GL – Den Norske Veritas- Germanischer Lloyd
DSM – Demand Side Management
DSO – Distribution System Operator
ENTSOE - European Network of Transmission System Operators for Electricity
EU – European Union
EV – Electric Vehicles
GHG – Greenhouse Gas
GW – Gigawatts
HVDC – High Voltage Direct Current
H_2 – Hydrogen (and hydrogen gas)
IEEE – Institute of Electrical and Electronics Engineers
ITRE - European Parliament Committee on Industry, Research, and Energy
kWh – Kilowatt Hours
PEM – Polymer Electrolyte Membrane
PHS – Pumped Hydro Storage
PTES – Pumped Thermal Electric Storage
PV - Photovoltaic
RES – Renewable Energy Sources
SSB – Statistisk sentralbyrå – Statistics Norway
TFEC – Total final Energy Consumption
TJ - Terajoules
TRL – Technology Readiness Level
TSO – Transmission System Operator
TWh – Terawatt hours
UN – United Nations
VRES – Variable Renewable Energy Sources

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1 Introduction

1.1 Motivation

That the world is undergoing rapid climate change due to human activity is no longer seriously disputed. To mitigate against this, several wide-spread agreements have been developed Some of which are the Paris Agreement and the European Green Deal. The latter was published in December 2019 by the European Commission [1, 2]. The deal has the ambition for the continent to have net-zero emissions of greenhouse gases (GHG) by 2050. The European Commission states that it is "*Striving to be the first climate-neutral continent*" and is doing this by "*Turning an urgent challenge into a unique opportunity.*"

Reaching this EU target requires action from all sectors and long-term strategic vision for a modern, prosperous, competitive, and climate neutral economy. Sector coupling has the possibility to provide the needed flexibility for the power grid in an economically viable fashion, by coupling the electrical power sector to controllable loads like heating, industry, transport and power storage.

1.2 Scope and Limitations

This thesis will be centred around the efforts to implement sector coupling as a decarbonising strategy throughout the energy sector and, more specifically, what the state-of-art is in Europe.

The perspective of the power grid and the flexibility options sector coupling might provide, will be the focus. To research the topic and gain an outline of the subject, a literature review was considered appropriate. The literature review will create the basis for evaluation of technology readiness levels.

The subject matter of this thesis is a vast array of possible areas of study. This has forced an informed selection of material for coverage and analysis. Where appropriate, an effort has been made to further clarify this within the text.

Some of the literature reviewed does not reveal fragments of detail that might otherwise assist in their evaluation. The reason for this is the protection of commercially sensitive information and of intellectual property rights.

The thesis, for both source material and analysis, is limited to the situation in Europe only, and only publications newer than 2009 were considered. Furthermore, only data that is publicly available at the time will be used to estimate technology readiness levels.

Norway's geography and topography give the country significant advantages in many fields touching renewable energy resources. This makes Norway an obvious point of focus. During the research phase, representatives of the Norwegian TSO, Statnett SF, expressed an interest in the thesis. For these reasons, the thesis has, in part, a Norwegian emphasis. It is the author's view that this perspective in no way diminishes the general relevance and value of the thesis findings.

1.3 Research Questions

This thesis is built around the following research question:

"What is the state-of-art of sector coupling in Europe today?".

This thesis has studied this by exploring

- "What kind of sector coupling technologies are available and at what TRL-level are they currently?"
- "Are there currently any sector coupling-projects that are of interest for Norway and/or Statnett?"

2 Power Systems

Any electrical power system has three main components: the means and equipment for power production, its network for distribution, and the demands for its consumption. A particular trait of electricity is that it must be consumed at the same time it is produced, if not, it must be stored. For example: whenever an electric car is charged or a light is switched on, the power required must simultaneously be produced at a power plant and distributed through the power grid. This is described as instantaneous balance, defined in a simple equation as:

$$Production = Demand + Losses. \tag{1}$$

This must be controlled somehow for the system to be sustainable. For every power system, there is a transmission system operator (TSO) to ensure this balance is kept. In Norway, this is Statnett SF [3]. In addition, power is traded across national borders, making a more complex equation:

$$Production + Import = Demand + Export + Losses. \tag{2}$$

Stability for this is maintained through the planning of production and distribution, based on weather and consumption forecasts, and using data and experience collected over many years.

2.1 Sector Coupling – Definitions and Relevance

The German Association of Energy and Water Industries defines sector coupling as

"*the energy engineering and energy economy of the connection of electricity, heat, mobility and industrial processes, as well as their infrastructures, with the aim of decarbonisation, while simultaneously increasing the flexibility of energy use in the sectors of industry and commercial/trade, households and transport under the premises of profitability, sustainability and security of supply*" [4].

While the European Commission defines it with broader strokes as

"*a strategy to provide greater flexibility to the energy system so that decarbonisation can be achieved in a more cost-effective way*" [5].

Even if there are discrepancies between the different definitions in the articles covered by the scope of this thesis, the general idea is the same. It is a strategy to increase flexibility and the robustness of the power system by coupling the different sectors like buildings (cooling and heating), industry, carbon capture and storage (CCS), and mobility with the power sector (illustrated in Figure 1)

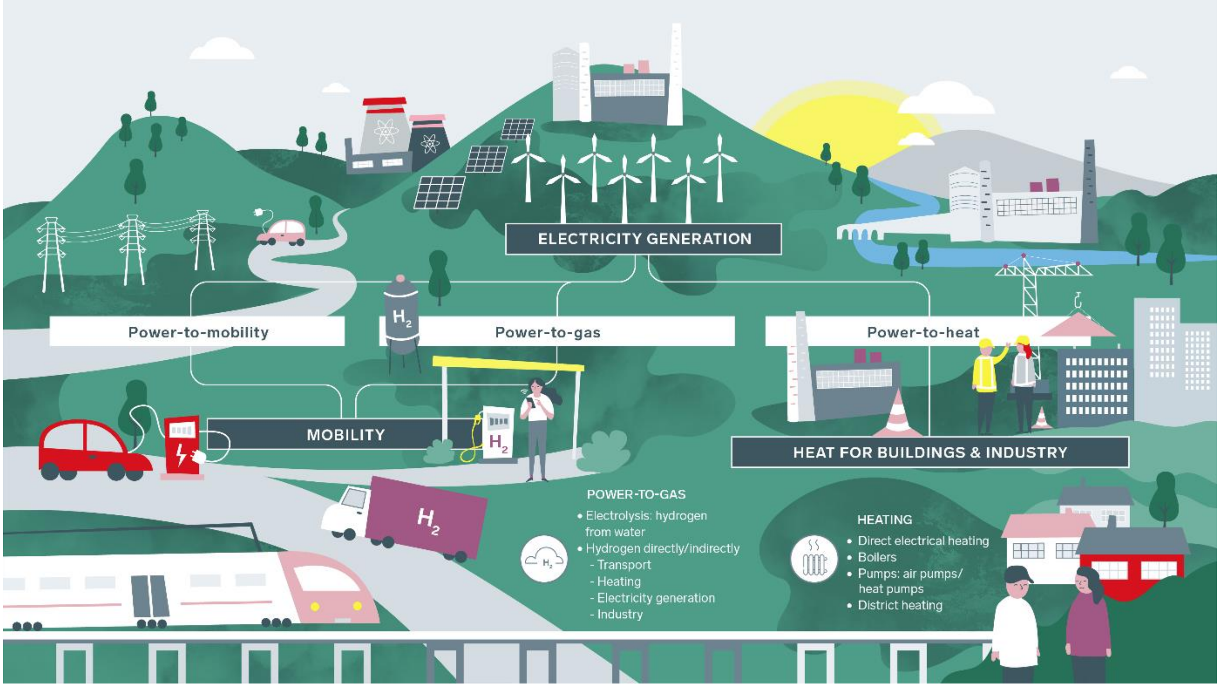

Figure 1: Illustration of sector coupling by Fingrid [6]. It shows different power sources and consumers, and their connections: power-to-mobility, power-to-gas, and power-to-heat.

By coupling the sectors, the power system can handle more variable renewable energy (VRE), and thus decrease the use of conventional power sources emitting GHG.

Because GHG emissions do not solely come from the production of electricity, but also from heating/cooling, transport, industry, and agriculture, many countries are taking action to decarbonise the entire energy system, including all energy sectors.

The density of CO_2 per produced kWh declines every year due to the ongoing expansion of wind and solar power. As these low-carbon options increase, there is a broad consensus that this power can be used to help decarbonise other sectors, for example the heating sector, which is heavily based on fossil fuels in the EU. This is part of sector coupling. It plays an increasing role in debates among researchers and politicians about future energy systems. Sector coupling can also provide the power grid with flexibility, a decreasing property when VRE is increased and thermal power production is phased out. [7]

In 2018, 171 gigawatts (GW) of power were installed worldwide from additional VRE sources [8]. Relative to the traditional energy conversion such as thermal power generation, renewables are gaining cost-competitiveness. As a result, 26 % of global electricity was being provided by renewables by the end of 2018. However, because the strong support policies needed were still lacking, sectors such as cooling, heating, and transport saw a smaller decrease in their carbon footprint. Combining all the energy sectors, the total final energy consumption (TFEC) of 2017 was estimated to be 18.1 % sourced from renewables. That percentage is still rising [9].

To reach the EUs ambitious goals, the power sector must become fully decarbonised. But it must, of course, remain reliable. This is a huge challenge to flexibility arrangements.

The Federal Minister of Germany for Economic Affairs and Energy, Peter Altmaier, stated that:

"*Germany's energy transition rests on three pillars: expansion of solar and wind energy, digitalisation in the energy sector and sector coupling..."*[10]

While this may be true for Germany and countries like it that have relied heavily on gas and coal power, Norway is in a different situation. With large amounts of hydro power, creating the backbone of the energy system, Norway produces electrical power in a reliable, renewable, and flexible fashion. Still, Norway has the potential to produce significantly more VRE from installations such as offshore wind power. To be able to introduce this into the national grid in a cost-effective way, sector coupling would be beneficial. Norway's reservoirs may thereby extend their use as a flexibility option for an increasingly VRE dependent Europe, while being economically profitable for Norway, having 50 % of Europe's reservoirs.

2.2 Integration within Europe

As a response to the warming atmosphere, the destruction of forests and the pollution of the oceans, the European Commission has set out The European Green Deal for the EU and its citizens. This deal involves an economy that is decoupled from resource use so that it can become GHG emission–neutral by 2050 while being economically competitive, prosperous, and fair. In the communications from the European Commission, they state that this deal will provide the solid foundation required to facilitate the accelerated transition needed in all sectors [1].

On their own, new measures are not enough to achieve the European Green Deal's objectives. Together with the Member States, the European Commission has worked for relevant legislation now in place to be effectively implemented and enforced, in addition to the 2050 goals being put into legislation through the first 'Climate Law' that was proposed in March 2020. [1]

For the European power sector, plants burning coal and fossil gas must be phased out rapidly. Instead, renewable energy resources must supply the lion's share of the power to be generated. If this is to happen, the power sector must have a fully integrated, digitalised, and interconnected energy market, both international and intersectoral.

Electrifying the end-user will make a significant contribution to the reduction of GHG emissions. Cooling and heating of industry and buildings made up more than half of the European Union's TFEC in 2017 [11], and only 19.5 % of that came from renewable energy sources (RES). This number has increased by more than 10 % since 2004, but still, more than 80 % of temperature-regulating energy is sourced from fossil fuels [12]. In the transport sector, only 7.6 % of the consumed energy was sourced from RES in 2017 [13]. Energy consumption has been stable in Europe since the 1990, showing only a small decrease in the industry sector and a small increase in the transport sector, as shown in Figure 2.

