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THE PROMISE OF SEASONAL STORAGE

SAFER, SMARTER, GREENER

THE PROMISE OF SEASONAL STORAGE

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DISCLAIMER
The insights presented in this paper are partly based on the DNV GL Smart Grid Scenario Model (DSSM), implementing basic market rules and generation dispatch. Implications of generator start/stop cost, part load behaviour, minimum load constraints, reserve capacity for scheduled maintenance of power units, value of ancillary services, grid constraints, differences in weather conditions for larger regions, etc. are not implemented. Although we are confident the trend behaviour is valid, the absolute numbers are not reliable enough for, for example, investment decisions.

The central generation mix and VRES mix have a large influence on the electricity prices, as have other country specific characteristics. For investment decisions, a more detailed load/price forecasting study, dedicated to the specific country is necessary.

CONTENTS

EXECUTIVE SUMMARY

The world's energy system is changing profoundly as we move towards a net-zero carbon future. Introducing more variable renewable energy sources (VRES), namely wind and solar PV generation into the energy mix puts pressure on the power system. So too does the increased demand for the electrification of transport, heating and cooling. We need more production facilities, new power plants, significant grid infrastructure, but also the application of storage and other flexibility options.

This paper explores the need for, and viability of, seasonal storage in the power system. Seasonal storage is a form of storage typically accommodating yearly cycles in electricity demand and VRES generation. It stores energy during one seasonal condition (summer or winter) and discharges the stored energy in the other seasonal condition, depending on the load demand. Seasonal storage is, therefore, closely related to seasonal variations in temperature, wind speed and solar irradiation as these mainly determine the need for heat- and cooling demand and the generation of solar and wind power.

Hourly and daily fluctuations in the balance between electricity demand and generation can be solved to a large extent with short-term storage and demand response, which could eventually be provided in the future by smart (dis-)charging of electric vehicles. Yearly fluctuations require different measures, because of the long storage times and limited number of cycles per year. Solutions for fluctuations between years are only needed every other couple of years and may be considered adequacy measures – a measure that is collectively financed, for example, through a system operator.

To specifically assess the business case for seasonal storage, we use the Netherlands as a case study. Daily, weekly and yearly patterns are analysed; as well as yearly fluctuations over a period of 58 years with historic weather data – identifying where seasonal storage could potentially play a role. These insights are summarized as five main conclusions:

1. Seasonal storage must compete with other applications for low-priced electricity
2. Compressed hydrogen is the first viable option for seasonal storage
3. Variability in demand and VRES generation between years blur the distinction between seasonal storage and adequacy capacity
4. Seasonal storage is not a single-company business and needs a market for synthetic fuels to develop first (e.g., for mobility or industrial use)
5. Seasonal storage is both an opportunity and need

If the need for fully decarbonized, fossil-fuel free electricity supply is high enough, this will reflect in a significantly higher carbon price, making seasonal storage a viable option. And when the need is high enough, seasonal storage transfers to a business opportunity.

Today, we face a climate emergency. The transition predicted in our Energy Transition Outlook is fast, but not fast enough to meet the Paris Agreement's objectives to limit global warming to 'well below 2°C', let alone 1.5°C. With the need great, seasonal storage could be viewed as a potential solution to decarbonize electricity generation and hence play a role in accelerating the transition.

1 INTRODUCTION

1.1 The energy transition puts pressure on our power system

- The energy transition impacts both sides of our power system: the generation and demand side.
- On the generation side, the production of electricity from variable renewable energy source (VRES) introduces a large weather dependency mainly based on wind speed and solar irradiance.
- On the demand side, the electrification of domestic, commercial, and industrial heating demand also introduces a large weather dependency.
- This leads to an increasing gap between generation and demand that is putting the power system under pressure.
- Increasing flexibility in the system, for example, by seasonal storage, cuts on both sides. It uses potential surplus electricity from VRES to provide CO_2-free dispatchable power.

The energy transition – that is, decarbonization of our energy supply through the shift from fossil fuels to carbon-free energy sources, such as solar, wind, hydro, and geothermal – changes the power system both at the generation side and demand side. The main capacity for renewable energy generation consists of solar PV and wind turbines that are variable and not dispatchable at will. They generate electricity depending on wind speed and solar irradiance, also when the demand for electricity is limited. This increase in variability in electricity generation is accompanied by an increase in demand variability[1]. Demand of energy is more and more electrified, especially by the electrification of mobility through electric vehicles and space heating and cooling.

The resulting effect on the electricity demand for dispatchable electricity generation is illustrated in Figure 1. It shows the forecasted total electricity demand in the Netherlands in 2050 with a high penetration of renewables, a high electrification of demand, and limited use of electricity storage and demand response. The hourly load is sorted according to the contribution of dispatchable generation to the total load. This case study is based on the DNV GL Smart Grid Scenario Model (DSSM). More details of this case study can be found in our position paper 'Future-proof renewables'[2].

Curtailing of renewable generation[5] is shown as a negative demand in Figure 1. It illustrates potential renewable generation ('surplus electricity') for which there is (without flexibility options) no demand, and thus must be curtailed. The requirement for dispatchable power, today generally fossil based, is shown as a positive demand (grey area). This increasing mismatch in time between generation and demand is putting the power system under pressure.

Figure 1 illustrates that in a carbon-free future, there is both opportunity and need for flexibility. The surplus electricity provides an opportunity for dispatchable power, which requires flexibility options (typically storage and demand response). Seasonal storage, for example, by generation, storage, and conversion of hydrogen, may be one of these options.

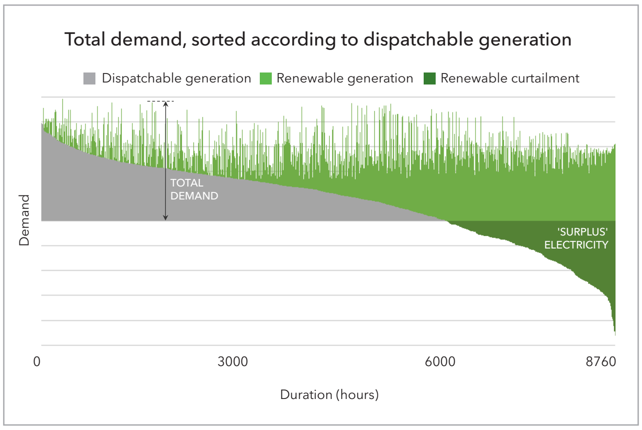


Figure 1 - Typical example of the total electricity demand in a system with a high penetration of variable renewable generation (approx. 75% of the total demand) and limited flexibility[2,3,4]

1.2 The need for flexibility in the power system

- Seasonal storage provides flexibility in the power system typically to accommodate yearly cycles in VRES generation and electricity demand.
- Daily and weekly demand and generation variability is typically accommodated by other flexibility options, such as batteries and pumped hydro.
- Variability in demand and generation over multiple years is an adequacy issue, not a seasonal storage issue. The cost of adequacy capacity is generally socialized.

One often mentioned solution to the challenges of the energy transition is increasing the flexibility in the power system. Flexibility is the ability to respond to changes in demand and/or supply of electricity thus maintaining the balance. Flexibility can be provided by flexible load, flexible generation, and/or energy storage. For grid operators, this can be of value for keeping the voltage and current of the grid within required boundaries. For the system operator, this is of value to control the grid's frequency and power balance. And lastly, for market players, this is of value to meet electricity demand (or generation) of their customers to control the energy balance and to provide flexibility services to the other stakeholders.

