Sector coupling and battery storage as flexibility options in the 2050 renewable power system

An assessment of North West Europe and the Netherlands with the IRENA FlexTool

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Abstract: To meet the goal of the European Union of becoming climate neutral in 2050, the Netherlands and North West Europe will integrate more and more variable renewable energy sources (VRE) into their power system. The uncertain weather conditions on which the VRE are dependent, will increase the need for a more flexible power system**.** An important measurement to control the balance of supply and demand in a power system with a lot of variable renewable energy is curtailing the excess power of renewable energy. However, the large amount of renewable energy that is currently integrated will result in an increase in lost power through curtailment. This increase in lost power can result in renewable energy projects (current and future) not getting the expected economic benefits, which can result in less investments in these projects. To prevent this, it is necessary to reduce this curtailment by either storing the otherwise lost power with batteries or by using it through sector coupling possibilities such as power-to-heat, power-to-gas, or power-to-mobility. The aim of this study is to research the potential of sector coupling options and batteries in utilizing the lost power from VRE curtailment by means of the IRENA FlexTool. In order to reach the objective of this study, two scenarios were used on two scales, the Netherlands and North West Europe and were modelled with the IRENA FlexTool. In order to compare the different sector coupling possibilities and batteries, an optimal design of experiments was used. The results of the sector coupling and batteries in this design of experiment were compared on their levelized cost of energy (LCOE) and the loss of load and curtailment of the power system. The modelling results of the IRENA FlexTool shows that the costs for utilizing the lost power of curtailment and avoiding loss of load differs for the Netherlands and North West Europe. For North West Europe, batteries have the lowest LCOE when almost all lost power trough curtailment is used. Hydrogen provides a good solution for the loss of load. Therefore, both battery storage and hydrogen could be a good substitution for natural gas in NWEU. For the Netherlands hydrogen storage is the option with the lowest LCOE when all lost power through curtailment is used and loss of load is avoided. Therefore, hydrogen could provide a good substitution for natural gas in the Netherlands.

Key words: Renewable Energy Curtailment, IRENA FlexTool, Sector Coupling, Battery Storage

1. Introduction

In December 2019 The European Union (EU) presented their Green Deal with the aim of becoming the first climate-neutral continent by 2050 (European Commission, 2019). In order to achieve this, the EU member states will have to strongly increase the share of renewable energy sources in the next decade (Newbery, 2020). The international energy agency (IEA) expects that most of this renewable energy will be coming from photovoltaic (PV) and wind (IEA, 2019). However, both PV and wind energy sources depend on uncertain weather conditions, which make them variable over multiple timescales, hours, days, seasons and years (Després et al., 2017). These uncertain weather conditions will increase the need for a more flexible power system (Després et al., 2017).

The expectation of the IEA that these goals will be met through integrating more wind and PV into the power system is confirmed by the recently published national energy and climate plans (NCEP) of the EU member states (European Commission, 2020c). These NCEPs show that both the North West of Europe (NWEU) and the Netherlands have very ambitious plans for integrating these variable renewable energy sources (VRE) in order to meet the 2050 climate neutral goal of the EU. Due to this increase in VRE, both North West Europe and the Netherlands will have to incorporate more flexibility into their power system (Després et al., 2017; Papaefthymiou et al., 2018).

Traditionally, flexibility in the power system was mostly provided by conventional power plants (Ameli et al., 2020). But because of to the climate neutral goal these have to be phased out eventually. Another important measure to control the balance of supply and demand in the power system is curtailing the excess power of VRE. With integrating more and more VRE into the system, the current transmission infrastructure is not always able to transfer the increased levels of wind and PV generation in certain peak hours. Causing the power system to meet operational or transmission constraints, causing the system operator to decline PV or wind while it is available in order to assure grid stability (Lund et al., 2015; Bird et al., 2016; Arabzadeh et al., 2019). Transmission congestion and system balancing are common reasons for the curtailment of VRE (Gu & Xie, 2013). Due to a large amount of renewable energy that is currently integrated into the power system, more renewable energy can be lost through curtailment. This possible increase in curtailment of renewable power could have a negative effect on current and future renewable energy projects. Since they might not be able to get the expected economic benefits. This can eventually result in less investments in these renewable energy projects (Li et al., 2015). Therefore, it is necessary to either reduce this curtailment by increasing transmission capacity or by finding a use for this lost power (Lund et al., 2015; Bussar et al., 2016; Wang et al., 2017; Bloess et al., 2018).

This lost power through curtailment can be used by either battery storage or sector coupling (Carton & Olabi, 2010; Després et al., 2017; Luca & Pregger, 2018; Arabzadeh et al., 2019). Sector coupling is the process of interconnecting different energy sectors (e. g., electricity, heat, gas and transport) with the goal of decarbonizing these sectors while at the same time enhancing the energy flexibility (Robinius et al., 2017). Sector coupling can provide both flexibility to the power grid and provide use for the excess power generated by VRE though power-to-thermal (P2T), power-to-hydrogen (P2H) and vehicle-to-grid (V2G) (Lund et al., 2015). Power-to-hydrogen makes it is possible to chemically store electricity through three components. The electrolyser produces hydrogen from water with electricity, the electricity can then be stored in a hydrogen reserve and can later, when necessary, be converted back to electricity via a fuel cell (Kauranen et al., 1994; Lund et al., 2015). Power-to-thermal converts electricity into thermal energy, through either a heat pump or electric boiler. This thermal energy can directly be used or stored in a thermal storage unit, which is easier than storing electricity, and can later be used for heating or cooling (Lund, 2012). Electric vehicles are most of the time standing still and can therefore offer charging, storage and discharging options when the vehicle is connected to the power grid (Ekman, 2011). Battery storage can be used to shift the delivery of power in time, which helps in solving short term mismatches between demand and supply (Lund et al., 2015). Batteries have a very fast response which makes them suitable for improving the network stability (Lund et al., 2015). In this research the term sector coupling and sector coupling options will be interchangeably used to refer to the P2H, P2T and V2G as is described here.

Most studies in current scientific literature focus on only battery technologies (Després et al., 2017; Branco, 2018; Liebensteiner & Wrienz, 2019) and others focus only on one sector coupling option (Guandalini et al., 2015; Arabzadeh et al., 2019). With the exception of one paper by Kurpat et al., 2017 which focussed on both coupling the heating sector and hydrogen. As the paper of Bloess (2018) advocates; more research should be done regarding the comparison of the different sector coupling options and batteries in using the lost power through curtailment. This research will therefore study the comparison between the different sector coupling options and battery storage.

As countries need to reform their generation mix with including PV and Wind, the International Renewable Energy Agency (IRENA) began with addressing the issue of flexibility to policy makers (IRENA, 2018a). Because, as stated earlier, IRENA also notices the need for flexibility in the power system when the goal is to increase the integration of VRE. Therefor additional flexibility sources need to be planned for in time (IRENA, 2020a). In order to plan for this need in flexibility, IRENA developed the FlexTool. This tool is specifically designed for countries that want to increase their shares of renewables and help them with assessing the flexibility needs in combination with providing solutions to their power grid, with solutions primarily focussed on sector coupling and storage (IRENA, 2020b). The outputs of this model provide insight in the curtailment and loss of load of an energy system (IRENA, 2018b). These insights are measures widely used in scientific literature (Abdin & Zio, 2018; Poncela et al., 2018; Akrami et al., 2019), which makes the FlexTool suitable for studying sector coupling and battery storage. However, the IRENA FlexTool is, besides policy documents by IRENA (IRENA, 2018a, IRENA, 2018b), not yet used in the academic literature.