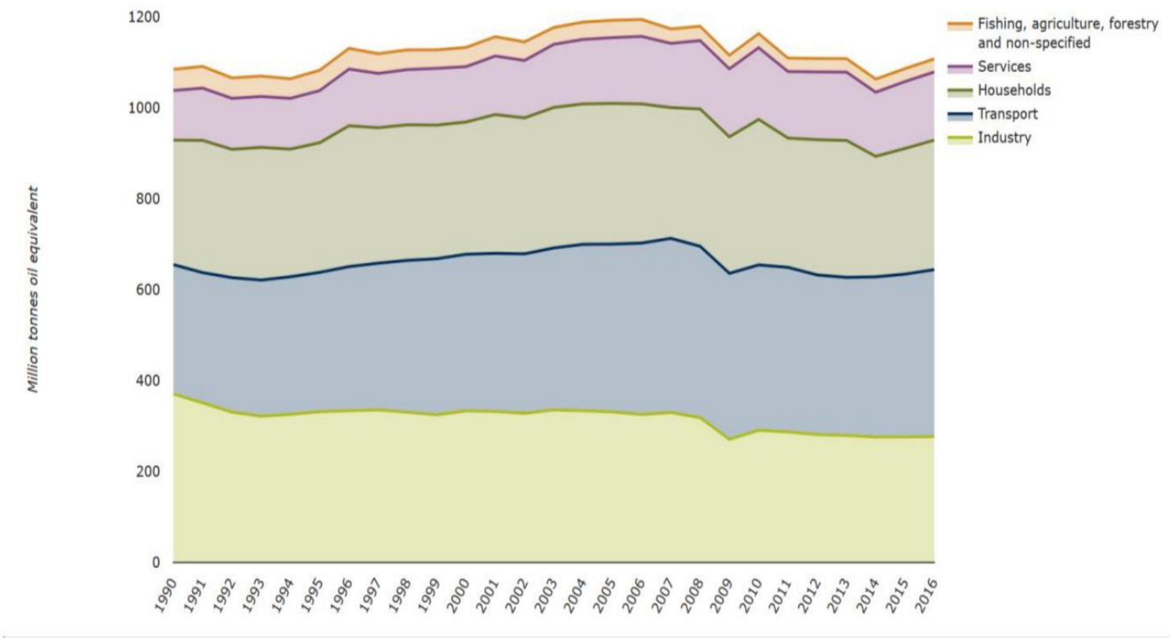

Figure 2 Final energy consumption by sector in EU 28 from 1990 to 2016 from industry, transportation, household, services, and Fishing, agriculture, forestry, and non-specified [14].

The EU has set a target of increasing the share of cooling and heating sourced from RES by 1.3% per year [15]. Both the transport and heating/cooling sectors are expected to gain more significant percentages of RES rapidly as a result of the European Green Deal, resulting in the desired increases of VRE in the power grid [1].

2.3 European Network of Transmission System Operators for Electricity (ENTSOE)

ENTSOE has five synchronous areas, having synchronously interconnected TSOs. These are Ireland-Northern Ireland, Great Britain, Baltic, Continental Europe, and Nordic [16], as shown in Figure 3.

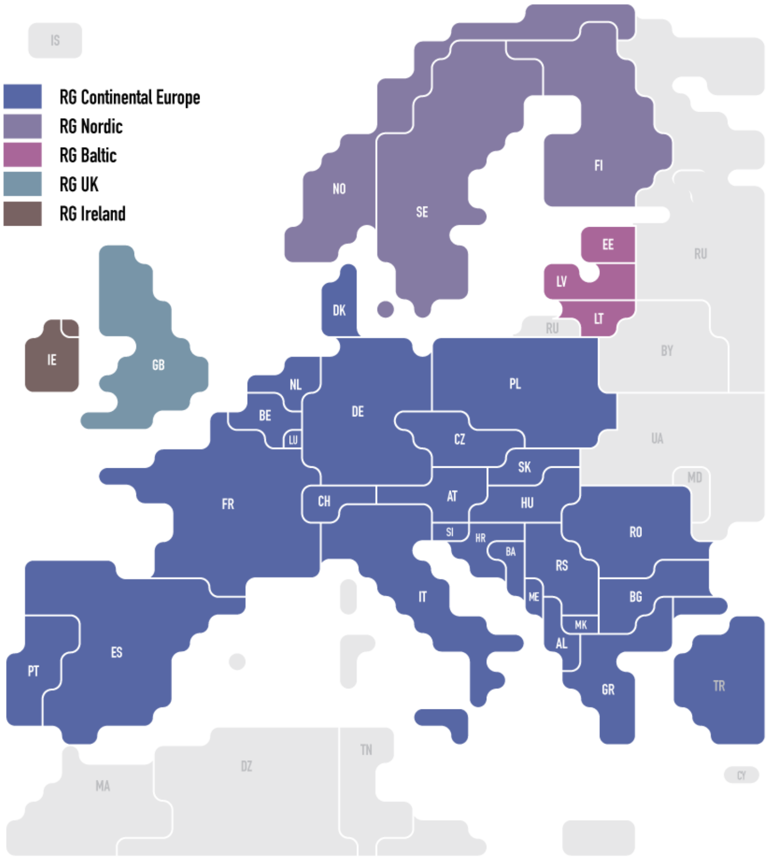

Figure 3: The five synchronous areas of Europe, Continental Europe, Nordic, Baltic, Great Britain, and Ireland, according to ENTSOE.[17]

2.4 The Nordic Power System

Norway is a part of the Nordic Power System, together with eastern Denmark, Finland, and Sweden. Being in the same synchronous area with the exact same frequency means that they directly affect one another. When more wind power is installed in eastern Denmark, more nuclear power generated in Finland or phased out in Sweden, this affects the Norwegian power grid directly. In addition, the increasing amounts of interconnection between the other synchronous areas gives the grid greater capacity, but inevitably increased complexity. Currently the Nordic synchronous area has connections to The Netherlands, Germany, The Baltics, Poland and Russia. New connections are in continual production. To meet these new challenges, new measures must be put in place. According to the document by Statnett and Svenska kraftnät called “The Nordic Balancing Concept” [18], minor improvements over time will not be enough. The whole system, both supply and demand, must be modelled in a new way. New optimal solutions based on the latest technology modelling must be put in place. This will require cooperation between the TSO’s of the respective countries (Statnett for Norway, Energinet for Denmark, Fingrid for Finland, and Svenska kraftnät for Sweden) working together with regulators and stakeholders.

2.5 The Norwegian Power System

According to Statistics Norway (SSB) [19], Norway had a total power production of 147 TWh in 2018, of which 95.0 % came from hydropower. More than 75 % of the hydropower produced in Norway comes from that stored in reservoirs. The remaining 25 % is derived from run-of-river production [20]. The stored hydropower puts Norway in a unique position in Europe with considerable reserves of flexible power production. This has given Norway a very reliable and stable power supply. A stable power system is defined as that having the ability to recover to an acceptable steady state after a disturbance. Every year between 1996 and 2017, the power system has had deliverability above 99.96 %. In previous decades, there was always a predictable balance in the Norwegian power system. Due to increasing VRE in both the Nordic and the rest of the European power systems [21], the challenges in foreseeing other production needs are increasing. The amount of power produced by wind turbines in Norway increased by 35.8 % from 2017 to 2018 [19], but, even so, contributed only 2.6 % of total production.

2.6 Variability and Flexibility

According to Gerbaulet et.al.[22] the electricity sector is the easiest and least expensive to decarbonise. It is an essential part of the low-carbon energy transformation strategy, but it is certainly not without challenges.

“Generation follows the load” is the conventional axiom for power production. Thermal power production is a well-established method for generating electricity. Traditional balancing of the grid is done through the prediction of power demand in an upcoming timeframe. Some generators’ production is slow to ramp up and down, such as nuclear and coal (several hours), but have low running costs. This makes them an economical option for continuous operation at maximum capacity to meet the grid’s baseload. However, they lack the responsiveness needed for TSOs to match actual demand. If demand differs from that predicted, the frequency will deviate from its reference, see Figure 4. In Europe, the reference frequency is 50 Hz with an accepted variation between 49.9 – 50.1 Hz [23].

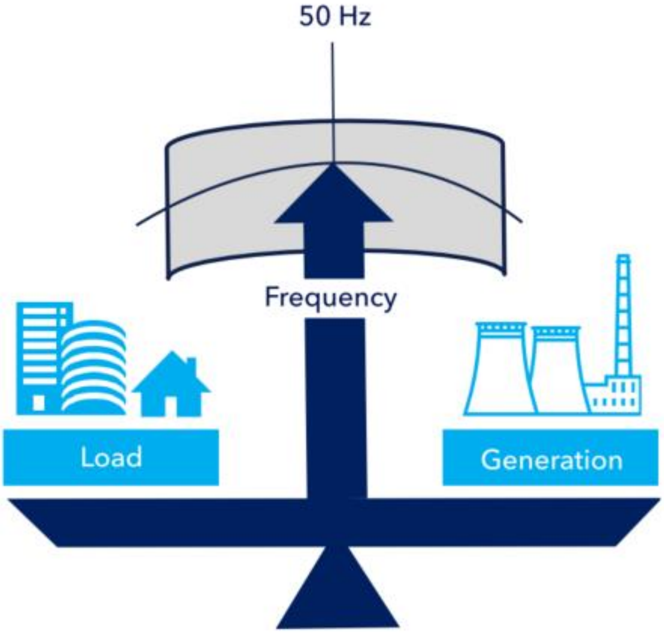

Figure 4 Illustration of the balance between supply and demand, and its effect on the system frequency. The figure is from DNV-GLs white paper on Flexibility in the Power System [24]

The TSO's mandate is to balance the grid through correcting-actions in real-time. Gas and hydro generators are best suited for this. They have low minimum stable operational levels and can ramp up and down quickly, making them agile enough to match the ebb and flow of actual power demands. Traditionally this gave TSO's full control on the production side of the equation (1), leaving demand as the only variable. However, this is no longer the case. The perspectives of Münster et.al. on the past, present, and future of generation profiles operational philosophies are shown in Table 1 [25].

Table 1: The generation profile, and operational philosophies of the past, present and future as Münster et.al. sees it. Table adjusted from "Sector Coupling: Concepts, State-of-the-art and perspectives [25].

	Generation Profile	**Operational Philosophy**
Past	Flexible (due to directly connected storage vector)	Generation follows the load
Present	Mostly flexible, but challenged by "residual load" profile	Pursuing the needed balance with flexibility means in infancy stages
Future	Mostly inflexible (varying RESs)	Load (+storage) follows the generation

As indicated by Table 1, the power generation of the past was fully controllable and therefore flexible. With increasing amounts of VRE in the system, flexibility decreases. The future's operational philosophy thus moves towards the opposite of the past: load must begin to follow generation. To avoid system failures arising from inevitable power imbalances, the means to increase options for flexibility must be introduced.

When a power imbalance occurs in the grid, it can be buffered by the kinetic energy stored in the synchronously rotating masses of the generators: their inertia. Imagine for example a sizable active power load suddenly being disconnected from the grid. For a split second, more power is produced than consumed. This imbalance must be equalised somehow to avoid system failure. With conventional thermal or hydro turbines, surplus power can be absorbed by allowing it to speed up the turbine. The result is a slightly raised grid frequency for a short period before TSOs reduce production, but there is no system failure. The same is true for a reverse situation. If a large load is suddenly connected to the grid, the required extra power can be drawn from the rotating masses, slowing them down until more power is produced [26].

The convenience of having all the unpredictability on the demand side, while the large turbines provide grid inertia to buffer the system, is diminishing as VRE inputs increase. In addition, new loads are being connected to systems through the increased electrification of transport, cooling and heating sectors. Unpredictability is now derived from both the supply side as well as the expanding demand-side variability. This calls for an expanded range of flexibility options if systems are to remain robust and reliable. Fortunately, some of the new load demands also double as flexibility options, such as battery EV. [24]

The industry sector is already tightly connected to flexibility through demand-side management (DSM) [27] agreements between power suppliers and industry stakeholders. These agreements can include parts of industry being shut off in hours of high domestic demand, for example after regular working hours when people return home to start cooking, charge their electric vehicles and so on. A requirement for this is that such turned-off loads in industry are deferrable, requiring specific power levels within specific and limited periods; but the exact timing of these periods is not crucial. Lights, are not such a load, needing electricity the moment they are required.

Examples of deferrable loads in some sectors are heating and cooling, charging of batteries, production of hydrogen, or pumping water. For loads such as these to contribute to flexibility, they must be connected in such a way that TSO's can turn them off and on as required.

Large increases of VREs as substitute power sources in the grid come with other challenges beyond their unpredictable nature; they cannot contribute to the systems inertia. The technical characteristics of wind- and solar power are different from conventional generators. VRE sources' interface with the grid is through power electronics, meaning that grid dynamics are decoupled from the power source. If an error occurs, VREs cannot buffer the problem to the same extent as the directly connected rotating turbines mentioned above [28]. The more significant the number of VREs, the higher becomes the demand for flexibility in the system.

DNV-GL defines flexibility as

"*a service that provides capability to the electric power system to respond to fluctuations and uncertainty in supply and demand to maintain and restore stable and safe operation within the limits of the system"* [24].

How flexible a system is can be measured through the duration of the service, speed of delivery, amount of adjustable power available, and the location of the point of connection. [24]

2.6.1 Power System Needs

Power systems need to be flexible enough to balance demand and production on all timescales. The requirements that need to be met are:

- **Stable frequency:** frequency stability needs to be preserved by maintaining the short-term equilibrium (fractions of a second up to an hour) between supply and demand through any disturbances and contingencies.
- **Adequacy:** mid- and long-term equilibrium between supply and demand (hours to several years) must be maintained.
- **Reliability of supply:** interruptions, failures and unplanned outage occurrences must be minimised.

From the grid perspective there is a need for transfer capacity, and both voltage and power quality. In particular

- **Congestion management:** activation of remedial action to transfer power between supply and demand in both the short and medium term (minutes to hours), wherever local or regional limitations may cause bottlenecks.
- **Voltage stability:** maintenance of bus voltages within predefined limits on local and regional scales for the short-term (seconds to tens of minutes).