Changes to the electricity system happen on very different timescales, requiring different solutions. The ability of the system to respond to very short and fast fluctuations is generally called 'stability', while the ability to adapt to long-term trends taking years is generally called 'adequacy'. Figure 2 shows a framework where these three types of variability issues are summarized together with typical causes and solutions. Load shedding typically functions as emergency reserve to maintain adequacy and will only be called upon once every few years.

- Stability issues: fast response to load variations, maintaining stable voltage and frequency and used constantly.
- Flexibility issues: adapting to variability of the power demand and VRES-generation, partly to stochastic load variations and partly to cyclic patterns up to seasonal generation and demand patterns.
- Adequacy issues: long-term availability of sufficient resources to meet the long-term electricity demand, typically planned to be used for emergencies and sparse periods of high demand and low VRES generation.

Flexibility in the power system is comprehensively discussed in DNV GL's white paper 'Flexibility in the power system'[6] and in our 2019 Energy Transition Outlook[7]. The white paper describes the need for flexibility, how it can be provided, the barriers for deployment, and a business case for several flexibility options.

Adequacy is capacity that is reserved for emergencies and situations that happen less than once a year. For instance, in very cold years with high space heating demand, or in years with low solar or wind generation, reserve generating capacity must be available to fill the gap. Unlike seasonal storage, this 'adequacy capacity' is an insurance against infrequently (and stochastically) occurring situations. The sporadic (and unpredictable) need for this capacity makes for a very risky commercial business case, with potentially very large, but also infrequent revenue streams, as (individual) commercial traders are only willing to pay for this capacity if it is needed, which is perhaps once every few years.

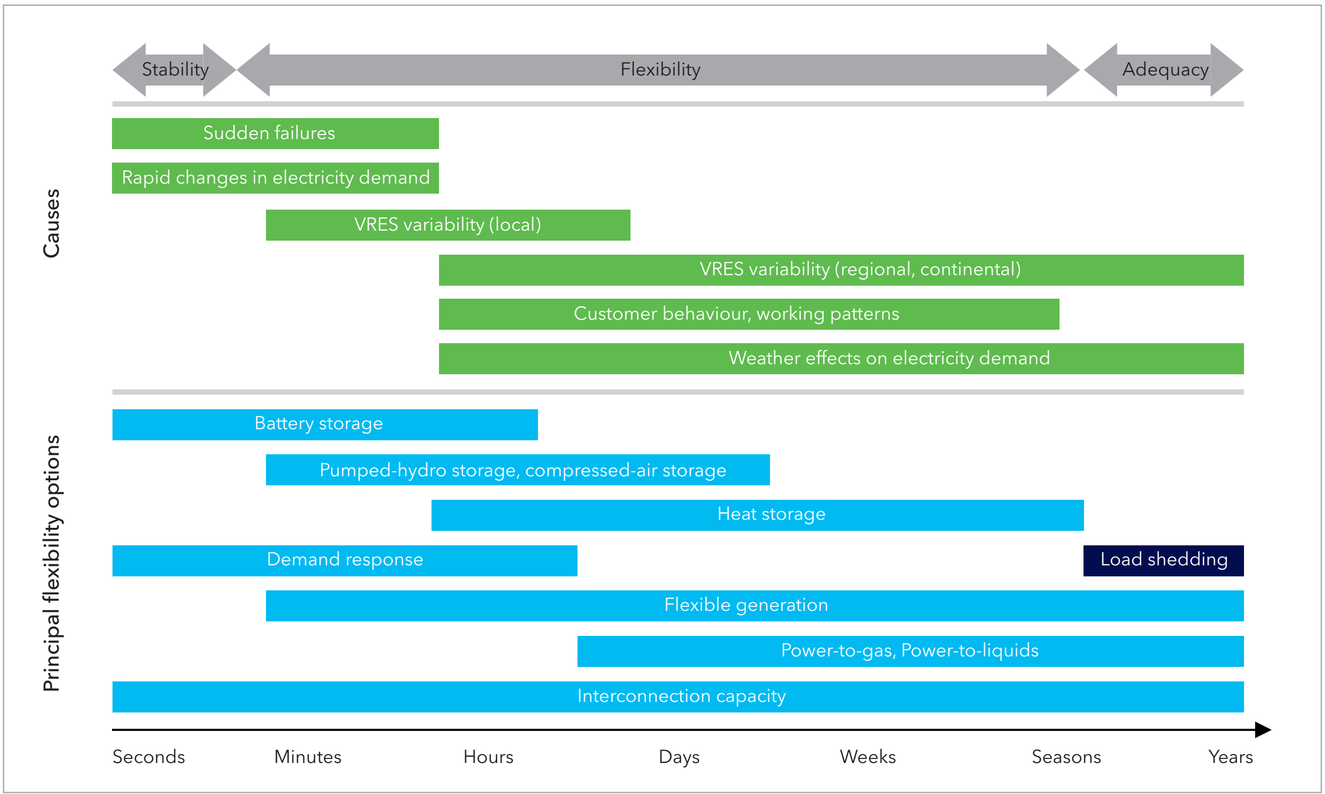


Figure 2 - Time scales for flexibility needs in the electricity system[7], including principal flexibility options

As this capacity is needed to avoid a blackout every few years, it is typically procured by the system operator for a capacity fee and costs are socialized. Load shedding by industries is continuing to be a viable option to provide (part of) this capacity.

Seasonal storage typically accommodates yearly cyclic demand and generation patterns, and these are to a certain extent predictable. Therefore, the revenue streams occur yearly and are more predictable, thus, the business case resembles the business case for shorter cycle storage options.

In an energy-only market, revenues of storage scale with energy throughput. This throughput scales with the cycling frequency, so it is very likely that storage solutions addressing the variability in daily and weekly demand and generation will emerge before seasonal storage. Part of this daily and weekly variability will be accommodated by flexibility options, such as demand response, dedicated batteries in the power system, electric vehicle batteries (vehicle-to-grid), and pumped hydro.

If we want to quantify the need for seasonal storage in the power system, we must focus on yearly cycles and filter out the effects of daily and weekly variations addressed by other solutions, as well as multi-year variations addressed by adequacy solutions.

2 QUANTIFYING THE NEED FOR SEASONAL STORAGE

2.1 Variability in electricity demand and weather patterns

- Cyclic variability in electricity demand and weather parameters is analysed based on a power spectrum analysis.
- Weekly patterns are only visible in the power demand, not in weather parameters, and are due to the working day–weekend cycle.
- A yearly cycle prevails in the temperature. For wind speed and solar irradiance, the daily cycle is the most pronounced.

This paper uses a case study to assess the need and opportunities for seasonal storage. We presume that seasonal storage is related to yearly weather patterns, such as wind speed, temperature, and solar irradiation. Electricity demand for lighting, space heating, and air conditioning is strongly related to the outside temperature, wind speed and solar irradiance. Electricity generation by wind and solar power generation depends on wind speed and solar irradiance as well.

Additionally, our working day-weekend cycle causes a weekly pattern in electricity demand; and the day-night cycle causes daily patterns in temperature, wind speed, solar irradiance, as well as electricity demand.

These three above mentioned cyclic patterns emerge nicely from the weather and demand data when using a power spectrum analysis based on Fast Fourier Transform. Essentially, this analysis shows us how much variability is related to which cycle.
Appendix A goes into further details of this analysis and the results are summarized in Figure 3, for Dutch weather data (1961-2018) and the Dutch total electricity load (2004-2018)[8]. Other climate conditions, for example, land climate, will provide other relative contributions.

Figure 3 shows that weekly patterns emerge only in the total load, which is obvious as there is no natural cause for weekly patterns in weather data. Temperature has the strongest relative yearly pattern, suggesting that seasonal storage will be important to accommodate space heating demand cycles. The data suggests that cyclic variations in VRES (solar PV and wind) can for a significant part be accommodated by daily storage. This analysis does not show the contribution of cyclic variability relative to non-cyclic variability (stochastic changes, trends).