This research will focus on the use of batteries and sector coupling options, when the climate goals of the EU are met with only the integration of the renewable energy sources wind and PV for North West Europe and the Netherlands by means of the IRENA FlexTool. In order to reach the objective of this study, two scenarios were used on both scales of the Netherlands and North West Europe and were modelled with the IRENA FlexTool. Then in order to compare the different sector coupling options and batteries a design of experiment was used, part 2 of this paper will elaborate more upon this. The results of the sector coupling and batteries in this design of experiment were compared on their levelized cost of energy, loss of load and curtailment of the system and are presented in part 3. Finally, the paper ends with a conclusion and a discussion of the results.

2. Method

2.1. IRENA FlexTool

The IRENA FlexTool is a dispatch model to analyse system operations that is also able optimise investment in generation, storage and transmission capacity, divided in the dispatch and investment mode (IRENA, 2018b). The time horizon that the model can analyse has the minimum of one hour and the maximum of a year. Since the model optimises everything at once, the problem can become too large to solve, especially when investment variables are included in the model (IRENA, 2018). The study therefore used a design of experiments (Gunst & Mason, 2009) in order to compare the sector coupling options and batteries instead of the investment mode of the IRENA FlexTool.

The IRENA FlexTool is able to represent more complex forms of electricity consumption and generation with the use of different energy grids. Figure 2.1 shows the main input data in the grey boxes and the model variables in the orange boxes. Also, the energy can be converted from one grid to the other, with each sector coupling node also having its own annual demand and demand time series. Through this ability, the different sector coupling options can be modelled. The FlexTool is capable of optimising generation, transmission and storage planning and a full year of hourly (or sub hourly) operations.

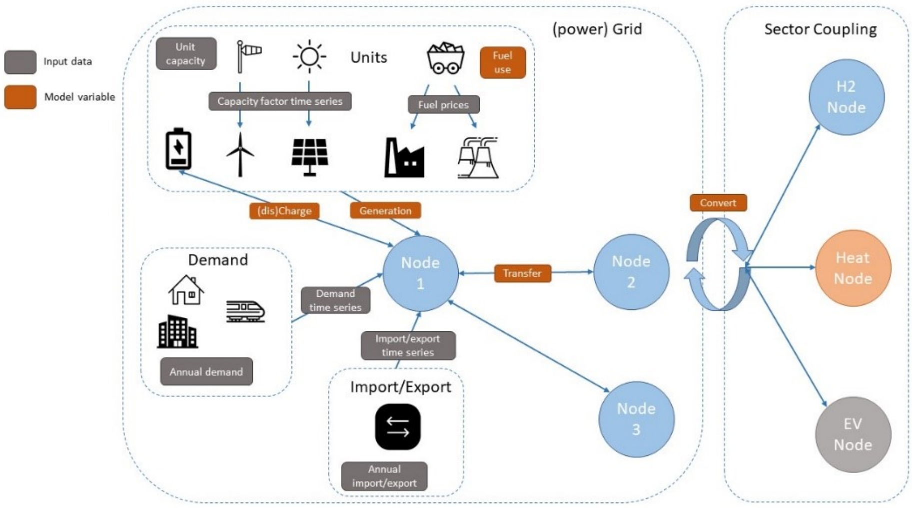


Figure 2.1. input data and model variable FlexTool based on IRENA, (2018b)

There are three options to model sector coupling with the IRENA FlexTool, these are illustrated in figure 2.2. In this research the sector coupling options are modelled according to the following options: EVs are modelled as option 3. This was done by creating a separate grid for EVs. To this grid a node was added that included the EV demand and units. The EV node had a charging unit that converted the energy from the power grid to the EV grid and a charging unit that converted the energy back from the EV grid to the power grid. A storage unit was added that represented the electric vehicles storage capacity. To each EV node a separate annual demand and demand time series were added to represent the use of the electric vehicle. For power-to-hydrogen option 3 with the same method was used. Option 2 was used for power-to-heat. Since the power-to-heat option did not include a charger that converted the thermal energy back to the power grid. Including all the sector coupling options in the model resulted in a total of 4 different energy grids, one for EVS, one for hydrogen, one for heat and one for power.

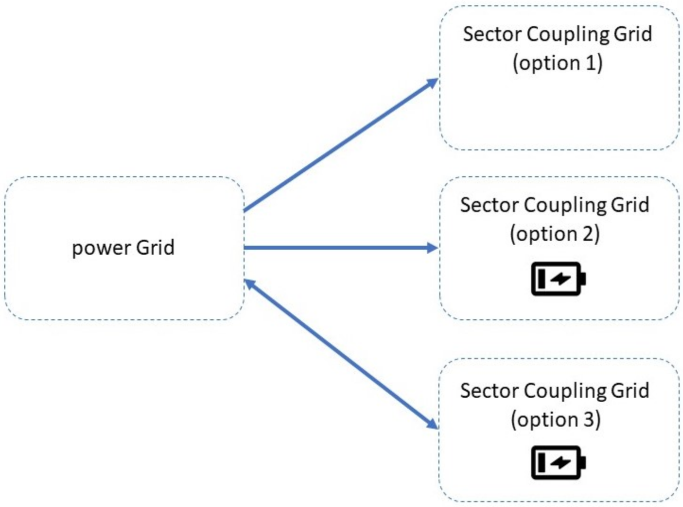


Figure 2.2. Options FlexTool for modelling sector coupling

2.2 Scenarios

2.2.1. Scale

Mentioned in the introduction this research will focus on two different scales, North West Europe and the Netherlands. The North West of Europe is a region defined by the European Commission in their regional policies with a special focus to become an attractive place to work and live on the basis of innovation and sustainability (European Commission, 2020). The goal of the European Commission is to transform North West Europe to a low carbon region. The North West of Europe as defined by the European Commission includes the countries of France, the United Kingdom (UK), Germany, the Netherlands, Belgium, Ireland and Luxembourg (European Commission, 2020). Since these countries have the specific goal to become a low carbon region, they made plans in their NECPs to increase the share of wind and PV in the power mix strongly (European Commission, 2020c).

The Netherlands defined in their climate agreement to use a regional energy strategy (RES) where the country is divided in 30 energy regions. These 30 regions each have to decide where and how they are going to meet the climate targets of the Netherlands for 2030 (RES, 2020). Most energy regions focus on building new wind and PV parks to generate more renewable energy (RES, 2020). Therefor it is important for these regions to also consider how to build in flexibility into their power system, due to the problem described in the introduction.