2.6.2 Power Grid Time Scale

To describe a power system's flexibility characteristics, the time scales relating to its recovery from a system failure must be defined. There are mechanisms that can be engaged when an error occurs in the grid, one taking over from another. These mechanisms are grouped into four categories of short-term reserves. Their activation is illustrated in Figure 5.

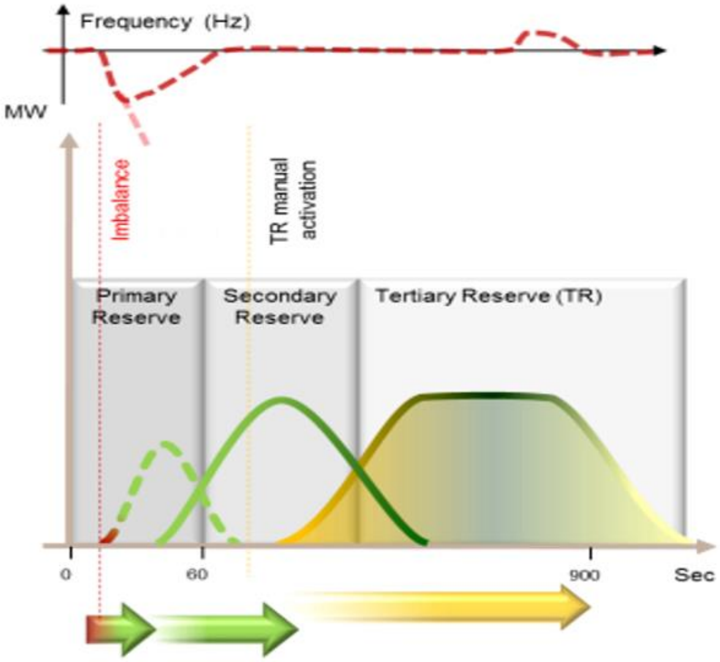

Figure 5: Illustration of the time scales in use in today's power system after an imbalance in the grid. Figure from Statnett [29]

Primary reserve/Frequency containment reserves (FCR) [30]**:** Immediately when an error occurs, the inertia of the generators' rotating masses buffers the error as described earlier. The result is a changed frequency which in turn activates the primary reserves, also known as the frequency containment reserves. This is an automatic response activated by TSOs.

Fast frequency reserve (FFR) [31]: Should the frequency drop below a certain threshold (usually between 49.5-49.7 Hz), the fast frequency reserve (FFR) is activated. This happens within a second of the error. However, it is relatively rare, and is not activated every year in Norway.

Secondary reserve/Load frequency control (LFC) [32]**:** If the frequency stays above the threshold for activating FFR, the next action is the automatic activation of the secondary reserves, also called the load frequency control (LFC). This happens within 2 minutes of the initial error. This is activated to make the FCR available to tackle another error, should one occur. After activating this reserve, the frequency is restored to 50.0 Hz.

Tertiatry reserve [33]**:** The last of the short-term actions is the tertiary reserve. All non-automatic reserves are defined as tertiary reserves. It can take up to 15 minutes to activate this reserve. In the Nordic Power System, there is a requirement for this reserve to be at least as much as the largest error the system is designed to handle. In Norway that is 1200 MW. Statnett SF has deemed it necessary to have an additional 500 MW to cope with regional bottlenecks and other imbalances. Tertiary reserves also extend into medium- and long-term reserves.

2.6.3 Sources of Flexibility

Flexibility sources are generally grouped into three categories

- Generation: the regulation of input into the grid.
    - Controllable generation
    - Variable generation
- Demand: modification of consumption patterns.
    - Small loads aggregated from residential and commercial sector
    - Large industrial loads limited to specific time periods
    - Electric vehicles’ charging patterns regulated
- Storage: the delivery or consumption of stored power to and from the grid
    - Electrochemical storage (for example, conventional batteries)
    - Electrical storage (for example, supercapacitors)
    - Mechanical storage (for example, fly wheels, compressed air, pumped hydro)
    - Chemical storage (for example, hydrogen, methane)
    - Thermal storage

However, not all sources of flexibility can meet all flexibility needs. Some are useful for power adequacy. Other options can benefit frequency stability. In their draft roadmap, ENTSO-E has mapped research of flexibility solutions and how they benefit the power grid. Table 2 illustrates ENTSO-E’s vision of what power system needs can be met by which technology.

Table 2: Table of flexibility sources and the power grids needs they can benefit

<table>
<tr><th></th><th></th><th></th><th colspan="5">Needs</th></tr>
<tr><th></th><th></th><th></th><th>Adequacy</th><th>Congestion management</th><th>Frequency balancing</th><th>Voltage Stability</th><th>Reliability of supply</th></tr>
<tr><td rowspan="10">Sources</td><td rowspan="5">Storage</td><td>Supercapacitor</td><td></td><td></td><td>Supercapacitor in hybrid storage</td><td></td><td></td></tr>
<tr><td>Thermal storage</td><td colspan="3">Thermal storage</td><td></td><td></td></tr>
<tr><td>Chemical storage</td><td colspan="3">Hydrogen and methane production</td><td></td><td></td></tr>
<tr><td>Mechanical storage</td><td colspan="3">Compressed air storage + flywheel</td><td>Liquid air storage</td><td></td></tr>
<tr><td>Battery</td><td colspan="4">Battery technology</td><td>Battery for reliability</td></tr>
<tr><td rowspan="2">Generation</td><td>Variable generation</td><td colspan="4" rowspan="2">Flexible generation</td><td rowspan="2">Black start from generation</td></tr>
<tr><td>Controllable generation</td></tr>
<tr><td rowspan="3">Demand</td><td>Small loads</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>EV charging</td><td></td><td colspan="3">EV demand Response</td><td></td></tr>
<tr><td>Large loads</td><td colspan="4">Industrial demand regulation</td><td></td></tr>
</table>

2.7 Technology Readiness Level – Estimation

To gauge how far along the technology has come, a technology readiness scale (TRL) scale is often used. These scales are not standardised, making them differ a bit between companies and institutions that use them. In this thesis, the same TRL-scale that Statnett uses will be applied. It is shown in Figure 6 and described in Table 3.

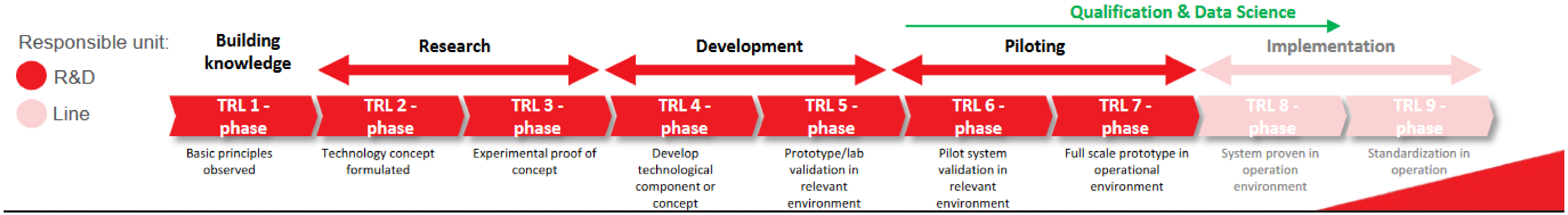

Figure 6: Illustration of the nine TRL-levels used by Statnett. [34]

Table 3: Requirements for the TRL-levels established by Research and Development at Statnett [36]

TRL-Level	Level qualifications	
1	Literature studies are executed to confirm the basic principles of the technology. A possible case based on the identified principles is suggested.	Building competence
2	Practical application of the method, the need for further research is established, and case limitations are established. Initial analytical studies are conducted to support the concept to generate new knowledge/data	Research
3	Initial work on the project has commenced, including analytical studies to prove that the concept is viable and new knowledge/data is serviceable.	
4	Fundamental parts of the new method are developed and adjusted to the current needs. The method for the development of knowledge/data is refined to verify its applicability.	Development
5	All parts of the method are now integrated to confirm that they link up. The concept is tested in realistic cases.	
6	The practical feasibility of the new concept is evaluated with realistic cases. The method for the development of knowledge/data is tested on a limited area by examining the whole process, including the analysis of data.	Piloting
7	The new concept is demonstrated in a working environment, integrated with former, operative solutions. New knowledge/data is produced, analysed, and applied in future operative processes.	
8	The concept is used and evaluated in real, operative situations.	Implementation
9	The concept is applied in its final form over an extended period of time.	

3 Sector Coupling – Applicability

3.1 History

The development of the electricity-grid has historically been driven by cost and reliability. Through different regulations imposed after such as the Paris Agreement and the European Green Deal, sustainability is now becoming a dominating factor making it a “trilemma” for further development, as illustrated in Figure 7. Now, providing consumers with power should not only be reliable and affordable, but also sustainable.

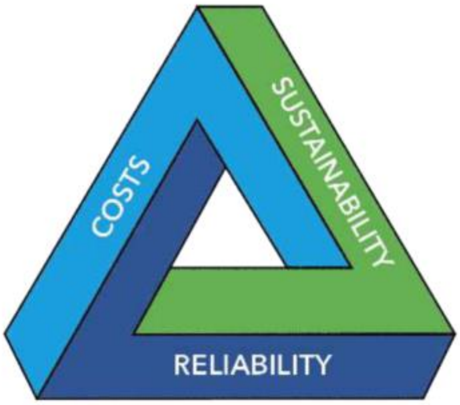

Figure 7: Illustration of the Energy trilemma. It illustrates the driving forces behind the development of the power grid-, costs, reliability and sustainability [24].

According to the ITRE committee (European Parliament Committee on Industry, Research, and Energy), sector coupling is a term that originated in Germany, but with popularity spreading throughout Europe. It came to life when new strategies were sought for tackling the energy trilemma. At first, the term was applied principally to connecting end-user applications that can be electrified, such as heating and mobility, to the power sector. However, the term has evolved to include supply-side sector coupling like power-to-gas in Germany. [5]

3.2 Applications and Technologies

Sector coupling brings a new complexity to the planning and management of infrastructure and operation. When implementing sector coupling, there are many components that need to collaborate both in the short and long term. This will require intelligent tools and methods. Münster et.al. [25] have classified the different devices and processes available that will aid this transition into:

- **Grid use:** Extended use of grid components, interconnections, and exchanges with neighbouring areas.
- **Flexible generation:** Use of traditional plants modulation and improved performances.
- **Flexible loads:** Demand response, interruptible customers, balancing services, aggregators, market and trading mechanisms, and smart EV charging.
- **Storage within electric system:** Batteries, fly wheels, supercapacitors and pumped hydro.
- **Storage in other energy systems:** EV, thermal, thermochemical, chemical, gasses/liquids.

This classification is made from the electric systems' perspective as a mapping of flexibility options (without delving into flexibility needs and characteristics).

An extended use of sector coupling options will most likely, if not inevitably, lead to a more significant electricity demand [35]. If sector coupling is to be a step in the right direction towards the goals of 2050, renewables need to cover primarily the increased demand for electricity [36].

There are different definitions of the sectors involved in sector coupling. Most commonly the sectors of transport, residential/building and industry are used. An overview of the possible interactions between sectors, conversion technologies and storage options is shown in Figure 8, as imagined by Münster et.al. [25].

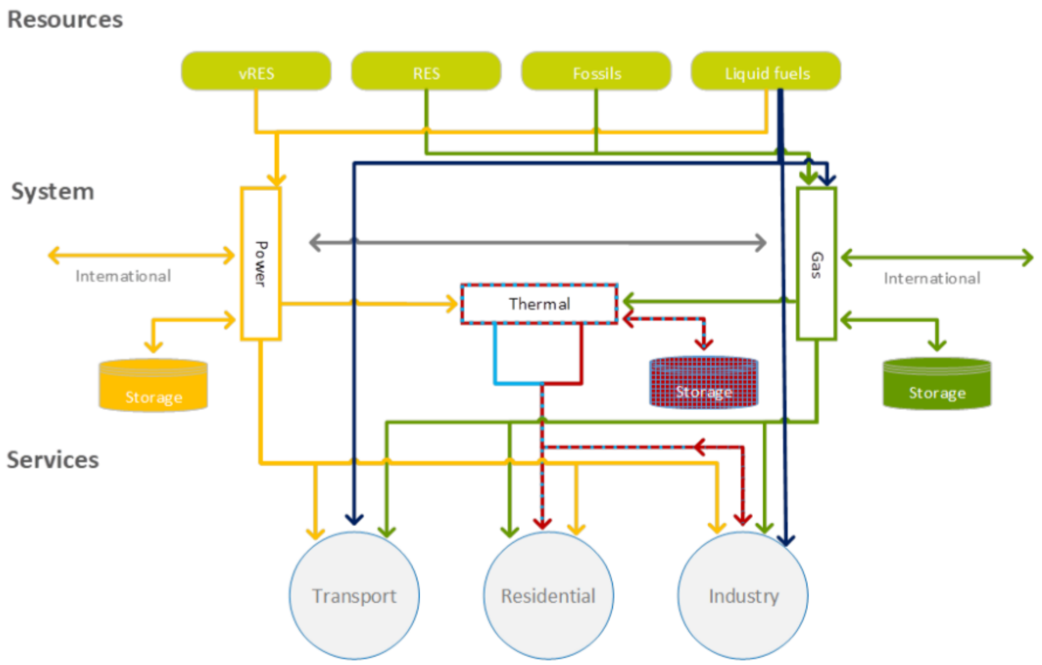

Figure 8: Scheme of possible interactions among energy vectors. Illustration from Münster et.al.[25]

3.2.1 Storage

Storing energy is one of the indispensable means to create flexibility and a key component in the development of a strategy for integrating VREs into the power grid. There are four main categories of energy storage.