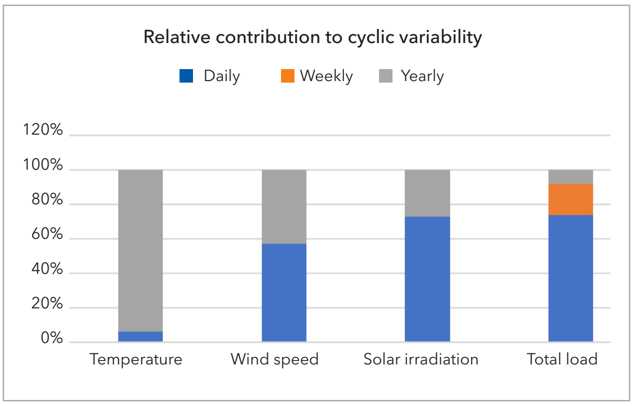


Figure 3 - Relative contribution to cyclic variability in weather and power demand patterns for the Netherlands

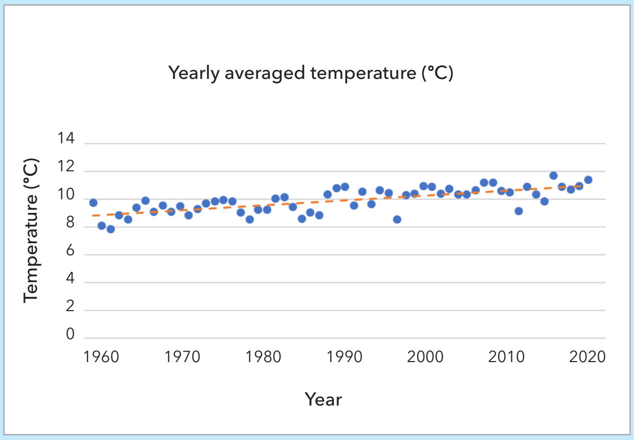


Figure 4 - Multi-year variation in average yearly temperature in the Netherlands

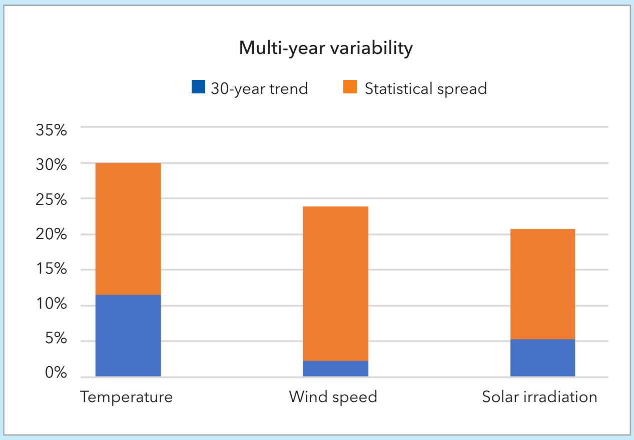


Figure 5 - Multi-year variability in weather patterns for the Netherlands

Besides the daily, weekly, and yearly cycles, there is variation between years, for example, because of statistical variations or trends. This multi-year variability is important for adequacy and variability in the potential needed seasonal storage between years. Multi-year variability can be illustrated based on the variation in yearly averages. Figure 4 displays an example of the average temperature in the Netherlands. It shows a year-to-year variability in the average temperature and, therefore, the potential electricity demand for space heating. The trend line in this graph illustrated the long-term trend. Based on the available data, this trend is significant[9]. Although it is tempting to attribute this temperature increase to the greenhouse effect, other factors such as urbanization or multi-year cycles may contribute to this increase as well.

Based on annual averages, the multi-year variability in weather data is quantified and shown in figure 5.
We distinguish between the variability due to the trend and the variability due to statistical variation. The trend variability is based on the historic 30-year linear trend (1961-2018). The statistical variability is calculated from three times the estimated standard deviation after detrending.

Figure 5 illustrates that 12-30% variability in load and weather parameters may be expected. The effects on the residual load must be met by reserve generation capacity that may be used only once every year or every few years. If the linear trend keeps up for the coming 30 years, part of this reserve capacity can be planned. Still, 10-20% statistical variability between years remains, resulting in an unpredictable average yearly variable renewable generation.

This case study is based on data for the Netherlands. The insights gained apply to countries with similar characteristics, such as significant difference in space heating demand between summer and winter, adequate solar irradiation for solar PV, and significant potential for onshore and offshore wind. For countries with less space heating demand or solar PV potential the seasonal differences may be lower, decreasing the potential for seasonal storage. On a European scale, solar PV and wind generation are not as significant due to regional differences in weather, also decreasing the potential for seasonal storage. However, limitations in electricity grid capacity between regions will mitigate this decrease. The findings of this study present a fair assessment of the potential of seasonal storage.

2.2 How to determine the need for seasonal storage

- Seasonal storage competes with other flexibility options for the use of surplus electricity. Economic optimization shows that part of the available surplus electricity will be consumed by short-term storage (for example, daily and weekly battery storage).
- The competition of short-term storage has an impact on seasonal storage:
  1. The price spread between summer and winter becomes smaller
  2. The volume of available surplus electricity decreases
  3. The load is averaged allowing for more continuous operation of seasonal storage
- We use a two-step approach to determine the need for seasonal storage:
  - We modelled short-term battery storage based on vehicle to grid. This meets the daily and weekly storage needs.
  - The remaining load is levelled by seasonal storage on a yearly basis. This results in a theoretical maximum need for seasonal storage capacity on a yearly basis.

The previous sections show that we can distinguish between:

1. daily and weekly cycles in demand and VRES generation,
2. yearly cycles in demand and VRES generation, and
3. multi-year trend and stochastic variability in demand and VRES generation.

We presume that in the future daily and possibly weekly cycles will be largely met by battery storage and pumped hydro storage. Battery storage includes both fixed batteries and battery capacity from electric vehicles that also will discharge into the grid[7]. Multi-year variability will be met by reserve generation capacity. In this paper, we define seasonal storage as electricity storage purely focussed on seasonal cycles.

To determine this need for seasonal storage, we use a case study for the Netherlands based on our DSSM model, in which we adjust VRES, electric vehicle and electrified heating penetration in line with DNV GL's 2019 Energy Transition Outlook forecast for year 2050. The DSSM model includes a simplified wind and solar generation module and a space heating demand module based on a linear outside temperature dependence. This model determines the hourly residual load. It uses weather data based on either a representative average climate year or Dutch historical weather data from 1961 to 2018[10].