Multiple test runs were done with a 30-region model and a 17-region model, but both models seemed too large for the IRENA FlexTool. The Netherlands therefore had to be reduced to five regions in order for the FlexTool to work. To further decrease the resolution but to still keep the variety of the energy regions as much as possible, the Netherlands was divided in the five regions of North, East, South, South-West and North-West regions. This distribution is defined in the RES as the RES land division based on the 30 energy regions of the Netherlands (Klimaatmonitor, 2020). As the model of the Netherlands with sector coupling worked with five regions, the choice was made to run the NWEU scale with five regions as well, in order to be sure that it would work. The choice was made to leave out Ireland and Luxemburg because of the rationale that this would have the least influence on the transmission network of the NWEU power system and still keeping the variety of the region intact.

2.2.2. EU reference scenario 2016 EUCO

The European reference 2016 scenario was used as a base scenario for the different scales. This scenario focusses on the EU28 member states and is developments regarding the whole EU energy system, greenhouse gas emission and transport developments (Capros et al., 2016). These developments are based on the input of all the EU28 member states experts, and is designed in a group of reference scenario experts of the European Commission (Capros et al., 2016). The time horizon of the reference scenario spans from 2015 till 2050 and the main goal of the scenario is to functions as a guideline for market trends and to help future policy making (Capros et al., 2016). Since the IRENA FlexTool needs as main data input the annual demand, annual import/export and the generation capacity.

The input data necessary to run the hourly time series in this scenario were retrieved from the ENTSOE transparency platform (ENTSO-E, 2019) for the year 2018. For the variability in solar and wind generation the hourly capacity factors from Pfenninger & Staffell, 2016 are used for the year 2018 as well. However, compared to the NWEU scale the EU reference scenario 2016 did not contain data regarding the different regions of the Netherlands. Therefor the data of the Netherlands in the reference scenario was divided over the different regions. This was done according to regarding the real data of 2018. For the population and annual demand per region the klimaatmonitor (2020) database was used. For the current installed wind and PV capacity, the sources WindStats (2020) and CBS (2018) were consulted, from this the installed capacity per municipality was retrieved and located in the concerned region. For the conventional power plants, the data base of Tennet (2018) was consulted, from which the installed capacities of the conventional power plants were retrieved per municipality and located to the concerned region. However, as detailed information regarding the transmission between regions could not be found, an assumption was made to use a very high transmission capacity (99999 MW) between the regions of the Netherlands.

2.2.3. Phase out scenario FLEX

As mentioned in the problem statement, in order to reach the goal of the European Union to become climate neutral in 2050, conventional power sources need to be phased out. Therefore, a specific scenario was created, in order to assess the problems that arise when, as described in the introduction, the goal of the EU is reached through replacing the conventional power plants by integrating VRE into the power system. Two assumptions were made to alter the EUCO scenario in order to create this scenario. The first assumptions included the phasing out of coal and oil in 2030 and natural gas in 2050. Because this was most in line with the NCEPs (European Commission, 2020c) were coal and oil are phased out first. This meant that in the EUCO 2030 scenario coal and oil were phased out and in the EUCO 2050 scenario natural gas was phased out. This resulted in two new scenarios, in this research called the FLEX 30 and FLEX 50 scenario. Where the FLEX 30 scenario is the alteration on the EUCO 2030 scenario and the FLEX 50 scenario is the alteration of the EUCO 2050 scenario.

The second assumption concerned how these conventional power plants are completely replaced by either wind or PV power generation. The replacement of oil, coal and natural gas was done according to the following method: first for both the NWEU scale and the Netherlands, two papers were found that researched the maximum installed capacity of VRE per country for North West Europe (Gils et al., 2017) and per energy region for the Netherlands (Wang et al., 2020). Especially the paper of Wang et al., (2020) provides a good base line of the maximum capacity of VRE. Since in this research the spatial constraints of the energy regions are also into account, providing more accurate maximum VRE capacities (Wang et al., 2020). This makes it therefor very suitable for this study. Regarding the maximum installed capacity of North West Europe, the spatial constraints were also taken into account but on a much higher level than in the paper of Wang et al., (2020) since Gils et al., (2017) generalized the maximum VRE capacities for each county in Europe. However, this paper was still sufficient to use in this study since the NWEU was modelled per country as well.

With the maximum capacities from these papers the ratio between the maximum capacity of PV and wind were calculated for each country and region. The amount of installed capacity of oil, coal and natural gas as defined in the EU reference scenario 2016 by Capros er al., (2016) that needed to be substituted was divided by this ratio in order to determine how much of conventional installed capacity should be substituted by either PV or wind. When the replaced conventional capacities were distributed over PV and Wind installed capacities, the total installed capacity of wind and PV had to be determined since their generation is depend on the weather conditions. This was done by retrieving the annual average capacity factors for the year 2018 of PV and Wind for each country in the NWEU and dividing the new installed capacity of wind and PV by their capacity factors. This data was retrieved from the database of Pfenninger & Staffell, (2016). The above described method is illustrated by the following two equations:

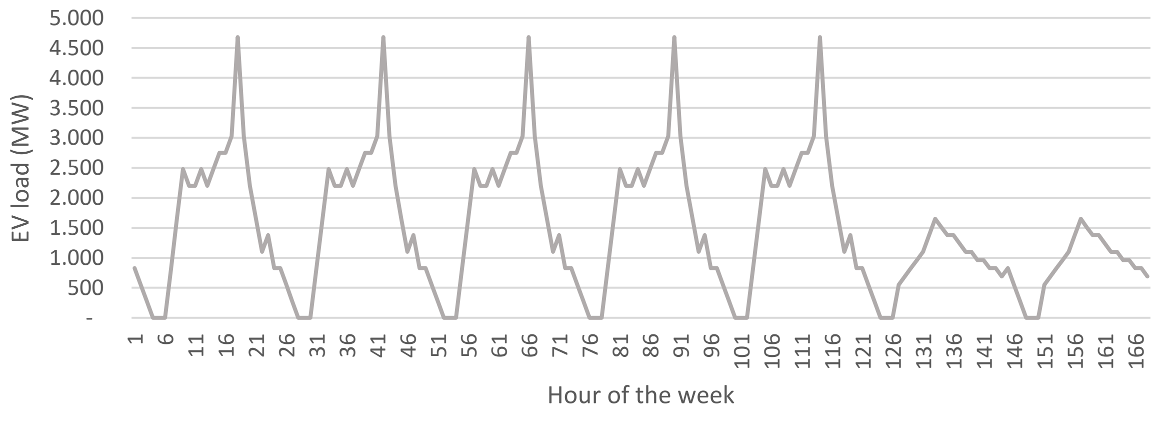
$$NCW = \frac{ICC * \frac{MCW}{MCPV}}{CFW} \qquad NCPV = \frac{ICC * \frac{MCPV}{MCW}}{CFPV}$$

Where:
$NCW = New\ Capacity\ Wind$
$NCPV = New\ Capacity\ PV$
$ICC = Installed\ Capacity\ Conventional\ Power\ Generation$
$MCW = Maximum\ Capacity\ Wind$
$MCPV = Maximum\ Capacity\ PV$
$CFW = Average\ Annual\ Capacity\ Factor\ Wind$
$CFPV = Average\ Annual\ Capacity\ Factor\ PV$

Besides the generation capacities, the rest of the input data such as demand and import from the EUCO scenario were used the same in the FLEX scenarios

2.3. Sector coupling and batteries
The input data for hydrogen storage was obtained from three main sources. Tennet (2019) and Wang et al., (2020a) provided the input data regarding the hydrogen network on respectively the North West Europe and the Netherlands scale. Whereas the study from Caglayan (2020) provided the countries total potential of hydrogen storage in salt cavern and the locations of those salt caverns ranging from 400 TWh in the Netherlands to 9000 TWh in Germany.