- Thermal energy storage. Typically, thermal storage is divided into three categories - sensible-, latent-, and thermochemical heat/cool storage.
- Electrical energy storage (capacitors and super-conductors etc.).
- Chemical storage (batteries, H_2, etc.)
- Mechanical energy storage (pumped hydroelectric storage, compressed air energy storage, flywheels etc. are known technologies.) [36, 37].

There are significant variations in the round-trip efficiency of these storing methods. They vary from above 90 % efficiency in flywheels to as low as 20-50 % in hydrogen storage [36]. However, these technologies are continuously improving and thereby providing increasingly better flexibility options.

Some of the characteristics used for evaluating energy storage options are:

- how fast, and how efficiently, the energy can be charged/discharged;
- the energy density (meaning the amount of energy that can be stored per cubic meter or mass);
- the losses that occur in storage conversions; and
- the losses that occur during "shelf time". [38]

The choice of energy storage option is, of course, firmly dependent on circumstances. Some methods of energy storage may be useful for daily variations, with a high conversion efficiency in charging and discharging, but have a high self-discharge effect, making them unsuitable for seasonal storage. Batteries for example, are well suited for daily variations in low voltage applications such as households, cars and other mobile devices. However, such ideas as seasonal battery storage for a small village seem unlikely to be practical. The size of the battery needed to handle the seasonal variations in demand in a small village would make it unlikely to be developed. Thermal storage might be a better option for that purpose, or perhaps even pumped hydroelectric storage.

Thermal energy storage allows thermal energy to be stored over a period of time and released later. The technology applies to both heating and cooling. As mentioned above, thermal storage is typically divided into three categories shown in Table 4.

Table 4: Table of thermal storage types and their energy storing method

Thermal storage types	Method
Sensible	Sensible heat/cold storage stores thermal energy by "charging" a medium. through changing its temperature, while providing a means to sense that change.
Latent	In latent thermal storage, the charging and discharging happens by changing the state of the medium without changing the temperature through phase change.
Thermochemical	Thermochemical storage involves a charging process from thermo-reversible chemical reactions.

The dominant storage option in Norway is pumped hydroelectric storage - a variant of mechanical energy storage. The technology utilises surplus power to pump water into reservoirs to store it as potential energy [39]. According to Statnett SFs report on flexibility in the Nordic power market [40], hydro power will remain the least expensive form of storage in the years 2018-2030. However, there are limitations in both power and storage capacity. Looking into the future, there may be some scope to invest in increasing capacities in existing hydropower stations. For the time being, more significant investments are not likely until they can show promise for a considerably greater return.

3.2.2 Power-to-Heat/Cooling

The heating and cooling sector has great potential to reduce its carbon footprint in addition to contributing to the flexibility of the energy system. Currently, buildings are the single largest energy consumer in the EU with 40 % of the total energy consumption as well as making 36 % of CO_2 emissions. [41]

About half of the EUs energy consumption comes from heating and cooling in buildings and industry. In the European residential sector, slightly less than 80 % of final energy use is spent on hot water and heating. According to data from Eurostat, 19 % of heating and cooling is generated from renewable energy, while 75 % comes from fossil fuels. The remaining 6 % comes from nuclear power production [42].

In Norwegian households, 75 % of total energy is spent on space and water heating, 83 % of total energy consumption is consumed as electricity [43]. Cooling is a relatively small part of energy consumption in households, but demand from the food industry is rising and peaks during the summer months. 70.6 % of Norway’s energy consumption in the industrial sector was used for space and industrial process heating. [44]

The combination of its large energy requirement and the use of fossil fuels gives this sector significant potential for making a substantial reduction in European emissions. Especially when combined with heat or cold storages, and acting to meet deferrable loads, VRE can be utilised to a greater extent in this sector.

Heat is either supplied by a large centralised heat plant where the heating grid is used to transport the heat, or a decentralised model located close to the points of use. Small scale power-to-heat technology for conversion in the residential sector is relatively common. [45]

For example, resistive heater or residential heat pumps. However, power-to-heat technology on grid-scale with thermal storage is still relatively new.

3.2.3 Power-to-Mobility

According to data provided by Eurostat, consumption in the transport sector made up 31 % of TFEC in the EU-28 in 2017 [14]. Road transport (73 %) and aviation (13.6 %) contributed the largest part of this [46]. European consumers used 3.25 and 8.63 million terrajoules (TJ) of energy from gasoline and diesel respectively in the transport sector. Together they consumed 92.8 % of the 12.8 million TJ of energy needs in the road transport sector. If the EU is to meet its targets of reducing GHG emissions by a minimum of 80 % by 2050, much of this energy will need to be derived from renewable resources. In 2017 only 0.04 % of road transportation in EU-28 was driven on electricity [46].

There are different approaches to shifting the transport sector to a more renewable model. What kinds of fuel the various transportation methods need are directly linked to their use and characteristics. Rail transport can be electrified directly from the grid, while personal vehicles, trucks, ferries, ships, and planes need some form of inbuilt storage if they are to use electricity as fuel. Typically, these electric transportation methods use either batteries or hydrogen for fuel cells as storage. Both these technologies can, however, help also with the problem of limited flexibility in the grid.

The number of electric vehicles is increasing, especially in the Nordic countries [47]. This can prove troublesome for grid providers if charging times coincide with residential peak hours and if there is no means for their control. However, EV could be considered as more than simply passive loads. They hold the potential to be a service provider beyond that of transportation. EV batteries are a relatively large load compared to other residential loads, but they are idle more than 90 % of the time. If EV were somehow to be connected when not in use, their aggregated potential could provide a quick response buffer for the grid, draining their batteries in peak hours and charging them in times of otherwise low demand. If managed properly, EV could supply the grid with a source of flexibility, making them an asset for DSOs [48].

3.2.4 Power-to-X

Power-to-X is a collective term for the conversion of power to either gas or liquid energy carriers. This creates a means by which energy produced from large scale VRE plants can be stored. It thereby aids in creating flexibility in the power system through DSM. It offers also a means for and a tighter coupling between sectors and applications.

Roughly 67 % of the global TFEC in 2017 came from fossil fuels [49]. These energy carriers are mainly used as fuels and feedstock in a wide range of applications. Even though RES such as wind and solar can be transformed into electricity without the release of GHG, some of the applications do not lend themselves to direct electrification. Long-haul aviation and maritime, for example, are particularly challenging to electrify. For those cases, production of gases and liquids with a low carbon intensity and a high energy density could offer alternative solutions in support of decarbonisation in all sectors.

Electrolysis is the predominant process for the production of H_2. It could provide a means for the use of surplus electricity from VRE sources, thereby creating added flexibility. No GHG would be emitted in the process, making it both attractive and sustainable. H_2 can be used to produce other biofuels or directly in a fuel cell. Electrolysis is a mature technology. The gas produced has high purity. There is, however, a downside - the round-trip efficiency of producing H_2 and recombining it in a fuel cell is only about 50 %. [50, 51]

In Continental Europe, there already exists a gas network. It covers most of the continent and is sophisticated and well established. Currently it is used for supplying fossil gas for heating and cooking. By storing energy from VREs as H_2 from electrolysis of water, the gas network exists as a possible solution to the means for distributing it.

4 Literature Selection

Sector coupling embraces several technologies and many sub-categories. The purpose of this literature review is to gauge the technology readiness level (TRL) of some of the more prominent technologies. The results of the review are then used to identify what steps need to be taken for sector coupling to be a possible energy strategy in Norway and for Statnett SF.

4.1 Literature Search

The selected literature was chosen after applying search engine keywords into relevant databases. The chosen databases were Science Direct and the Institute of Electrical and Electronics Engineers (IEEE). These are deemed sufficiently large, covering an estimated 21 million scientific entries. The literary search was divided into two sections.

1) The preliminary search was based on the overall topic of sector coupling. This search aimed to identify which countries are focusing on the topic, the nature of the involved institutions, and by considering the dates of the publications, whether sector coupling is active as an area of research. The following search string was used:

   "sector coupling" AND (“energy” OR “power” OR “grid")

2) The second part of the search was focused on the technologies involved. This was done by varying the combination of technology-name keywords with the search phrase “sector coupling” in search strings. Only publications with search results in the metadata (title, abstract, or author-defined keywords) were included in the search results. The same search strings were applied in both databases. The used keyword combinations are shown in Table 5.

Table 5: Table showing the different technologies researched in this review, the searches performed and the number of results in each search

Technology	Search string	No of hits
Batteries	"sector coupling" AND (“batteries” OR “battery” OR “chemical storage”)	21
Thermal storage	"sector coupling" AND (“thermal energy storage” OR “thermal storage” OR “heat storage”)	24
Pumped hydro	"sector coupling" AND (“pumped hydro" OR "pumped hydro storage")	2
Heat pumps	“sector coupling” AND "heat pump"	18
Power-to-Heat-District Heating	“sector coupling” AND ("district heating" OR "DH." OR "central heating") AND (“power to heat" OR "power 2 heat" OR "PTH" OR "P2H" OR "PTH/C")	1
Power-to-Heat – Residential	“sector coupling” AND "residential" AND (“power to heat" OR "power 2 heat" OR "PTH" OR "P2H" OR "PTH/C")	2
Vehicle-to-Grid	"sector coupling" AND ("VTG." OR "V2G" OR "vehicle-to-grid" OR "vehicle to grid" OR “battery electric vehicle”)	6
Power-to-Liquid	"sector coupling" AND ("power-to-liquid” OR "PTL" OR "P2L")	4
Power-to-Gas	"sector coupling" AND ("power-to-gas” OR "PTG" OR "P2G")	18

Note: The technologies from those listed in Table 5 above, that emerged as the most relevant for further work after the Literature Review Analysis in Chapter 6, were:

1) Battery Storage
2) Power-to-Heat with Thermal Storage
3) Power-to-Heat using Heat Pumps
4) Vehicle-to-Grid
5) Power-to-Gas

From the search results, one article was chosen as particularly relevant. To maximise the relevance of chosen literature, two additional constraints were applied in their selection:

- The literature should be no older than 2017.
- The literature should be European.

Each of the chosen individual articles is reviewed in Chapter 5, alongside a practical example of the technology in question. These cases will be evaluated on a technology readiness level scale in Chapter 2.7.

5 Sector Coupling in Action – Reviewed literature

5.1 Battery Storage

As the price of PV systems continue to decrease, increasing number of residences are installing them on their property. An article centred around the use of batteries from homes with PV to stabilise grid frequency was chosen.

The chosen illustrative battery case, described after the article review, was considered appropriate as it is an ongoing project in Norway with an exceptionally large battery and it uses a very high voltage connection. It also illustrates sector coupling between the power and mobility sectors.

The highlights of this technology are shown in Chapter 5.1.3.

5.1.1 Article Review

"*Evaluation of the effects of frequency restoration reserves market participation with photovoltaic battery energy storage systems and power-to-heat coupling"* was written by G. Angenendt et al.[52] and investigates homes that have installed PV- connected battery storage. How the batteries can both stabilise the power grid's frequency, and be used in a power-to-heat capacity to decrease the use of fossil fuels in heating, is studied. The number of houses with this technology is increasing steadily in Europe. By combining the PV batteries with a heat pump, households can increase the use of renewables and contribute to decarbonisation, without any significant cost increases.

As increasing shares of VRE enter the power grid, the demand for reserve power storage increases proportionately. Households with grid-connected batteries can contribute to providing control reserves if they are aggregated and connected as a pool of units. Since the European frequency restoration reserve is divided into both negative and positive reserve markets, it creates opportunities for households to participate in the negative frequency restoration reserve market and benefit from lower-cost energy. If there is an excess of power, this can be utilised if the households also have a power-to-heat technology, thereby increasing the operating range of the integrated battery installed. However, increasing battery use could reduce battery life by as much as up to 40 %.

One of the issues regarding the inclusion of privately-owned batteries into the energy system is financial compensation for additional battery aging, especially for those already making savings for reduced domestic energy consumption from the grid. The article addresses this and presents a calculation of the savings and marginal costs for such market participation.