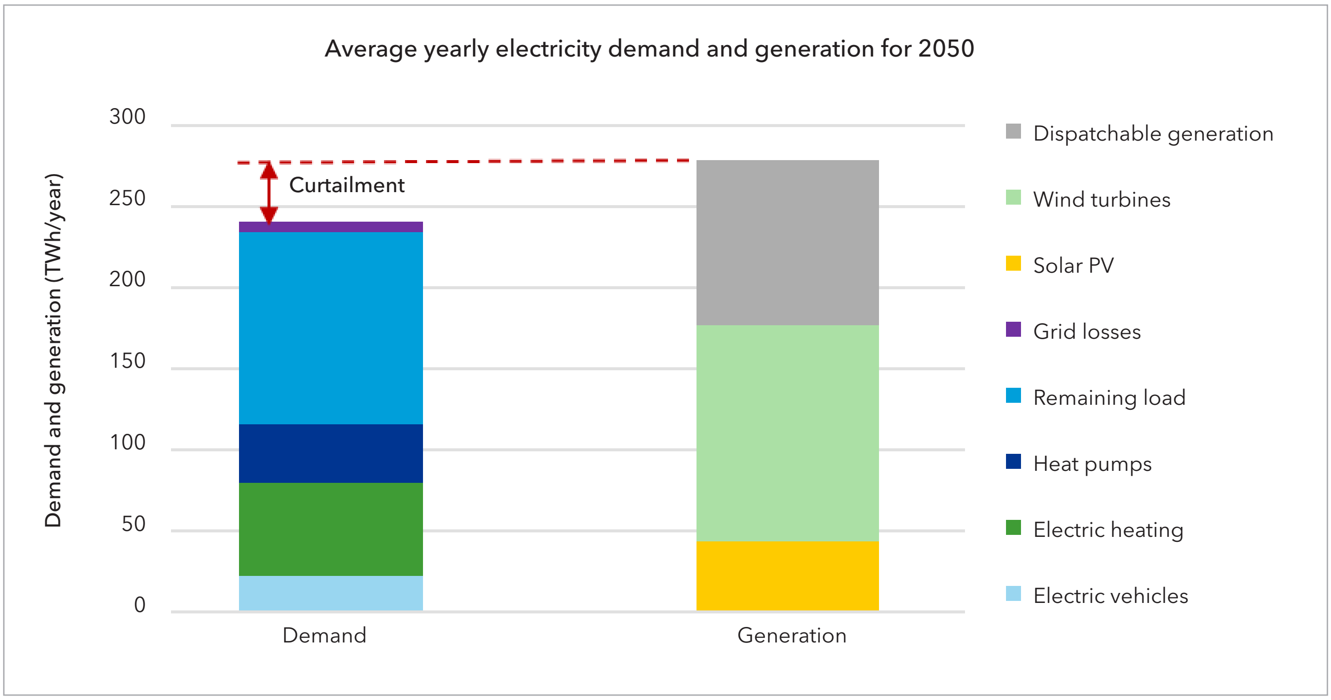


Figure 6 - Case study characteristics based on 42 GW solar PV, 39 GW wind power and 40 GW central (dispatchable) generation[4]

Main characteristics for the reference situation (average weather data, no storage or demand response) are summarized in Figure 6. More details of the DSSM model and the case study can be found in our position paper 'Future-proof renewables'[2]. Although the results presented in this paper are based on a case study for the Netherlands, the insight gained are more general.

Figure 7 shows an example of the residual load after daily and (partly) weekly cycles are accommodated by short-term battery storage provided by 3 million electric vehicles with vehicle to grid capabilities. This is about 1/3 of the total fleet and can provide 30 GW charge, 30 GW discharge, and 240 GWh storage capacity[11]. Dispatch of storage is optimized economically, based on optimal foresight. It shows two significant results of using this amount of storage:

1. The residual load is significantly flattened, either an almost constant generation by conventional units (dark grey in Figure 7) or an almost constant surplus of VRES (dark green in Figure 7).
2. Electricity prices are lowered significantly.

Both have an impact on seasonal storage. The flattened load allows for more continuous operation of storage facilities, while lower electricity prices will impact the economics of seasonal storage.

The utilization of surplus electricity is discussed in our previous paper about hydrogen in the electricity value chain[12]. Storage is competing with other uses of low-cost electricity, such as opportunity heating, partly decarbonizing heat; and electrolysis, partly decarbonizing hydrogen production for industrial applications. This is illustrated in Figure 8, which shows the result of an economic optimization of the dispatch of several flexibility options to cope with or use surplus electricity. It illustrates that opportunity heating, electrolysis and car battery storage (V2G) each have their role.

The value (merit) of battery charging is dependent on the spread between (short-term) low and high electricity prices. The merit of hybrid operation of both direct electric heating and hydrogen production by electrolysis depends on the price difference between electricity and carbon taxed natural gas. Because of the efficiency difference between steam reforming and electrolysis, the electrolysers will start operating at a little higher price than direct electric heating and will become price setting for as long the installed capacity is not fully used. As the price drops further and reaches the price of carbon taxed natural gas, installed direct electric heating will take over from gas heating and will become price setting until the full installed capacity is used and the remaining excess renewable energy will need to be curtailed.

While the produced hydrogen from electrolysis might be used for seasonal storage, this reasoning still assumes that hydrogen from carbon taxed natural gas is considered an alternative that provides a ceiling to the merit of electrolysis. Also note that Figure 8 indicates that all the excess options still use about 5 GW of dispatchable power between 5250 and 8600 hours.

To assess the requirement for seasonal storage, we calculated that daily and weekly cycles are almost completely accommodated by short-term options (batteries, demand response, pumped hydro).

The remaining load is levelled out on a yearly basis assuming seasonal storage with a cycle efficiency of 50% (electricity to electricity). This provides us with an upper limit for the yearly seasonal storage need and the need for additional generating capacity to serve the remaining load. We emphasize that this amount of storage capacity will not be economically viable as the remaining load (and thus the market price) are constant resulting in zero revenue.

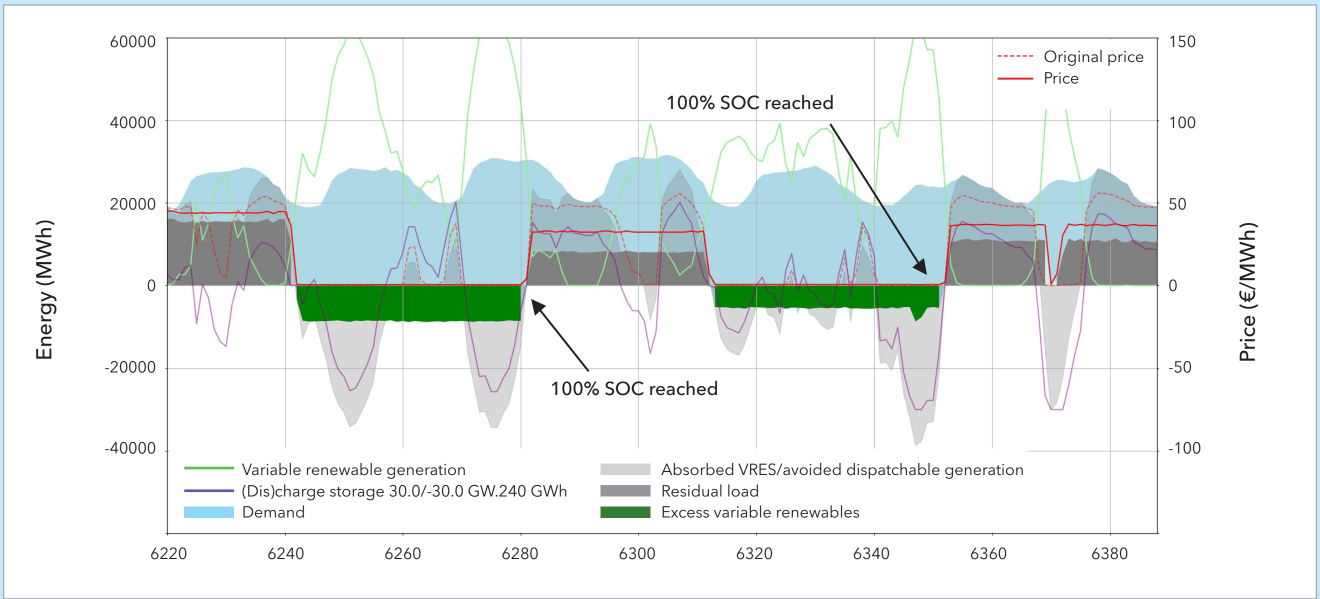


Figure 7 - Example of battery storage and its influence on load and price[4]