The input data for modelling the electric vehicles was obtained from three main sources, the number of electric vehicles in use in 2050 were retrieved from Nijland et al., (2012), the weekly load profiles were retrieved from Schäuble et al., 2017 as presented in figure 2.2, the technological data regarding the capacity of charging points and electric vehicles were retrieved from IRENA (2017). The capacity and storage capacity of electric vehicles as defined by IRENA (2017) are 50 kW and 60 kWh by 2030, but no data till 2050 was available therefor these capacities are used. The annual demand for transport was retrieved from the EUCO scenario.
Figure 2.2 load profile EVs (Schäuble et al., 2017)



The allocation of the battery capacity per country is based on the study an extensive study of the European union on energy storage (European Commission, 2020a). As many different battery technologies exist, for this study li-ion batteries are only taken into account since these batteries are already widely deployed in the current market (Lund et al., 2015). In the study of the European Commission (2020a) the current and projected projects regarding batteries are researched and an optimal amount of battery storage is calculated.

For the total annual heat demand the data from the EUCO scenario (Capros et al., 2016) was used. The study of Ruhnau et al., 2019 researched the different time series for heat demand of 16 European countries which are freely available. The heat demand time series of the year 2018 is used in this study. Figure 2.3 shows the heat demand for the Netherlands for a week in winter in 2018.

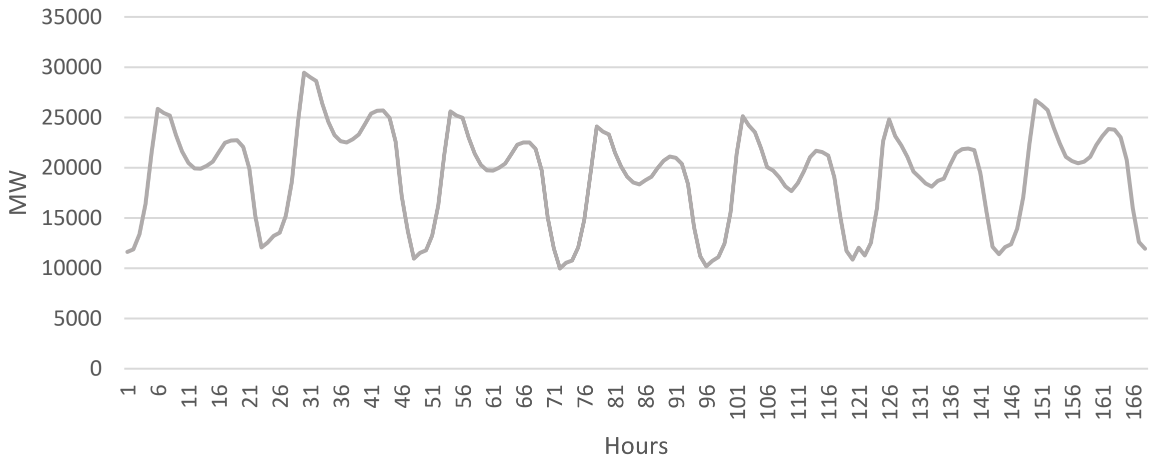


Figure 2.3 Heat demand profile (Ruhnau et al., 2019)

Most cost and efficiency data were already included in the IRENA FlexTool. The efficiency data regarding EVs, li-ion batteries and heat pumps and the operational costs of EVS were already included. Therefor the data regarding electrolysers, fuell cells, hydrogen storage and heat storage had to be included from external sources. The operational cost, efficiency and lifetime of electrolysers and fuell cells were retrieved from a study conducted by the International Energy Agency (IEA, 2015), the operational cost from Li- ion Batteries and Heat pumps are retrieved from Sabihuddin et al., (2015). The study conducted by Sabihuddin et al., (2015) summarized the current technical properties found in the literature of the most used storage technologies and from this study all discharge values and the CAPEX from heat storage are derived as well. For the other CAPEX and lifetime values the research of Murray et al., (2018) was used. In order to calculate the LCOE, the discount rate of 6,0% used in the study of Murray er al., (2018) was used. Table 2.1 show the life time, CAPEX, Operational costs, efficiencies and discharge rates per technology as used in the model.

Table 2.1. CAPEX technologies (IEA 2015; Sabiduddin et al., 2015; Murray et al., 2018)

	Electric vehicle	**Li- ion Battery**	**PEM electrolyser**	**PEM fuel cell**	**Hydrogen storage**	**Heat pump**	**Heat storage**
O&M (€/kW)	3	10	27	28	0	3,8	0
Efficiency	1,00	0,85	0,86	0,57	0,9	X	0,7
COP	X	X	X	X	X	4	X
Discharge rate (%/hour)	0,0075	0,0075	x	X	0	x	0,03125
CAPEX	X	356	703	890	X	1296	132
Lifetime	X	11,5	8,6	9,1	X	20	30

2.4. Design of experiments

The design levels for the different experiments are derived from the sources mentioned previously. To obtain a broad perspective on the different technologies, a large difference between the low, medium and high level was chosen. For the electric vehicles this is based on the study of the PBL where a scenario with 100% electric vehicles is outlined (Nijland et al., 2012). From there the other levels are drawn which are half of the previous level. For the Heat pumps the TYNDP is used as the low scenario (ENTSOE-E, 2019a). Projections made by the IRENA (2019) stated an 27% provision of electric heat pumps by 2050. However to obtain a broader field a 50% provision of heat pumps was used. With the medium level as the average of low and high, resulting in 28,75% which is close to the projections of the IRENA (2019).

For the design levels of hydrogen the European Comissions hydrogen strategy of 80000MW installed capacity of electrolysers (European Commission, 2020b) is used as a reference. To obtain a broader field, 25% was added and used as the high level, and the med an low levels are determined as the half of the previous level. The high level of li-ion batteries is determined according to an extensive study of the European union on energy storage (European Commission, 2020a), this study calculated a 187 GWh installed capacity for the European Union. Since this amount is for the whole European union this same amount can be used as the extreme level for the North West Europe as it should then also be sufficient for this region. The medium and low levels are, as well as with hydrogen and EVs, determined as the half of the previous level.