The results of this paper show that the annual cost for heating and electricity can be reduced by up to 14.5 % in homes that partake in the German frequency restoration reserve market. Other scenarios presented in the paper show that it is less economical to use the battery solely for frequency restoration reserve, than it is to use it in combination with a photovoltaic system.

5.1.2 Current Battery Storage Projects

In 2021 Norway's largest ferry connection, Moss-Horten, is to be electrified [53]. The ferries will have the largest battery pack ever installed on a ferry of this size.

Figure 9: Siemens' record-fast charging batteries are converting Norway's largest ferry connection to electricity [53].

The energy storage system will include a 4.3 MWh battery pack and an energy management system provided by Siemens. The battery is built for the ferry operation to be fully electric and will be the world's largest of its kind, in addition to being the largest battery pack on any ferry of its size in Norway. Siemens will also provide battery charging infrastructure for record speed charging while the ferry is docked.

The ferry schedule requires a high voltage connection with up to 7.2 MW charging capacity. Charging this fast places a high demand on the batteries onboard the ferries, creating significant heat. Siemens has solved this by using water-cooled batteries as a cost-efficient technology, cooling them to an optimal level.

Initially, there will only be a charging station on the Horten side of the route, resulting in the ferries only being operated by electricity 65 % of the time. Eventually, there will be charging stations on both sides, and they will operate entirely on electric energy.

When the ferries are operating 100 % on electricity, they will save the equivalent CO_2 emissions of 3400 new petrol cars per year, according to calculations made by Enova and Bastø Fosen. According to an analysis conducted by DNV-GL and Siemens/Bellona in 2015 [54], it is possible to fully electrify up to 50 % of Norwegian ferry routes, and up to 70 % if hybrid options are included. However, data collected from the electric ferry Ampere shows that the distribution grid must be augmented to be able to handle the power transfer needed for the fast charging required. A possible mitigation for this could be battery banks on the docks, such as in Flakk in the Norwegian region Trøndelag. Here, the dock-side batteries can charge the ferries' onboard batteries with 4.5 MW each time they dock. However, adding an additional link in the power conversion-chain, necessarily increases the losses associated with the power transfer.

5.1.3 Battery Storage Highlights

The highlights of this technology are shown in Table 6.

Table 6: Shows the advantages and disadvantages of battery storage.

+	Household can contribute to the frequency reserve
+	Is an option for decarbonizing the mobility sector
+	It is a known technology with high TRL
+	Can be beneficial for household economy if proper market regulations are in place
-	Batteries deteriorate faster when used for grid stability
-	How to compensate for this deterioration needs market solutions
-	If many ferries are electrified, large areas of the grid must be upgraded. Especially if there is no dock side battery that can be charged at a slower rate.
-	Does not contribute flexibility on a longer timeframe than frequency reserve

5.2 Power-to-Heat with Thermal Storage

Thermal storage is high-visibility technology within sector coupling. It produced the most hits in the initial technology search for this review. A very recent article (2020), taking a holistic approach, was chosen. This holistic approach is a key factor if sector coupling is to become a reality. By modelling Europe in such a way, insight is given into what a sector coupled Europe might look like.

The chosen illustrative project was selected, in part, because it is one of the new thermal storage technologies showing the state-of-art. It is particularly interesting because it can convert electrical power to thermal power for storage, and then back into electrical power using conventional components such as heat engines and cheap materials.

The highlights of this technology are shown in Chapter 5.2.3.

5.2.1 Article Review

In the article "*Impact of climatic, technical and economic uncertainties on the optimal design of a coupled fossil-free electricity, heating and cooling system in Europe,"* written by K. Zhu et al. [55], a model is presented depicting a plausible fossil-free energy system suited to European countries that are relatively self-sufficient for RES. A one-node-per-country network was modelled, with an hourly resolution that required the continent to have net-zero CO_2 emission. This was done to evaluate the impact of technical, economic, and climatic uncertainties of the coupled network.

The model assumes long-term market equilibrium and perfect foresight, meaning market revenues precisely recover the cost of the technologies involved. Furthermore, each of the 30 European countries (EU-28 plus Norway and Switzerland) in the model has power generation equal to the power demand in each country. Historical data provided by ENTSO-E from 2015, is used to estimate the electricity demand in each country. Power is derived from hydropower, wind, and solar PV generation, but the mix is optimised according to each country's particular individual resources. HVDC lines connect neighbouring countries as illustrated in Figure 10.

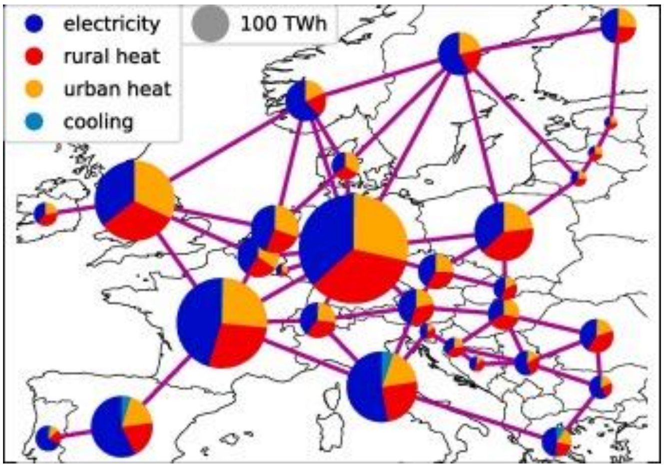

Figure 10: The map shows the annual national energy demand of the countries in the model with one node per country and HVDC connections between the neighbouring countries.

Heating in the industry sector is not included. Only commercial and residential heating is considered, further divided into hot water demand and space heating. The heating demand is covered by power-to-heat technologies such as heat pumps and resistive heaters and has dispatchable backup heating in gas boilers. According to Zhu et al., heat pumps play a vital role in the highly decarbonised coupling of heating and cooling systems within the electricity sector. This is the technology that can provide the largest share of thermal energy, capable of contributing approximately 40 % of the total thermal supply requirement.

The article discusses several options for demand-side management (DSM) for the heating sector. It introduces a simple solution for short-term thermal storage, without sacrificing the comfort of the indoor environment, by utilising buildings' thermal masses. This reduces the need for other forms of thermal energy storage, especially in rural areas where seasonal thermal storage might not be available. This type of DSM has the potential to alter the shape of the consumer demand curve, thereby decreasing peak demands. However, in urban areas with centralised heating, this method altered neither the optimal system configuration nor the cost. This is because the massive hot water tanks involved in centralised heating systems already have the desired smoothing effect on heating demands.

5.2.2 Current Power-to-Heat with Thermal Storage Projects

The University of Cambridge has an engineering department running a research and innovation project on pumped thermal electricity storage [56]. The UK has a target to make 20 % if its energy requirement from renewable sources by the end of 2020. This dictates a need for more storage to mitigate the effects of variability in supply. As of March 2020, the UK had 30 GWh of electric storage capacity with a maximum output of 3 GW. Nearly all of this is stored as pumped hydro storage (PHS), which has both economic and geographical constraints. The principal investigators of this project's expert view is that UK’s storage capacity needs at least to double in the coming decade to accommodate the expanding fractions of VRE.

The project aims to investigate the novel technology of pumped thermal energy storage (PTES). This technology uses high temperature-ratio heat pumps for the conversion of electric energy into thermal energy, stored in hot and cold gravel-filled containers. This makes it possible to store energy in a much more compact way than PHS. When needed, the thermal energy can be converted back to electricity by running a heat pump in reverse as a heat engine. The round-trip efficiency is estimated to be 75 %, which the project investigators claim is a little lower than PHS but has other benefits such as no geographical constraints and low capital cost. A schematic of the set-up shown in Figure 11.

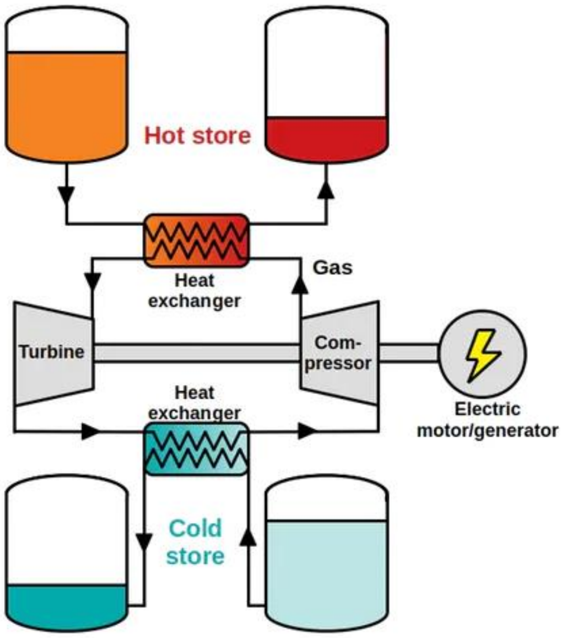

Figure 11: The schematic shows the set-up of the PTES as imagined by Pau Farres Antunez [57], who has published several papers on the topic.

The success of this technology hinges on the extent of heat losses in the stored energy and losses associated with the compression and expansion of the working fluids, while keeping capital costs low. The project investigators state that an essential part of the project is to optimise and validate the system's model and examine the benefits that PTES might bring to the electricity supply chain. Furthermore, they state that the proposed project has significant potential to stimulate interest and further research in the academic community.

PTES is a relatively new concept, about ten years old. Much research and development remains to be done. The proposed further developments on the project will include several other storage technologies such as compressed air and geothermal storage, in addition to using alternative transfer mechanisms including heat pumps, internal combustion, and Stirling engines.

Contributing to the field of power networks and markets, through the benefits PTES might bring, is part of what this project aims to do. Results will be published continuously in journals such as IEEE and ASME and through presentations at both national and international conferences.

This is an interdisciplinary project combining expertise in complementary areas. The project investigators believe this will increase its overall impact.

5.2.3 Power-to-Heat with Thermal Storage Highlights

The highlights of this technology are shown in Table 7.

Table 7: Shows the advantages and disadvantages of power-to-heat with thermal storage.

+	Highly researched area: many subcategories for different applications
+	Prober deferrable load for DSM
+	Has high TRL-level when used for urban DH
+	Can alter consumer demand curve: peak shaving
+	No geographical constraints
+	If large amounts of thermal energy is stored, it can contribute as seasonal flexibility
-	PTES: low TRL
-	PTES: a little lower roundtrip efficiency than PHS
-	Does not contribute flexibility on a longer timeframe than frequency reserve

5.3 Power-to-Heat with Utility Sized Heat Pumps

In 2018, 78 % of EU-28's entire market for building heat came from fossil fuels (if electricity sourced from fossil fuels is included) [58]. A strong alternative to this is district heating (DH), coupling power and heat sectors by utilising heat pumps that run on a combination of synthetic gas and VRE. The chosen article is the oldest of all the reviewed articles (2017), but its holistic approach to implement DH across all of Europe with increased use of heat pumps makes it particularly interesting. The illustrative case considers a project where this technology successfully in operation in Copenhagen.

The highlights of this technology are shown in Chapter 5.3.3.

5.3.1 Article Review

In the article "*Heat Roadmap Europe: Large-Scale Electric Heat Pumps in District Heating Systems"* [59] the authors, A. David et al. consider a potential increase in DH in Europe of up to 50 % by 2050, with approximately 25-30 % of it being supplied by large-scale electric heat pumps. Their study aims to show that developments to achieve this could begin with the technologies already available in 2017.

The article presents a database of the technologies, their current availability status and the potential for their expansion across Europe. The database is the first of its kind and is used as the basis for further analysis in the article. The article surveys existing European DH systems that create thermal power by utilising large-scale heat pumps with an output exceeding 1 MW. Heat-pumps such as this were found in only 11 countries.

The study quantifies the operation of 149 heat pumps found at 80 different locations in the 11 countries, with an aggregated thermal output of 1580 MW. Refrigerants, heat sources, efficiency, and types of operation were evaluated. The study observed that across all generations of DH, distribution temperatures tended to decrease. This increases the benefit of using heat pumps for DH, as lower temperature lift increases their coefficient of performance (COP).

The collected and analysed data is then used to consider deployment on a large scale in other locations in Europe. The study finally concludes that the technology has reached a satisfying level of maturity and is ready for replication in other European locations, with the condition that careful consideration is essential in the choice of refrigerants in order to satisfy local environmental requirements.

5.3.2 Current Power-to-Heat with Utility Sized Heat Pumps Projects

Copenhagen has set an ambitious goal of becoming carbon-neutral by 2025. To achieve this, they have chosen DH to play an important role. [60] The company responsible for this distribution of electricity, water, and heat is the Greater Copenhagen Utility (HOFOR in Danish). HOFOR also has wind turbines in their operation.