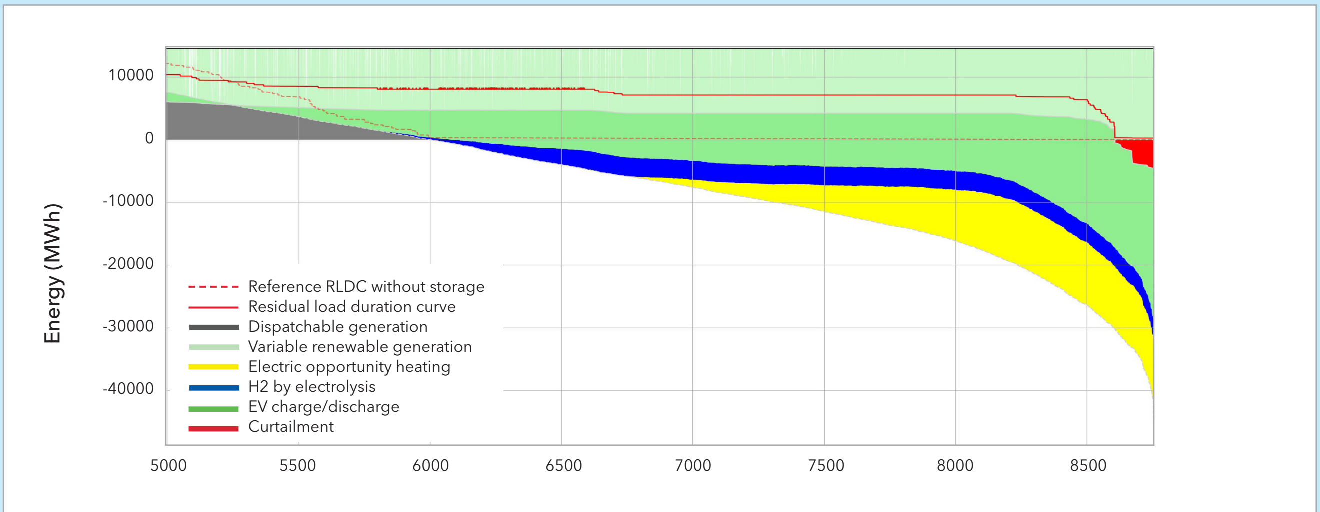


Figure 8 - Example of the dispatch of options for using surplus electricity[4]

2.3 Seasonal storage: case study results

- Modelling results suggest that the variability of the residual load for a given hour can be very large on a year-to-year basis. In this case study, a difference of approximately 60 GW is observed over a period of 58 climate years.
- The residual load duration curve, however, shows considerably fewer yearly variations, suggesting that that on a yearly basis, the effect of weather fluctuations evens out considerably.
- The required theoretical maximum seasonal storage capacity varies between 10 and 25 GW, depending on the climate year. This suggests that the distinction between adequacy capacity and seasonal storage capacity is not that strict.
- In this assumed high-VRES scenario, VRES production is not enough to cover the yearly electricity demand. For a fully renewable carbon-free scenario, other renewable or carbon-free dispatchable power sources are needed.

The case study provides insights in the variability of power demand for a multi-year period with varying weather conditions. Figure 9 shows the statistical analysis of a typical load for a summer week and a winter week for 58 climate years without storage. The average load shows a predictable shape with a summer load dip during day time and a winter heating peak in the morning. In a given hour, the residual load can vary significantly between years, in a range of approximately 40 - 60 GW. This variability is mainly due to VRES.

The statistical analysis of the residual load duration[13] curve with (30 GW, 240 GWh) storage and without storage (Figure 10) shows less variability between climate years. Apparently, differences between the hourly load for different climate years average out in the load duration curve.

Based on the previously discussed approach, we determine the theoretical maximum required seasonal storage capacity per climate year and the resulting dispatchable capacity. Both capacity duration curves (for a period of 58 climate years) are shown in Figure 11. It shows a considerable range in the (theoretical) maximum required seasonal storage capacity and dispatchable capacity (after short-term storage is accounted for).

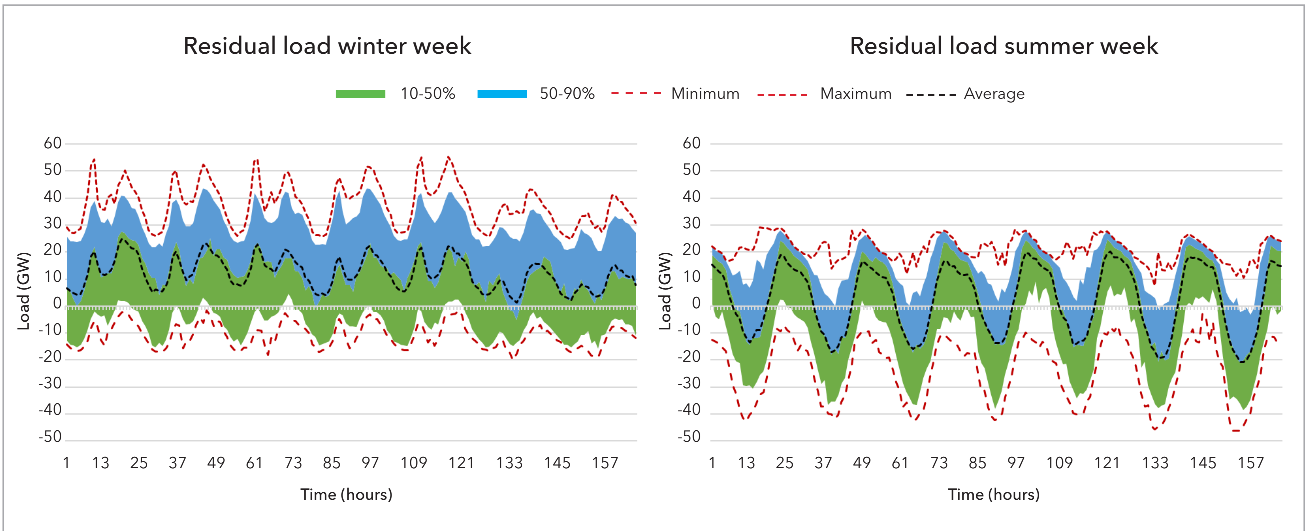


Figure 9 - An example of the hourly variability in the residual load for multiple climate years[4]

Each year, at least 10 GW of storage capacity for charging is needed, but once every 58 years 25 GW is needed. This range is considerable and is important to consider when dimensioning seasonal storage facilities. Capacity above 10 GW will be used less than yearly, and revenues decrease accordingly. It makes us reconsider the strict separation between adequacy capacity and seasonal storage capacity we made before, as seasonal storage capacity that is used only once every few years can be regarded as adequacy capacity instead of seasonal capacity.

The remaining (minimal required) dispatchable capacity will run continuously as, in this theoretical approach, we assume that the yearly load cycle is completely levelled out by seasonal storage. Figure 11 illustrates that this required capacity is positive for all climate years and, therefore, even in the assumed high-VRES scenario, there is a deficit of VRES electricity. For a fully renewable alternative, additional options like hydropower and biomass-based power are needed. For a fully carbon-free alternative, more options are available (fossil fuel-based power combined with carbon capture and storage, nuclear power).

For a fully renewable scenario, additional VRES capacity and additional storage capacity must be built. To illustrate the required VRES capacity, Figure 12 shows how much VRES capacity is theoretically needed to realize a fully carbon-free scenario for a reference climate year assuming sufficient seasonal storage is available to handle surplus electricity. The surplus ratio is the ratio of the required dispatchable power (without storage) and the available surplus electricity (including the effect of the storage efficiency). A surplus ratio of 100% means that, with sufficient seasonal storage, a fully carbon-free scenario is possible.