Technology	Low	Medium	High
HPs (% of heat demand)	7.5	28.75	50
EVs (% of total cars electric)	25	50	100
Batteries (total installed capacity MWh)	5241	10483	20966
H2 (total installed capacity MW)	2796	5591	11182

Technology	Low	Medium	High
HPs (% of heat demand)	7.5	28.75	50
EVs (% of total cars electric)	25	50	100
Batteries (total installed capacity MWh)	46875	93750	187500
H2 (total installed capacity MW)	25000	50000	100000

3. Results

3.1. North West Europe

3.1.1. Reference scenario EUCO

The EUCO scenario acts as a conservative reference scenario to portray the power system when a moderate increase of VRE is combined with an increase of the conservative flexibility option of natural gas. Table 3.1 shows the main results from the model runs with the EUCO scenario. The power system in this scenario does not show any issue concerning its flexibility. As the loss of load is in both 2020, 2030 and 2050, 0% of the annual demand and the curtailed VRE shows an increase of 0,6%. Despite being a reference scenario, the results show that the CO_2 emission and the share of renewables have a small decrease and increase. Figure 3.1 also shows that, despite an increase of installed PV and wind, the absolute generation of fossil fuelled power plants increases from 2020 to 2050 for NWEU.

Figure 3.1. Total generation EUCO NWEU

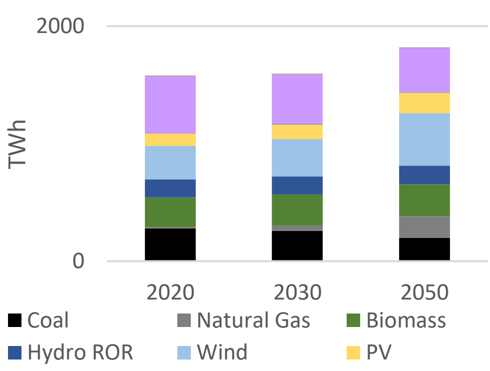


Table 3.1. Main results EUCO NWEU

		Curtailment (% of VRE gen)	Loss of load (% of annual demand)	CO2 (in Mt)	VRE share (% of annual demand)	Operational Costs (in million €)
NWEU	2020	0	0	340	35	61155
	2030	0,1	0	329	38	59448
	2050	0,6	0	316	43	65967

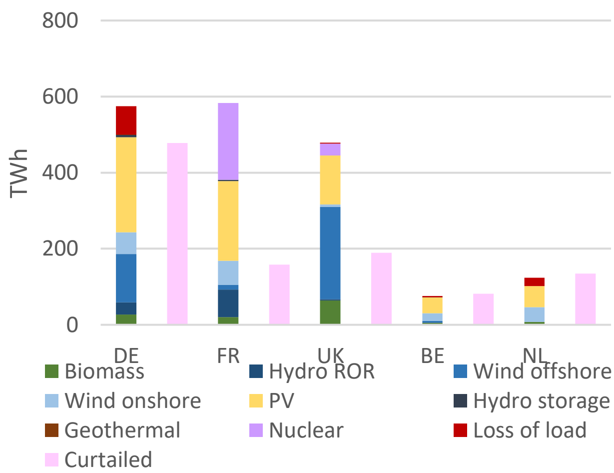
3.1.2. Phase out scenarios FLEX

Described in 2.2.3. the FLEX scenario portrays the replacement of coal and oil by VRE in 2030 and natural gas in 2050 to obtain a carbon neutral energy system, table 3.2 shows a summary of the results. In 2030, where natural gas still provides electricity in the power system, there is not a large flexibility issue due to an increase of 0.4% of loss of load, but compared to the EUCO scenario there is 266Mt less CO2 emitted. When natural gas is completely phased out and the power system does not emit any CO2 anymore, there is a significant problem regarding flexibility. Due to the fact that 5,7% of the annual demand cannot be met despite 76,2% of VRE generation being curtailed.

		Curtailment (% of VRE gen)	Loss of load (% of annual demand)	CO2 (in Mt)	VRE share (% of annual demand)	Operational Costs (in million €)
NWEU	2030	21,7	0,4	62,2	59,3	48351
	2050	76,2	5,7	0	75,7	59997

Table 3.2. Main results NWEU FLEX

Figure 3.2. FLEX generation per country



For the whole NWEU in 2050, a total amount of over 1042 TWh is curtailed while about 103 TWh of demand is not being met. Indicating the absolute discrepancy between demand and VRE generation in a system with high penetration of wind and PV with no back up to provide flexibility. When comparing the different countries in the power system, some differences can be noticed as. For the year 2030, only Germany show a large amount of curtailed energy and together with the Netherlands a small amount of loss of load. For 2050 however, the curtailment per country increases much more, and in the Netherlands and Belgium it exceeds the total amount of generated power in that year. For the loss of load there are more differences to be noticed per country which figure 3.2 shows. Germany and the Netherlands show the highest amount of loss of load with respectively 75,3 TWh and 21,7 TWh, followed by Belgium and the UK with 3,3 and 2,8 TWH and France does not have any loss of load.

3.2. The Netherlands

3.2.1. Reference scenario EUCO

The results presented in table 3.3 from the model of the Netherlands show that also here, no loss of load occurs, and a very low percentage of VRE is curtailed in the EUCO scenario. However, they show some differences when compared to the NWEU model. Here the CO2 emissions do not decline from 2020 to 2050, instead the emissions rise from 2020 to 2050 with a peak in 2030. For the VRE share they increase with 0.8% from 2020 to 2050 with a prod of 6.3% in 2030. As seen in the results of NWEU, the Netherlands model also shows an increase in absolute amount of fossil fuel use despite the increase of wind and PV capacity in the generation mix. With only a decline in the south-west region, illustrated in figure 3.3

Figure 3.3. Total generation EUCO Netherlands

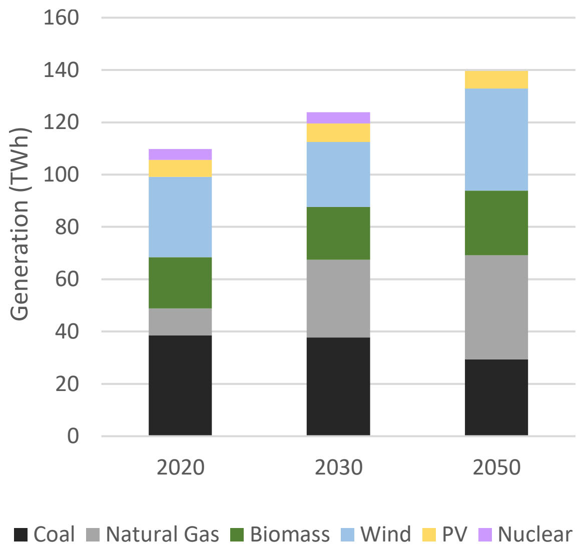


Table 3.3. Main results EUCO Netherlands

		Curtailment (% of VRE gen)	Loss of load (% of annual demand)	CO2 (in Mt)	VRE share (% of annual demand)	Operational Costs (in million €)
NL	2020	0,025	0	50,7	33.7	4859
	2030	0	0	58,1	27.4	6244
	2050	0,0061	0	52,5	34.5	6761

3.2.2. Phase out scenario FLEX

Table 3.4 shows a summary of the results. In 2030, where natural gas still provides electricity in the power system, there is not a large flexibility issue due to an increase of 0.14% of loss of load, but compared to the EUCO scenario there is 35.7Mt less CO2 emitted. When natural gas is completely phased out and the power system does not emit any CO2 anymore, there is a significant problem regarding flexibility as 18.3% of the annual demand cannot be met. For 2030 no large flexibility issues arise as only 0.14% loss of load occurs. Regarding the curtailment of VRE, the amount in 2050 is above 100%, this is due to the fact that the model compares the curtailed VRE to the VRE generation that is used for the demand, so not for the total VRE.