A demonstration plant “Flexheat” was established by HOFOR in 2018 in the harbour area of Copenhagen. It supplies three cruise ship terminals and the nearby UNICEF warehouse with DH sourced from VRE and demonstrates how effectively sector coupling can minimise GHG-emissions by electrification. It now emits 315 tonnes less CO_2 annually than it did with the previous liquified petroleum gas system.

The facility, shown in Figure 12, has a heating capacity of 1 MW and a 100 m^3 virtual battery with a storage capacity of 4 MWh.

Figure 12: Image showing the FlexHeat virtual battery of 4 MWh stored thermal energy in its 100 m3 storage tank [60].

This form of sector coupling can create flexibility for the power system by storing excess electricity in other energy systems. However, for this to be a reality, smart operation is required. The FlexHeat operational system currently has six different operational modes, making it run as effectively and economically as possible while considering the weather forecast and electricity prices. Historical power consumption data under similar conditions is also factored in. The data is fed into an algorithm that continuously improves the prediction for the next day's operation. By utilising machine learning, the system, step by step, achieves a better performance.

5.3.3 District Heating with Heat Pumps

The highlights of this technology are shown in Table 8.

Table 8: Shows the advantages and disadvantages of district heating with heat pumps.

+	High level for TRL
+	As distribution temperature decreases, the heat pumps COP increases
+	Decreases CO_2 emissions by replacing fossil heating options
+	Deferrable load: increases flexibility of the grid as all connected units are automatically aggregated loads
-	Smart operation needs to be developed further for optimal performance
-	Time for machine learning to optimize regulation is needed
-	If this becomes widespread, the distribution grid might need to be extended

5.4 Vehicle-to-Grid

As battery EV increase their market share, vehicle-to-grid technology has emerged as a way to make them an asset for the power grid. If aggregated, the grid-connected batteries can be a source of frequency restoration reserves. However, the charging patterns of EVs raise challenges that must be addressed. The reviewed article, in its more general coverage of the transition from fossil fuels, models how flexible electric vehicles can both benefit and challenge the power grid, by assessing the pattern in which the vehicles are used.

In the illustrative case this is put to the test and shown to be commercially feasible with a fleet of mass-produced EV.

The highlights of this technology are shown in Chapter 5.4.2.

5.4.1 Article Review

In the article *“Assessment of flexible electric vehicle charging in a sector coupling energy system model – Modelling approach and case study”* written by P. Sterchele et al. (2020) [61], the transition from fossil fuel driven private vehicles to electricity-based is discussed as a decarbonising strategy towards environmental goals of the near future. The entire power and transport system, including the patterns of use, are considered as a whole in order to analyse the opportunities and obstacles associated with this transition.

The scene for the proposed model is a sector-coupled, structurally optimised, model of Germany’s nearly-CO_2-neutral energy system. Two different methodological approaches are used to assess battery EV incorporation into the model. The first model altogether neglects driving profiles, and the use of the vehicles is randomised. The second model includes realistic driving profiles generated by considering average household vehicles, persons, average trip times, distances, and so forth. An illustration of the profile generator is shown in Figure 13.

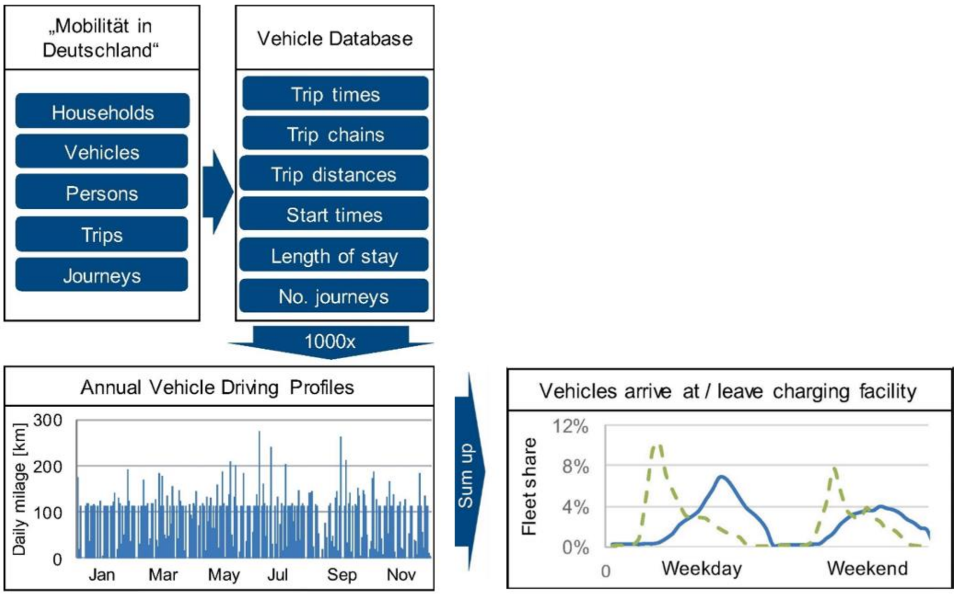

Figure 13: Illustration shows a schematic overview of the driving profile generation used in the second profile. Illustration adjusted from [61].

For every time interval in both models, account is taken of how many vehicles arrive or leave a charging facility. For the arriving vehicles, account is taken of how much of their stored energy is currently available to feed into the grid. This information is used to restrict draining the battery, ensuring that the vehicle battery can only be used to supply the grid if its charge level is higher than a given threshold value.

The results show that if realistic German driving profiles are used, large numbers of EV will be re-charging simultaneously. This results in higher peak loads and (eventually) will require an increase in power capacity. Upgrading the power grid for a higher peak load such as this will be very expensive and require many years of planning. This development can be mitigated through the implementation of controlled charging, effectively shaving both power load- and supply peaks. This projected cost-optimal system configuration integrates more power from VRE sources, potentially reducing annual overall system costs by several billion Euros that otherwise would be needed to expand the grid's peak capability. This reduces the disadvantages of battery EV, without diminishing the grid stabilising benefits.

While both the random and the profile-based models provide insight into the effects of large market shares of EV, for simplicity, all the users in the models are assumed to behave in a certain way. Ideally, users' profiles would be more diversified, leading to a more realistic model. The authors state that this should be taken into account in future studies. They also note that the additional costs for flexible battery operation and deterioration are not included in this model and are considered to be included in the purchase cost of the vehicle. The authors recommend future work to complement this modelling with a series of sensitivity studies.

5.4.2 Current Vehicle-to-Grid Projects

The Danish Parker Project [62] provides grid balancing services from a battery EV fleet through Vehicle-to-Grid (V2G) technology. The project aimed to validate that mass-produced electric vehicles can support the power grid by being an integrated resource both locally and systemwide. In addition, the project seeks to ensure that barriers regarding technology, market and users are dealt with to facilitate further commercialisation and also to evaluate specific battery electric vehicles' capability to meet the needs of the grid. Ultimately, the aim was to contribute to the role of battery EV as contributors when switching to a more renewables-based energy system.

The Parker project is based on three pillars:

1) Grid applications
2) Grid readiness certificate
3) Replicability and scalability

Regarding grid applicability, this project searches for viable business cases by identifying technical, regulatory, and economic barriers by studying the practical applications of energy and power services in modern battery electric vehicles.

The grid readiness certificate demonstrates the electric vehicles' ability to support the technical parameters needed to provide power and energy services to the grid. The Parker project calls this a Grid Integrated Vehicle (GIV) certificate.

Promoting replicability and scalability of the demonstration across user groups, technologies and geographies also have a place in the project. This is done by investigating the economic and technical impacts of the power system and markets.

The general conclusions published in the final report are:

1) It has been validated that the vehicles used in the project, together with DC V2G chargers, are ready to provide advanced services to the grid.
2) A field test in Copenhagen shows that it is possible to commercialise this technology through the provision of frequency containment reserves.
3) Further steps must be taken to support V2G services across all electric vehicle brands.

5.4.3 Vehicle-to-Grid Highlights

The highlights of the technology are shown in Table 9.

Table 9: Shows the advantages and disadvantages of vehicle-to-grid technology

+	Beneficial for the decarbonisation of mobility sector
+	Can provide a frequency containment reserve
+	Possibility to commercialise
+	Possibility for scalability for local needs
-	Batteries deteriorate faster when used for grid stability
-	If large amounts of vehicles are electrified, peak power might increase if charging is not regulated.
-	How to compensate for this deterioration needs market solutions
-	Not all electric vehicle brands support vehicle-to-grid
-	Does not contribute flexibility on a longer timeframe than frequency containment reserve

5.5 Power-to-gas

The last in-depth review is power-to-gas. The chosen article focusses on decarbonisation as the heart of sector coupling through power-to-gas technology. It also includes carbon capture technology. Carbon capture is in itself not defined as a sector coupling technology but is a part of most decarbonisation strategies in place today.

In the illustrative case a power-to-gas plant is presented that is fully integrated in the power system in Haßfurt, Germany.

The highlights of this technology are shown in Table 10 in Chapter 5.4.2.

5.5.1 Article Review

The article "*The role of power-to-gas and carbon capture technologies in cross-sector decarbonisation strategies*" [63] written by M. Berger et al. proposes an optimisation-based framework to tackle the multi-sector coupled energy systems of the future. The coupling integrates electricity, hydrogen, fossil gas, synthetic methane, and carbon dioxide in the same system.

The suggested model selects and sizes the parameters for power generation, storage, and carbon capture so that the cost of supplying the energy demand is minimised. Energy is supplied across the power, heating, transportation, and industry sectors while taking policy drivers such as energy independence, GHG emission-targets, and support schemes into account.

The usefulness of a model such as this is demonstrated in a case study in the article. The case evaluates the potential of sector coupling via power-to-gas and carbon capture technologies to achieve deep decarbonisation in a Belgian context.

The results seem to indicate that power-to-gas will only play a minor supporting role in sector coupling Belgium. Given the limited potential for RES in Belgium, there are no strong political incentives to expand into power-to-gas. Instead, Belgium is expecting post-combustion, and direct air carbon capture technologies to play a central role. This will help with decarbonisation but may also extend their dependence on fossil fuels.

5.5.2 Current Power-to-Gas Projects

Windgas Haßfurt GmbH [64] is a joint venture project in Bayern, Germany. The project commenced in October 2016 and is still running (May 2020). Among the companies running this project are Siemens AG, Next Kraftwerke GmbH, as well as Schweinfurt Technical College. At the centre of the plant is a container-sized polymer electrolyte membrane (PEM) electrolyser with a peak power of 1.25 MW, exceeding the project goal of a 1 MW connection. Other project goals are:

- Decentralised power grid stabilisation through load and consumption management.
- Frequency stabilisation in the power grid (primary reserves).
- Feeding the gas network with locally produced sustainable gas.
- Make use of normally non-integrated power (excess power from wind and solar).

The plant converts excess current, from the nearby wind park in Sailershäuser Wald and other wind and solar sources, into hydrogen gas. Annually, the container-sized electrolyser will supply 1 GWh of renewable gas to its nearly 20,000 customers in the Greenpeace Energy gas-network. In principle, the gas can be stored within the gas network over long periods for distribution later, when required. By utilising the existing gas network, the capital costs are minimised.

Electrolysers convert excess wind and solar power to hydrogen with an efficiency of about 70%. By doing this, power that cannot enter the grid due to overproduction can be stored for eventual use. The PEM electrolyser installed in Haßfurt is exceptionally responsive, resulting in an ability to stabilise the power grid while producing H_2. Within milliseconds, the electrolyser automatically changes service to stabilise the network, preventing failures caused by overload. In Haßfurt, this installation offers this service to Next Kraftwerke as part of their "virtual power plant," where several power plants, flexibility options, and consumers are coupled. Through this such regulated support, power-to-gas installations can also generate revenue.

5.5.3 Power-to-Gas Highlights

The highlights of this technology are shown in Table 10.

Table 10: Shows the advantages and disadvantages of power-to-gas technology.

+	Can make use of unintegratable (excess power) from VRE
+	Beneficial for the decarbonisation of mobility secor, also long distance
+	Can contribute to primary reserves
+	Possibility to commercialise
+	Possibility for scalability for local needs
+	Can be directly coupled with VRE
+	Deferrable load, DSM
+	High TRL
+	For Europe: can use exsisting gas-network
+	Possible to store
-	Converting efficiency at about 70 %
-	High investment cost

6 Literature Analysis

The analysis will be in two parts. First, the first literature search will be analysed, cataloguing and discussing its results in three different ways. Then the technology search and the in-depth articles will be analysed.

6.1 Analysis: Literature Selection

The first section of the search was on the general topic of sector coupling. This gave a total of 131 results in the two databases of ScienceDirect and IEEE. However, only 94 of these were deemed relevant. The reasons for the removal of the 37 excess publications were:

- The given additional search limitations requiring the words “power”, “energy” or “grid” to be included in the metadata was not sufficient to exclude all irrelevant publications.
- The words *sector* and *coupling* are both relatively common words in academic writing, even in combination with the additional requirements. This was thought to make publications outside the scope turn up in the search results.
- As this thesis has focussed on the European energy system, all publications that originated in non-European countries were removed. They made up 4.5 % of the initial search.
- Publications newer than 2019 were not included in the first section of the search. This was done as this thesis will be published by mid-2020 and will, therefore, not be respectably comparable with earlier years.