In summary:

- Our high-VRES scenario includes 81 GW of VRES capacity (42 GW wind, 39 GW solar PV).
- 30 GW of economically optimized short-term battery storage for a large part accommodates daily (and partly weekly) load cycles.
- The maximum required seasonal storage capacity after using battery storage varies from 10–25 GW, depending on the climate year.
- The minimum required dispatchable capacity after using battery storage varies from 5–15 GW.
- To realize a full-VRES based carbon-free scenario, the total VRES-capacity must be more than three times the maximum demand.

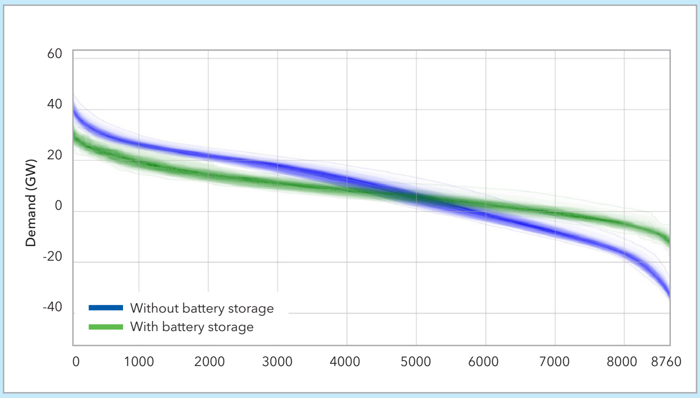


Figure 10 - A density plot of hourly variability in the residual load duration curve (year 2050) for 58 climate years, with and without short-term (battery) storage[4]

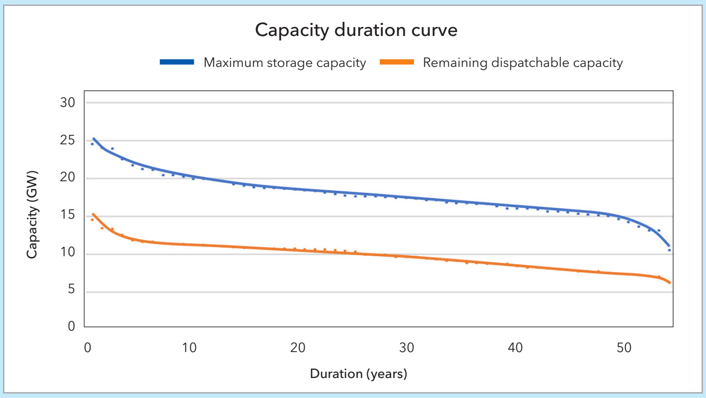


Figure 11 - Duration curve of the theoretical maximum required seasonal storage capacity and resulting remaining dispatchable capacity[4]

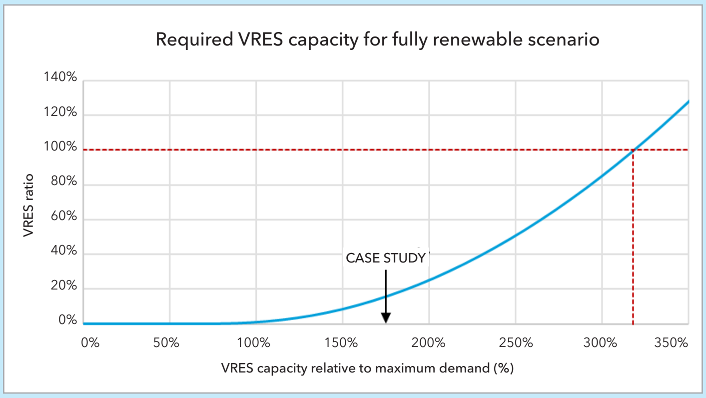


Figure 12 - Illustration of the break-even point for a fully VRES-scenario[4]

3 TECHNOLOGIES FOR SEASONAL STORAGE

3.1 Some thoughts about seasonal storage

- Typical required properties for seasonal storage are low storage losses, large storage volume, low cost of storage, and an acceptable cycle efficiency.
- These properties suggest seasonal storage based on 'molecules' (synthetic fuels).
- Currently, seasonal storage is not a big issue because the market for fossil fuels (coal, natural gas) provides intrinsic storage capacity that leads to a limited seasonal price difference.

As discussed, seasonal storage is used to accommodate yearly cycles in the electricity demand. Daily and weekly cycles are accommodated by other flexibility means (battery storage, pumped hydro, demand response). Capacity that is only sporadically used (typically once every few years) is defined as adequacy capacity that probably needs another revenue mechanism than the current energy-only market. We already mentioned this distinction cannot be made very strictly because the required seasonal storage capacity differs considerably from year to year.

Seasonal storage typically charges during (over) production of electricity from VRES during summertime and discharges in wintertime, when electricity demand is large and VRES electricity production (specifically solar PV) is low. In this paper, we limit the scope to a renewable electricity-to-electricity solution[14].

Some obvious prerequisites for seasonal storage are:

- Energy must be stored with a low loss percentage (self-discharge) as it is stored for several months.
- Energy must be stored in sufficient quantity to accommodate an expected seasonal load swing.
- Cost of large-volume storage must be acceptable compared to the expected revenue from a winter-summer electricity price difference.
- The cycle efficiency must be acceptable. A low cycle efficiency means a 'waste' of energy and storage capacity. It is also an economic issue as the storage efficiency determines the minimum required winter-summer price ratio.

These prerequisites suggest a conversion of electricity to a chemical energy carrier ('molecules') that can be stored cheaply and easily over a long period without significant losses. Several studies address this issue[15]. Figure 13 summarizes the energy density and specific energy of some potential energy carriers (synthetic fuels).

An analysis of historic wholesale gas prices suggests an average seasonal price spread of less than 10%[16]. This is not an incentive for a large seasonal storage market.

Thirdly, the carbon price, although gradually increasing the last year, is still too low to make a difference. The carbon mark-up on the fossil-based electricity price is low enough to avoid competition from seasonal storage of renewable energy. This might change when the carbon price increases significantly. In the financial analysis, the electricity price based on carbon taxed natural gas will be the benchmark for the levelized electricity production cost for seasonal storage.

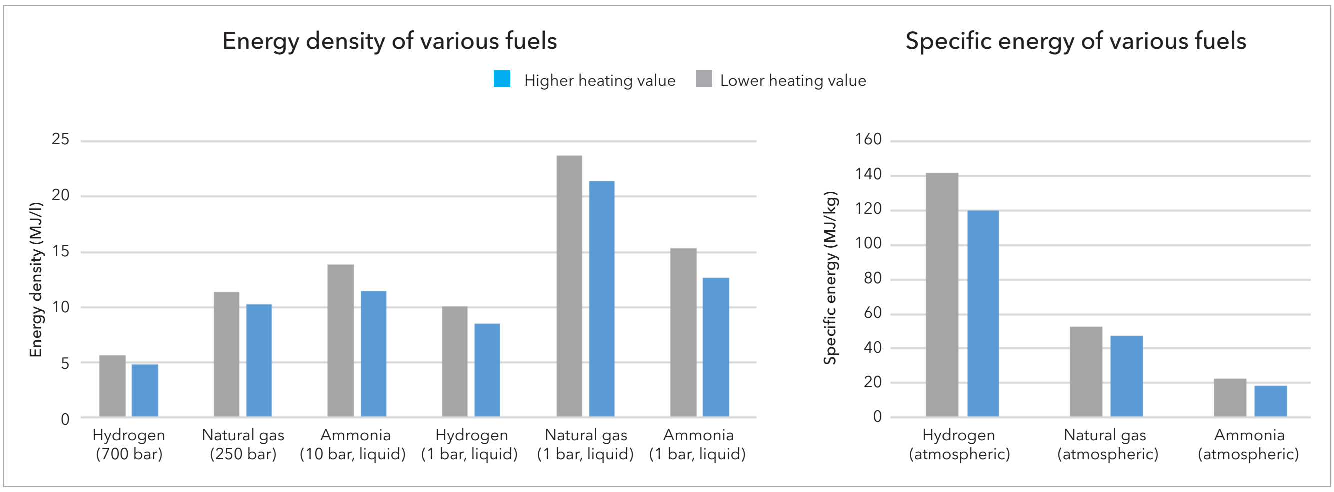


Figure 13 - Energy density and specific energy of potential fuels for seasonal storage[4]