Table 3.4. Main results FLEX Netherlands

		Curtailment (% of VRE gen)	Loss of load (% of annual demand)	CO2 (in Mt)	VRE share (% of annual demand)	Operational Costs (in million €)
NL	2030	22,4	0,14	16,8	57,2	4852
	2050	146,2	18,3	0	78,1	2588

The amount of curtailment and loss of load increases in absolute terms when natural gas is phased out and replaced by solar and wind. Comparing this with the Netherlands in the NWEU power system the absolute amount of curtailed VRE is 2.6 TWh higher in the model of the Netherlands in 2050. The regional difference in power generation and curtailment is illustrated in figure 3.4 Most renewable energy is curtailed in the North region, followed by the Eastern, North-West, South and South-West region. The region where the most demand cannot be met is in the South with 11 TWh, this is almost half of the total loss of load in the Netherlands.

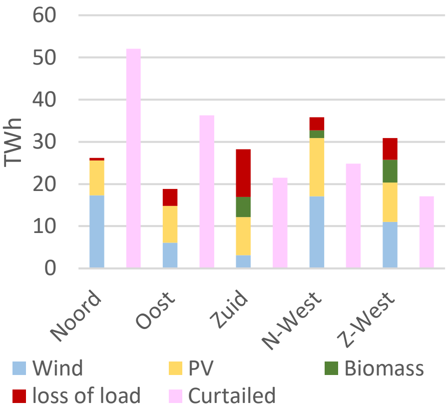


Figure 3.4. Average annual electricity price

3.3. Design of Experiments

3.3.1. The Netherlands

3.3.1.1. Main effects

Figure 3.5 shows the relation between the levels of the different technologies and the percentage of VRE generation that is curtailed. For both the EVs and batteries there is a decline from low to medium to high regarding the total amount of curtailed VRE. For EVs with 15,5% from low to medium and 2,5% from medium to high. For batteries this the decline is 2,3% from low to medium and 2,3% from medium to high. For both hydrogen and heat pumps the percentage of curtailment does decline from low to medium, 5,6% for hydrogen storage and 3.6% for heat pumps. But both technologies increase from medium to high, with the heat pumps increasing to above the percentage of VRE curtailment of a low integration of heat pumps with 5,2%. And hydrogen storage increases with 2,8% more curtailed VRE with high integration.

Figure 3.6 shows the main effect of the technologies on the total loss of load of the power system. This figure shows that for both the hydrogen storage and batteries the loss of load declines from the low to medium and medium to high integration. With a decline of 1,8% from low to medium and 0,47% from medium too high for hydrogen. For battery storage this is 0,04% from low to medium and 0,5% from medium to high. However, the two other technologies show a different pattern. For heat pumps there is an increase in loss of load from low to medium and from medium to high of respectively 0.23% and 0.27%. Whereas EVs first show a decline from low to medium of 0.26% followed by an increase of 0.26 from medium to high.

Figure 3.5. Main effects curtailment

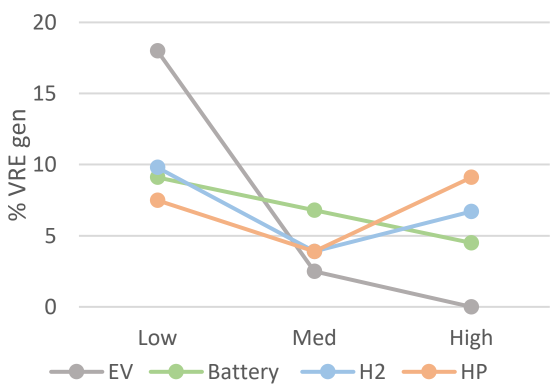
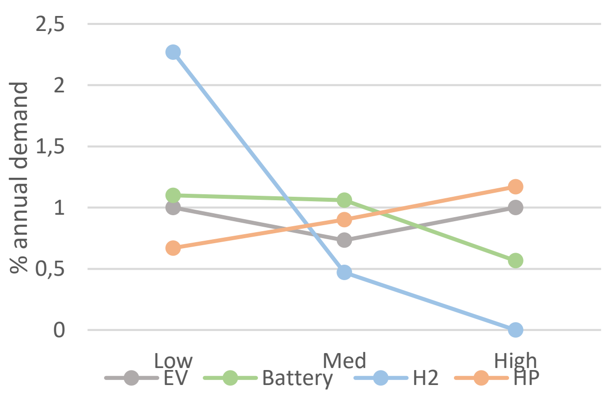


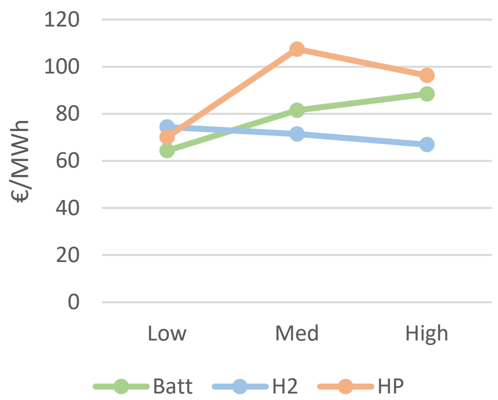
Figure 3.6. Main effects loss of load



3.3.1.2. Levelized cost of energy

Figure 3.7 shows the relation between the levels of the different technologies and the LCOE. The Heat pumps show the lowest LCOE also at their low level with €70,0/MWh, then the LCOE increases to €107,5/MWh for the medium level and decreases again to €96,3/MWh. For the batteries as flexibility option the LCOE is also at its lowest point in the low level with €64/MWh. The LCOE then only shows an increasing line with a LCOE of €81,5/MWh in the medium level and €88,4/MWh in the high level. For hydrogen the pattern is the other way around compared to batteries as it highest LCOE is in the low level with €74,4/MWh. From there in only show a decreasing line with a LCOE of €71,4/MWh in the medium level and €66,9/MWh in the highest level. When comparing the technologies with each other, hydrogen has, at the low level the highest LCOE and battery storage the lowest. Whereas in the high-level hydrogen becomes the technology with the lowest LCOE, heat pumps with the highest and batteries in the middle of the three but more towards the same price as heat pumps.

Figure 3.7. Levelized cost of energy



3.3.2. North West Europe

3.3.2.1. Main effects

Figure 3.8 shows the relation between the levels of the different technologies and the percentage of VRE generation that is curtailed. The EVs show a decline from low to medium with 9,2% and from medium to high with 2,3% regarding the total amount of curtailed VRE. For both hydrogen and heat pumps the percentage of curtailment does decline from low to medium, with 2,1% for hydrogen storage and 3,6% for heat pumps. But both technologies increase from medium to high, with the heat pumps increasing to above the percentage of VRE curtailment of a low integration of heat pumps with 5,2%. And hydrogen storage increases with 2,8% more curtailed VRE with high integration. Batteries show again a different patter with an increase from low to medium of 1,5% and a decline from medium to high of 1,3%.