Filtering out these publications was essential for gaining the correct insight, as the non-relevant publications amounted to 28 % of the initial search results.

The search for literature was ended when the results from the two defined databases were considered adequate. The use of other combinations of search strings and databases were considered superfluous. It is a safe assumption that the search has provided a representative literature constellation.

After discarding the irrelevant search results, there still remained too large a number of publications for in-depth analysis. This risked the findings in this thesis giving merely an overview of sub-categories, rather than an in-depth assessment of each sub-category. After a general overview to ensure a complete picture, a careful selection of the articles for review was made.

There may well be many publications that by definition are included in the topic of sector coupling, but are not tagged as such. Authors might use terms like "integrated energy" or "energy internet" to describe the similar technical arrangements, or write directly about the technologies involved, without mentioning sector coupling per se. The results give more insight into what *is* included in the term sector coupling, rather than an overview of everything that *could* be included in the topic.

6.1.1 Publications timeline

From the first part of the search, a trend graph was made to show when publications regarding sector coupling were published. This is shown in Figure 14.

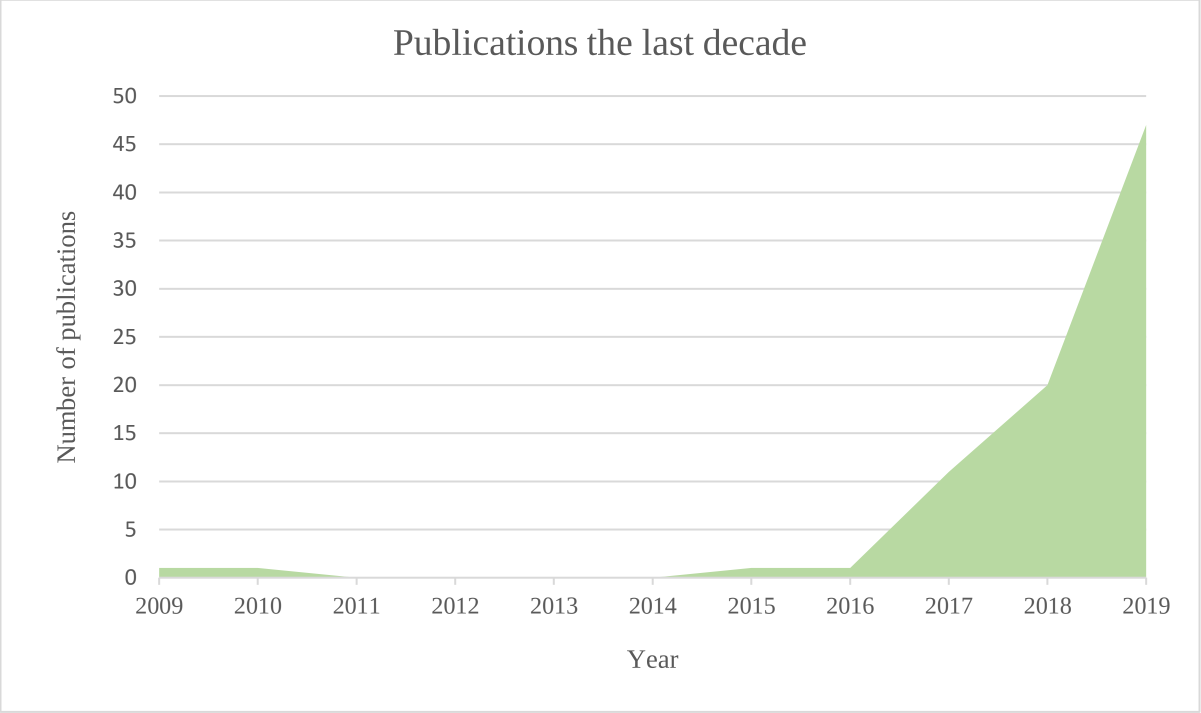

Figure 14: Graph showing the number of publications on the topic of sector coupling in the last decade. The publications increase strongly from 2017 and onwards.

The number of publications per year increases from 1 in 2016 to 11 in 2017. It continues to increase to the time-constraint of the search, 2019, a year in which there were 47 publications. This confirms there has been increasing interest in researching this area. This is a more than plausible response to political incentives being increased, at the same time that researchers were identifying sector coupling as a potential means of mitigating the decrease in grid flexibility caused by increasing VRE.

6.1.2 Countries of origin

The search results were also catalogued to determine which countries were publishing most. When the authors stemmed from different countries, the leading author's affiliation was used. The results of this cataloguing is presented on the map of Europe in Figure 15.

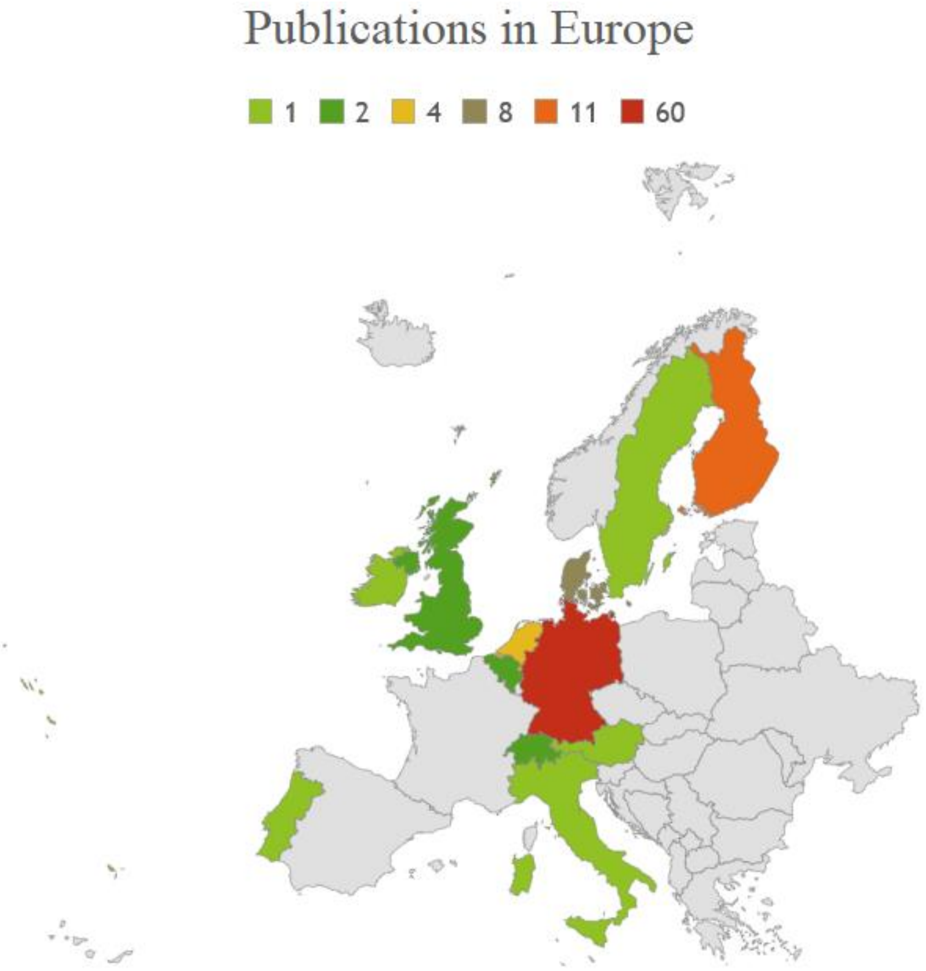

Figure 15: Map of Europe showing the intensity of sector coupling publications across the continent.

Germany published the most, with 60 publications in the last decade, 64 % of all of the publications in this review. Germany is followed by Finland with 11, Denmark with 8 and the Netherlands with 4. In total there were publications from 12 European countries; Norway was not among them. The fact that Germany had the highest publishing intensity on the topic is no surprise. The term originated in Germany and is considered a part of the three pillars in the German energy transition statement [10]. The Finnish government has set an ambitious goal of becoming climate neutral by 2035, which might be the reason for Finland to be the runner up. Fingrid, the Finnish TSO, writes in a press release that sector coupling will help to clean up the energy system and bring more flexibility into the grid where it is needed [6].

It is noticeable, perhaps even remarkable, that countries such as Spain and France have no visible publications on the topic. This might be because this thesis has limited literature review to publications in English or possibly due to the use of different terminology or databases in those countries. This does not necessarily imply that those countries are not studying sector coupling strategies.

6.1.3 Technology Readiness Level

One way to gauge technology readiness levels is to consider what kind of institutions are publishing on the topic. The results were, therefore, grouped into institutions and the results are shown in Figure 16. In the same figure, the TRL-scale has been placed to show a possible link between publishing institutions and technology readiness level. When multiple institutions were involved in a publication, the leading author’s affiliation was used.

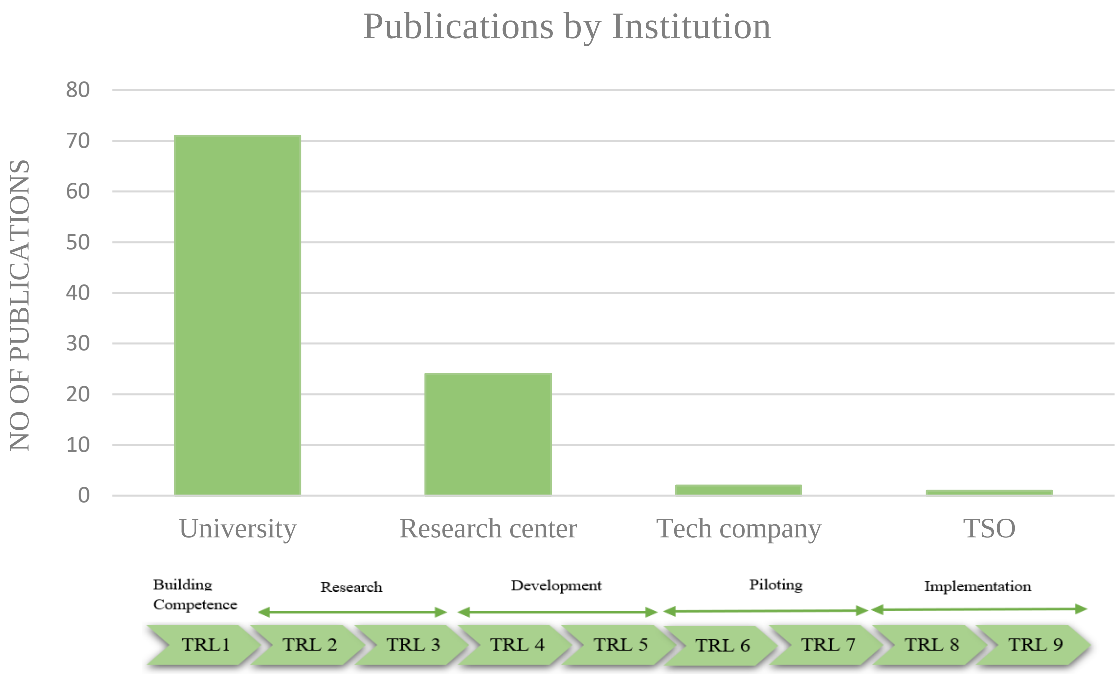

Figure 16: Illustration that shows a possible link between the publishing institutions and TRL.

Figure 16 shows that the search results are dominated by titles published in cooperation with institutions typically tied to the earlier stages of TRL: competence building, and research. That said, it would be misleading to say that all of sector coupling is in its infancy, as many sector coupling technologies are already in use today. Battery electric vehicles, electrolysis, heat pumps, and so on are technologies that have been in use for several years. However, the concept of a holistic approach to an integrated and flexible energy system on a national, or even international level across all sectors could be correctly placed in the early stages of TRL. From the literature reviewed in this section, TRL 3 would fit the bill from a holistic sector coupling perspective. From the description of the TRL-scale used by Statnett, shown in Table 3, level 3 indicates that:

TRL 3	Initial work on the project has commenced, including analytical studies to prove that the concept is viable and new knowledge/data is serviceable.

The reason for believing that sector coupling is not yet at TRL 4, is because fundamental elements such as appropriate market solutions and complete, smart, software systems have not yet been developed and adjusted to meet current needs.

Another comment on this illustration is that the institutions with low publishing numbers on the graph, such as tech companies and TSO, may be doing research without publishing.

6.1.4 The Literature Search on Sector Coupling Technologies

The second part of the search was focused on identifying the technologies involved and which technologies featured most as sector coupling facilitators. Nine main categories were found, and automatic searches were established for all of them, as shown in Table 5 in Chapter 4.1. The results from these searches showed that thermal storage was the technology most written about in the scope of sector coupling, closely followed by battery technology, power-to-gas and heat pump-technology. How much each of the technologies contributed to the total results is shown in Figure 17.