3.2 Options for seasonal storage

- A multitude of technical options for seasonal storage is available.
- They differ mainly in the way electricity is converted and stored (for example, as hydrogen, methanol, methane, ammonia, or methylcyclohexane).
- We present seven seasonal storage options and a benchmark based on carbon taxed natural gas that will be used to provide insight in the feasibility of seasonal storage.

To obtain insight in the feasibility of seasonal storage we evaluated seven options and a benchmark based on electricity from carbon taxed natural gas (resembling the current situation). These options are summarized in Figure 14.

The first option in Figure 14 is our benchmark. It is based on carbon-taxed natural gas. It is not a renewable option and, strictly speaking, not a carbon-free option either. However, we assume that the carbon price is determined based on obligations for CO_2-reduction on one side and a merit order of CO_2-reduction measures on the other side. Paying the carbon price means that somewhere else in the system a reduction measure is taken to obtain the same CO_2-reduction as caused using natural gas. In that sense, it could be considered carbon free and we can use it as our benchmark. An example of such a measure is carbon capture and storage (CCS). If this measure is socially accepted, it will provide a measure for the carbon price equal to the added cost of CCS to natural gas use. In our benchmark, transportation cost of natural gas is not included as this is part of the system cost.

The (second) fuel switch option (between synthetic gas and natural gas) also relies on the intrinsic storage capacity provided by the natural gas market. During the summer, with low or negative electricity prices, electricity is converted to hydrogen and subsequently to methane. The methane is injected in the natural gas grid, thus avoiding the use of energy-equivalent amounts of natural gas[17]. During the winter, natural gas is used to produce electricity. This is a virtual storage option that is limited by the amount of natural gas used during summertime. The natural gas burned to produce power during winter might be linked to the synthetic gas sustainably produced in summer through a certification system, such as a transfer of the guarantees of origin[18].

The other options rely on the production and storage of synthetic fuels. This paper is specifically focused on hydrogen, ammonia, and synthetic natural gas. This choice is based on assessing advantages and disadvantages of synthetic fuel options:

- Does it require costly pressurization, liquefaction or cooling or costly storage facilities?
- Does it require multiple and/or inefficient conversion steps (adding to the cost and energy losses)?
- Does the synthetic fuel synergize with current energy infrastructures?
- Are there other uses of the synthetic fuel (for example, industrial feedstock)?
- Does producing the fuel require an additional source of carbon?

Options 3 to 5 in Figure 14 are using liquified synthetic fuels, and are based on a dedicated large scale solar PV field on a location with favourable conditions (for example, the Far East) that produces renewable electricity. This electricity is converted to fuel (hydrogen, ammonia, methane), liquefied and shipped all over the world. As this is a global solution with year around fuel generation, we assume that only one week of storage capacity is needed. After storage, the fuel is re-gasified and (in case of ammonia) converted to hydrogen. Hydrogen is converted into electricity in fuels cells. Fuel cells are assumed to be the technology of choice in 2050, the time horizon for this study. Methane is converted to electricity in a combined cycle gas turbine. Both electricity production technologies are especially feasible because daily and weekly cycles are levelled out by other storage options, avoiding frequent starts and stops.

In the last three storage options – based on compressed gases – regional synthetic fuels are produced using low-priced electricity. These options feed the fuels into existing national or regional infrastructure and avoid the need for long-distance transportation. They do need a seasonal storage facility and depend on volatile electricity market prices. These options represent the traditional way of looking at seasonal storage.

Appendix B summarizes the technical and financial data used to evaluate the eight options presented in Figure 14. The cycle efficiency of the seven storage options varies from 34 to 47%. Compressed hydrogen storage (option 6) offers the highest cycle efficiency as it avoids the production of synthetic fuels and the energy loss of liquefaction.

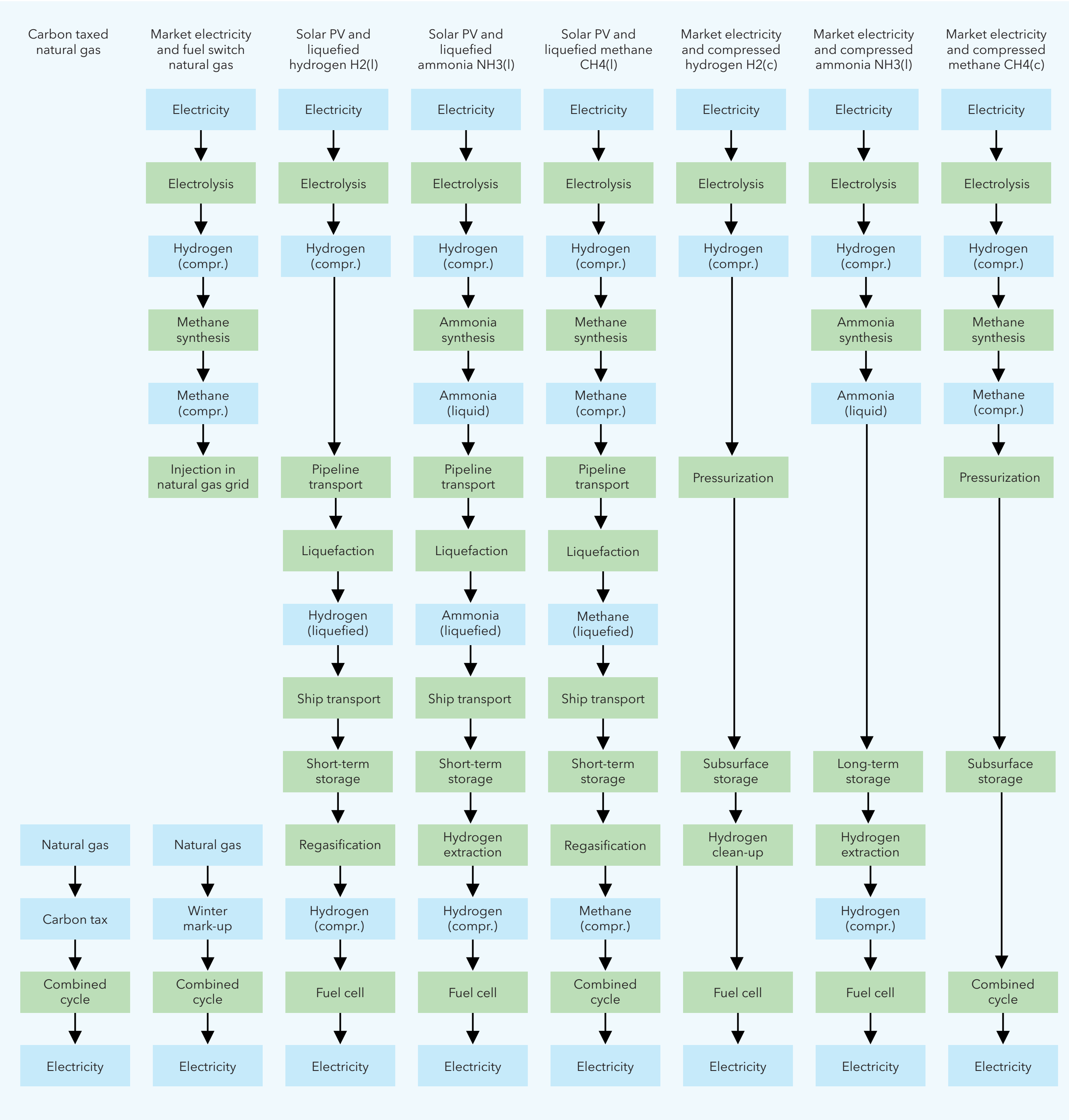


Figure 14 - An overview of options for seasonal storage that are assessed in this paper[4]