Figure 3.9 shows the main effect of the technologies on the total loss of load of the power system. This figure shows that for both the hydrogen storage and EVs the loss of load declines from the low to medium and medium to high integration. With a decline of 0,11% from low to medium and 0,10% from medium to high for hydrogen. For EVs this is 0,223% from low to medium and 0,04% from medium to high. However, the two other technologies show a different pattern. For heat pumps there is an increase in loss of load from low to medium and from medium to high of respectively 0.03% and 0.03%. Whereas batteries first show a decline from low to medium of 0.03% followed by an increase of 0.01% from medium to high.

Figure 3.8. Main effect curtailment

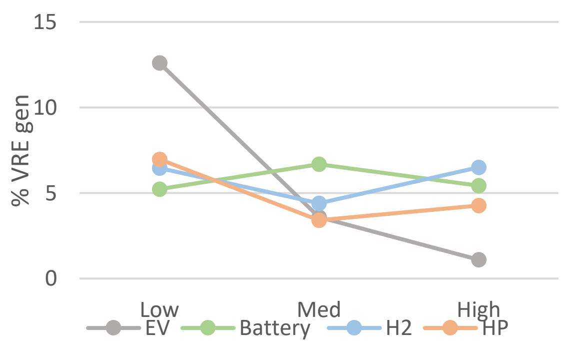
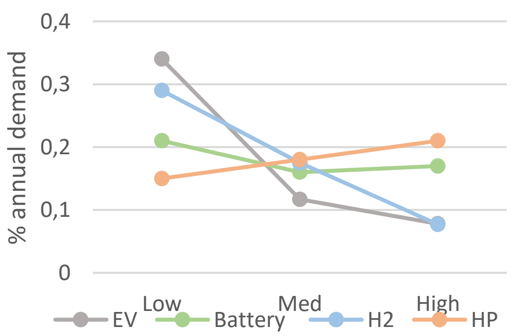


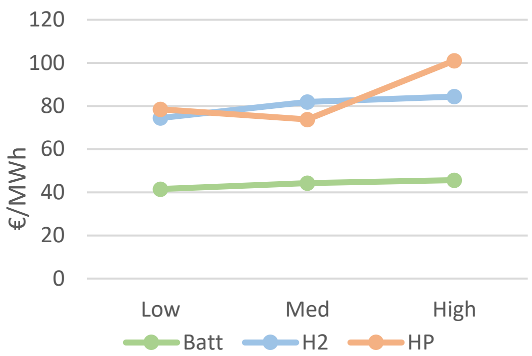
Figure 3.9. Main effect loss of load



3.3.2.2. Levelized cost of energy

Figure 3.10 shows the relation between the levels of the different technologies and the LCOE. The Heat pumps show a LCOE of €78,5/MWh at their low level, then the LCOE decreases to €73,8/MWh for the medium level and increases again to €101,1/MWh. For the batteries as flexibility option the LCOE is at its lowest point in the low level with €41,5/MWh. The LCOE then only shows an increasing line with a LCOE of €44,2/MWh in the medium level and €45,6/MWh in the high level. For hydrogen the pattern is the same as for batteries. The lowest LCOE is in the low level with €74,4/MWh. From there in only show a increasing line with a LCOE of 81,9/MWh in the medium level and €84,4/MWh in the highest level. When comparing the technologies with each other, heat pumps have, at their low level the highest LCOE and battery storage the lowest. Whereas this is the same the high level. However, the medium level is the only place where this is different as the LCOE of hydrogen becomes the highest here. Batteries have in all levels the lowest LCOE, whereas the costs of hydrogen and heat pumps is closer to each other.

Figure 3.10. Levelized cost of energy



4. Discussion & Conclusion

Before discussing the results related to the main question the findings related to the IRENA FlexTool will be discussed first to provide the right context to interpret the results. The IRENA FlexTool has two main shortcomings. The first shortcoming relates to the disability of running the investment mode when sector coupling is used in the model. The second shortcoming relates to the number of nodes that the FlexTool is able to model, which causes to reduce the variety in the researched power system.

4.1. IRENA FlexTool

The first shortcoming relates to the number of nodes that the FlexTool is able to model. The research initially focussed on the 30 RES regions of the Netherlands but the FlexTool could not provide results for that many nodes. Modelling sector coupling options in the combined regions as described in chapter 4 did not provide any results as well. Therefor the number of regions for the Netherlands had to be reduced severely to 5 instead of 30 regions. Taking some of the variety of the regional energy strategy taken in the Netherlands. Therefore, the results are prone to more simplification and the conclusion can only be drawn on a less detailed level. The FlexTool itself comes with multiple template examples of models used by IRENA. In those templates the models are never larger than 6 nodes in total, including the different sector coupling options. And the sector coupling options are never modelled together in one model, but always in separate templates. The FlexTool is thus suitable to indicate the problems of curtailment and loss of load, but less suitable to compare different sector coupling options as the calculation time of the model becomes to large or it does not provide any results anymore. The IRENA FlexTool could therefore be better suited to model smaller energy systems to gain a quick insight into the flexibility issues of a country or region, instead of modelling a very complex energy system. However, as this is the first study that included this model, more research should be done to confirm this statement.

The second shortcoming of the FlexTool was the inability to use the investment mode. The FlexTool has the feature to freely optimise investments in generation or storage units, and therefore also in sector coupling options and batteries. However, chapter 3 showed that it was better to not use the investment mode when modelling multiple sector coupling options. In order to cope with this shortcoming a design of experiments was used. By using the design of experiments, a comparison became possible, but brought extra limitations to the research.

The use of a DOE instead of letting the model freely chose the investments has its downsides. Due to the levels that had to be chosen in order to perform the DOE, the choice of these levels do influence the results. Since the levels of the DOE in this research are chosen to reach a very broad spectrum, the answers of this research regarding sector coupling and batteries can also only be interpreted broadly. Another shortcoming of the DOE in this research is that it only considered a 1 term analysis. Therefor only the relation of a sector coupling option and batteries to the objective is measured and not the relation between the options. This does alter the results because all options are modelled in each run on either a low, medium or high level. While the interaction of these options is not taken into account in the DOE. Therefor the results of each sector coupling option and battery storage on the curtailment, loss of load or peak prices is not a direct effect, but is influenced by the other options. In order to find a more specific answer future research should consider the two options with the IRENA FlexTool. Either doing a full factorial analysis and including more levels that are more narrowly scoped. Or by modelling a smaller system, in which, for example the Netherlands is only modelled as one node, with other nodes only representing the sector coupling options. The second option makes it possible to use the investment mode of the IRENA FlexTool and therefor the model is able to freely choose investments in the sector coupling solutions or batteries. Providing more accurate results regarding the needed installed capacity of the flexibility option.