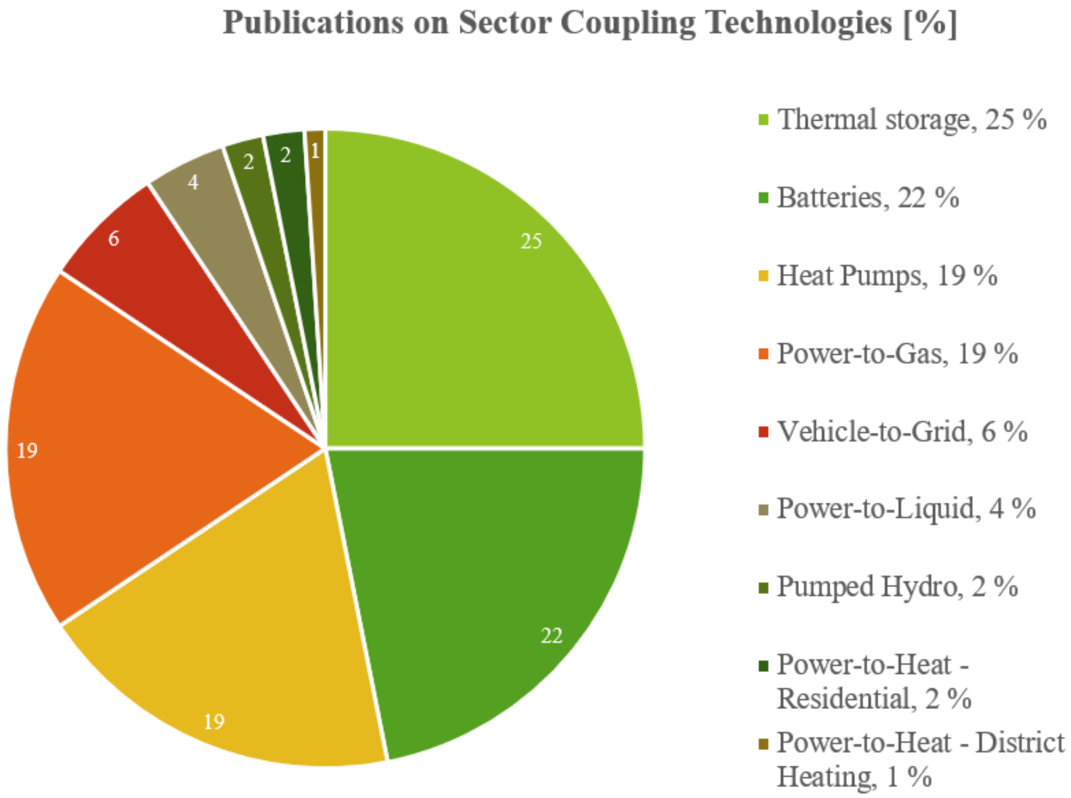

Figure 17: Pie chart of the results from the sector coupling technology-search. Most results were found about thermal storage, batteries, power-to-gas and heat pumps. The total number of publications was 96 in this search

The selection of the five topics chosen for in-depth analysis was strongly influenced by the technologies with most results in this search.

6.2 Analysis: In-Depth Articles

The chosen technologies from the in-depth articles will now be reviewed. Their technology readiness level will be estimated, as will their connection to the power grid needs described in Table 2.

All the chosen technologies contribute to the EU target of decarbonisation; either through allowing more VRE in the grid, through making use of otherwise non-integrable power from VRE, through direct replacement of fossil fuels or a combination of these. All the chosen technologies have the ability to alter the demand curve through peak shaving/load shifting. This benefit could contribute big savings in grid development. Power grids are dimensioned according to their peak load. Sector coupling will, in all likelihood, increase the overall demand for power. But if new large loads are configured to be amenable to DSM, peak power loading might be limited to avoid the huge expense of an expansion of power grid capacity.

That being said, not all *applications* of the discussed technologies will lead to peak shaving/load shifting. An example of this is battery charging applied in projects such as the electric ferry. This is because it runs on a schedule, needs to be charged perhaps every hour, and will certainly increase the overall grid demand as it cannot be deferred. This is especially so if the ferries are charged directly from the grid, and not from a dock side battery or other storage source.

The chosen technologies are almost all fundamentally at a high TRL as nearly all of them have been around for years in some shape or form. The exception is vehicle-to-grid, relatively new, as are the large numbers of personal vehicles now driven on electrical power from the grid. But, most of the cases evaluated in this thesis are on a slightly lower TRL as they represent further developments on existing technology. For example, storing electrical power as thermal energy has been around for many years, but the PTES case described in Chapter 5.2.2 is still being developed.

Another example of an adjusted TRL is the power-to-gas installation in Haßfurt. It has been operating for an extended period of time; it is integrated into both the power system and the economic market and the software needed for it is mature. It therefore has its place in the later stages of TRL. However, considering the implementation of similar technology in Norway would necessarily lower readiness levels, as both the necessary IT and structured market solutions are lacking. The same can be said for other piloting projects. Integration in Norway cannot happen on a larger scale, such as that for power-to-gas installations, without solutions to these or similar deficiencies. Taking all of this into consideration, the technology averages at about TRL 7.

An installation like the one in Haßfurt is also the only technology mentioned in this thesis that states that it can provide the grid with both a fast frequency stabilising reserve and seasonal flexibility through storage, in addition to currently being able to create revenue in Germany. This makes this technology particularly interesting. However, it is possible that thermal storage could provide the same service if the technology can be made adequately responsive.

The technologies involving batteries can benefit the frequency reserve if the batteries are connected to the grid when they are not in use. Furthermore, smart charging in hours of low demand help distribute the peak load. Some congestion management at DSO-level is also possible, however, that is not possible at TSO-level.

According to the concept of Design Thinking [65], there are three main drivers behind any true innovation. These are desirability, feasibility, and viability, shown in the Venn diagram in Figure 18.

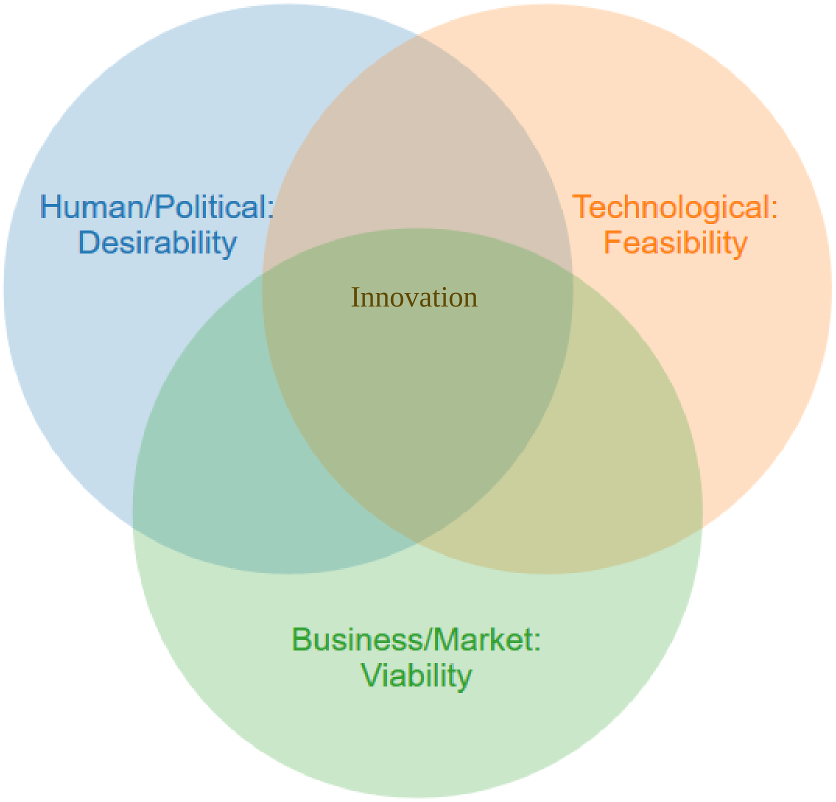

Figure 18: Venn diagram of innovation, and the three drivers desirability, feasibility, and viability.

Is sector coupling innovation plausible? Is it desirable? Is it feasible? Is it viable? With all the new decarbonisation targets and general political willingness to protect the environment, one can surely state that there is a desire for a technological strategy like sector coupling to aid in decarbonisation and increase grid flexibility. In Chapter 5, five different sector coupling technologies were reviewed, all with a relatively high TRL, and some already “up and running” in European countries. If smart control is implemented so that TSOs and DSOs can control the demand side, it is definitely technically feasible.

The segment missing for innovation (at least in Norway) is market viability. How flexibility providers are to be compensated needs to be identified. With so many competing interests this is going to be, to say the least, difficult. New flexibility options will not be implemented until there is a viable market and the market will not be created until flexibility providing technology is in place. As of now, Norway has cheap, reliable and flexible power in stored hydro. It might require a simulation of what the power system will look like in 2050 to highlight the need to start the work on a flexibility market.

7 Conclusion

7.1 Conclusions

There is broad political agreement across the EU to start the implementation of decarbonisation strategies, to move towards a net-zero emissions society. The need to use increasing VRE within the energy system, to replace existing "polluting" systems, is self-evident. The demand on TSOs, to maintain a reliable and dependable grid, in the absence of the needed flexibility and response mechanisms to support more VRE, has led a search for solutions. Sector coupling is one such solution that can contribute handsomely to both efficiency and reliability in the grid. Happily, it can contribute generously also to decarbonisation.

Publishing on the topic has increased steadily from 2017 (Figure 14, p. 48). This development is derived from a combination of political incentives together with the drive to make use of the growth of VRE as it comes more available. Eleven European countries have published accessible material in the chosen databases since 2017 - led by Germany (64% of material found), Finland (12%) and Denmark (8.5%) (Figure 15, p. 49).

This literature review has been executed to study the current state-of-art of sector coupling in Europe. Term origins, working definitions, relevant technologies and their readiness levels have been described. Nine technologies were found to be directly connected to the term sector coupling (Figure 17, p. 52). The five most prominent of these: batteries; power-to-heat with thermal storage; power-to-heat with heat pumps; vehicle-to-grid; and power-to-gas, were chosen for in-depth study.

The technology developers have seen the evolution of this situation: more flexibility and responsiveness are required within the power grid. Diverse technologies, engineered to bring different types of sector coupling to life, have been created. Much of the technology needed for a holistic sector coupling strategy is now at a high level of technology readiness (TRL 7).

However, sector coupling as a conceptual whole is at no more than TRL 3 (Figure 16, p. 51). Essential elements are missing for the development of a complete, innovative strategy (Figure 18, p. 54). Smart coordination between coupled technologies needs to be developed further, to enable the efficient management of the flow of energy through production to consumption via different storage options. Market regulations, governing how new infrastructure arrangements for flexibility might fit into the existing power market, must be developed. The rewards or compensation for those providing such arrangements must be negotiated and agreed before sector coupling can begin to become a wide-spread reality.

Determining how to compensate those involved in the delivery of these flexibility options must, surely, be a first step, if the search for sector coupling options for Statnett SF is to avoid both pitfalls and missed opportunities.

7.2 Further Research and Recommendations

In this thesis many topics have emerged as deserving of a closer look. Because the scope was to give an overview on sector coupling, and insight into its general state-of-art in Europe, some of these topics have been considered only superficially. The following suggestions are offered as recommendations for further research:

- The quantification and realistic availability of the power grid's future needs for flexibility. This should have a high priority.

- Large scale simulations of what the grid might look like in 30 years, to highlight and prioritise the need for economically viable flexibility options in 2050.

- Large scale sector coupling pilot studies, within which multiple sectors might be coupled, should be initiated to show how and where sector coupling can make the best contributions.

- More in-depth, perhaps “hands-on”, research into each of the technologies would be of value. It might also be rewarding from an economical/commercial point of view.

- When the data from current projects comes available, a study into how to scale them to meet future power grid needs would be relevant.

- Standardisation of the term flexibility is something Statnett SF and ENTSO-E need to address. Power flexibility is a term in use, but without standardisation the problems of comparison between apples and oranges will soon interfere with progress. Flexibility for the maintenance of frequency stability is, for example, very different from seasonal flexibility. Agreed-upon flexibility terminology would be of significant benefit in the further development of the power grid, both nationally and internationally.

Based on the findings in this thesis, a final recommendation would be for Norway and Statnett SF to look into a power-to-gas project. They might also investigate if it is possible to make thermal storage as responsive as the power-to-gas plant in Haβfurt. If Norway is to produce more offshore wind power in the future, for connection to the mainland grid, power-to-gas technology could provide the flexibility needed across all of the grid’s time scales. A project like this would be of particular interest if Norway’s hydropower is to become a more significant commodity within the EU flexibility market, through increasing connections to the continent.

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