4.2. Curtailment and loss of load

The modelling results showed that a significant amount of renewable energy provided by wind and PV will be curtailed in the Netherlands and North West Europe when conventional power generation is substituted with renewable energy generation in the form of wind and PV. But when natural gas was still part of the power system, the integration of VRE resulted in much less loss of load and curtailment. This has the implication that the first steps towards a renewable energy system will not cause much problems related to flexibility. But when the Netherlands or NWEU want to accomplish the goal of climate neutrality, the integration of VRE will cause for flexibility problems. These large amounts of curtailed power for VRE in a climate neutral power system can severely threaten the bankability of renewable energy projects. This could result in investors withholding their investments in renewable energy and in return hampering the Netherlands and the NWEU in reaching the goal of climate neutrality. But these problems are not uniform for all the countries in the North West of Europe.

Both France and the United Kingdom show differences in loss of load to the other countries in the NWEU. These differences could be explained due to the nuclear power that is installed in the generation mix of France and the UK and are therefore less prone to the fluctuations of renewable energy when it comes to the loss of load. As this could be a result of nuclear power generation in the energy mix, this should not be a conclusion from the results. The nuclear power plants in both countries only run on average for 4200 hours in the year. A study from the World Nuclear Association (2008) has shown that a nuclear power plant should run on average 6000 hours in a year to become economically viable, while in this scenario it only runs for 4200 hours. Therefor the results regarding nuclear power should not be compared to the reality as no costs studies regarding the start and shut down costs of nuclear energy have been done here. This does however explain the differences in loss of load between France and the UK compared to the other countries. As is stated in the study of Jenkins et al., (2018) that nuclear power does help with integrating renewable energy of wind an PV in reducing both curtailment and loss of load. So, the problems of reaching climate neutrality by integrating VRE can differ per country. This has the implications that the incentive to obtain new flexibility options can differ a lot between countries in the NWEU region.

Besides the difference in the countries of the NWEU, a large difference can be noticed between the energy regions as well. The curtailment in the north is very high with almost no loss of load, but the curtailment is much lower in the south, with a much higher loss of load. This difference can be explained by the imbalance of demand and supply at the specific locations' sites. As in the north a lot of wind and solar is installed compared to the south region, the demand in the north is also lower than in most other regions. As the oversupply of the wind and PV has to be curtailed locally and cannot be stored in the FLEX scenarios, the loss of load will be much greater in regions with lower installed capacity of wind and PV and higher demand. This due to the larger differences between the moments where demand is high and wind or PV generation is low. Another difference between the regions can be noticed between the regions with a high PV integration. The South of the Netherlands integrates much more PV then wind, resulting in the more loss of load compared to the other regions where wind is integrated more.

This indicates that the need for flexibility differs a lot on the regional level as well. Therefore, solutions to flexibility issues have to be solved from a regional perspective as well.

Considering the Netherlands in both scales, a difference in loss of load and curtailment can be observed as well. As the loss of load is 3 TWh higher and the curtailment is 15 TWh higher in the Netherlands scale compared to the Netherlands in the NWEU scale. This can be explained through both the workings of the FlexTool and transmission capacities. In the NWEU scale the import and export of the Netherlands is just partially determined by its input data, because of the connection to its neighbouring countries. Therefor the model is able to optimise the import and export as a variable to the other countries whereas in the Netherlands scale, this factor is solely determined by rigid input data over which the FlexTool cannot make any decisions. Thus, when the FlexTool is able to determine the import and export more as a variable, the curtailment and loss of load are reduced as well. This indicates the role of transmissions as a flexibility source as is studied in multiple studies (Lund et al., 2015; Child et al., 2019; Liebensteiner & Wrienz, 2019).

4.3. Sector coupling and battery storage

Besides the increasing occurrence of curtailment and loss of load, the modelling results show that both issues can be solved with sector coupling options and battery storage. For the Netherlands and NWEU both the curtailment and more importantly the loss of load can be reduced to 0 through these options. It would be expected that the pure storage technologies, batteries and hydrogen would only decrease the loss of load and curtailment since they would only store the energy to provide it when it is needed (Denholm, 2019). However, both batteries and hydrogen storage do not show this expected pattern, since hydrogen shows higher curtailment rates in its high level than medium in the NWEU and Netherlands. And batteries show a higher loss of load percentage in its high level than medium in the NWEU. This could be explained through the fact that not a full factorial analysis is performed but rather only a main effects design of experiments. Therefor no relation between the different technologies is measured and the main effect on the objective can be altered due to another technology being set on a high or low level and in this way reducing or increasing the curtailment or loss of load.

For the EVs and heat pumps, another pattern would be expected. Since both EVs and heat pumps add more demand to the energy system, there would be a trade of between the added storage and added demand in providing flexibility. This trade of happens because of the added peak demand at certain moments that cannot always be served, resulting in extra loss of load (Luca & Pregger, 2018). In the results the heat pumps show only an increase in loss of load for both scales indicating that a potential optimum should be lower than the levels chosen in this study. For the EVs the pattern regarding the loss of load only decreases for the NWEU scale, indicating a potential optimum higher than the chosen levels and for the Netherlands the pattern show a potential optimum in the medium level. Since this study uses very broad levels to research the different options, the results presented here cannot say where this trade of happens, since it possibly happens for some of the options outside of the borders chosen. Therefore, more research towards the trade-off of the added demand and storage of EVs and heat pumps is necessary.

The modelling results show that the LCOE of hydrogen is the lowest in the Netherlands and the second lowest in North West Europe where battery storage is a much more economical choice due to the low LCOE compared to the other options. The result workbook of the IRENA FlexTool shows that the batteries in NWEU generate more power back to the power system proportionally to their OM costs compared to the Netherlands. This means that they produce relatively more power and therefore their LCOE is lower. This can be explained through the fact that Belgium does not contain any salt cavern storage. Therefore, when power is needed in Belgium, battery storage will be chosen above the use of hydrogen from other countries. This results in more use of battery storage then hydrogen in Belgium, increasing the average use of batteries in the NWEU. And thus, lowering the LCOE compared to the Netherlands.

The modelling results show that EVs and Heat pumps can provide extra flexibility to the power system, but are dependent on their demand. This will create a trade-off of when EVs and Heat pumps will add to much demand resulting in no extra flexibility benefits. Hydrogen and battery storage as used in this research do not have this characteristic and only provide storage to the power system. Batteries can to a certain extend diminish the loss of load by using the curtailment of renewable energy. But only hydrogen is able to completely reduce the loss of load because of the possibility to store energy over seasons. The explanation of the LCOE difference of battery storage in the Netherlands and NWEU shows that when the relative percentage of battery storage is higher, the LCOE decrease. The LCOE resulting from the modelling approach are compared to other studies, ranging in the higher LCOE of the technology (IEA, 2019). This could be explained by the DOE where all the options are included in each run, resulting in non-optimal use of the stored energy for each option, increasing the LCOE of the technology. Future research is needed to study the interaction between the different options. This could provide useful results on how to efficiently allocate and use the different options when they are used in combination with each other.

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