4 ECONOMIC FEASIBILITY OF SEASONAL STORAGE

4.1 Effect of short-term storage on the electricity price

- In a high VRES scenario, large electricity price differences can be expected because of the variable production of electricity from VRES.
- Short-term (daily and weekly) storage profit from this price difference but at the same time reduce the price difference as their dispatch will impact market prices (price maker effect).
- This will negatively affect the business case of seasonal storage.

A high VRES penetration will lead to variability in the electricity prices and surplus hours when VRES electricity production is larger than the demand. This will lead to significant hours with a zero electricity price[19]. Short-term (daily and weekly) storage will profit from this price difference reducing the price-volatility. Seasonal storage will, therefore, profit less from this volatility. This effect is illustrated in Figure 15. This figure shows the price duration curve for the year 2050 high-VRES scenario, based on a year with a typical climate, with and without 30 GW of short-term storage (approximately 3 million EVs[11]). It shows that large-scale short-term storage, for example provided by electric mobility, has a significant impact on the volumes of excess renewable electricity, as well as on prices when these batteries discharge to the grid, but have limited impact on prices when these batteries charge from the grid.

Although not shown in the graph, this also applies to demand that would be triggered by these low electricity prices, such as 'opportunity heating' (switching to electric heating if heat from electricity is cheaper than heat from traditional sources). Price volatility and the number of hours with zero-priced electricity diminish because of short-term storage, hampering the business case for seasonal storage. If we assume that seasonal storage will be charged for 2200 hours in summertime and discharged 2200 hours in wintertime (approximately 3 months), the average capture price (assuming seasonal storage is a price taker[20]) is 0 EUR/MWh and 56.7 EUR/MWh without short-term storage. With short-term storage, it is 1.4 EUR/MWh and 45.9 EUR/MWh. This is still a significant ratio allowing for a relatively low cycle efficiency for seasonal storage.

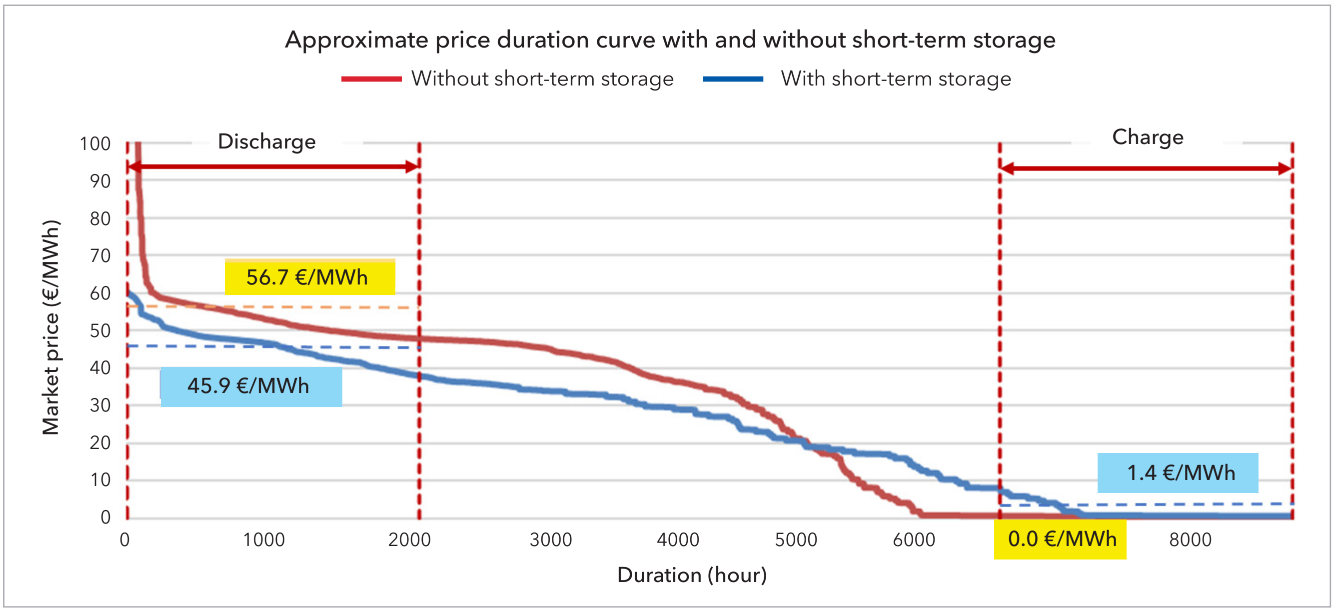


Figure 15 - The effect of daily and weekly storage on the electricity price[4]

4.2 Levelized cost of electricity from seasonal storage options

- Levelized cost of electricity (LCOE) from seasonal storage varies significantly per storage option.
- All options show a significantly higher cost than the reference based on carbon taxed natural gas, except for compressed hydrogen-based storage.
- Seasonal storage based on storing compressed hydrogen in depleted gas fields seems the most cost-effective option.
- Other seasonal storage options suffer from higher conversion cost (production of synthetic fuel, liquefaction) or high losses during (long-distance) transportation.

Based on the data in Appendix A we calculated the levelized cost of the seasonal storage options discussed earlier.

Main assumptions for this calculation are summarized here:

- 2200 operating hours for charging and 2200 for discharging (approximately three months of summer and winter, assuming charging during summer and discharging during winter)
- Average electricity market price during charging: 1.4 EUR/MWh (based on a price taker approach[21])
- Electricity production cost from dedicated solar-PV unit: 10 EUR/MWh[22]
- Gas price: 5.9 EUR/GJ (HHV)
- Carbon price: 54.1 EUR/tonne

The results of the levelized cost calculation are summarized in Figure 16. It shows a considerable difference in levelized cost. Electricity production based on carbon taxed natural gas offers the lowest LCOE, followed by compressed hydrogen seasonal storage. All other options suffer from higher cost due to additional conversion steps (methane and ammonia synthesis, liquefaction) or high transportation losses (liquefied hydrogen).

The levelized cost are well above the market price shown in figure 15. As discussed in an earlier paper[2], market prices for electricity are based on marginal production cost (excluding investments). Levelized cost of electricity includes investments. The price gap between the marginal cost based electricity price and the levelized cost of electricity from seasonal storage indicates a challenge for seasonal storage.

As discussed in our white paper regarding hydrogen in the electricity value chain[12], hydrogen can be used in other markets than the power market, for example, for mobility or as industrial feedstock. The same holds for other synthetic fuels applicable for seasonal storage (see Figure 14). Whether these synthetic fuels are an alternative for fossil fuel derived fuels depends, amongst others, on the price. Synthetic fuel costs are summarized in Figure 17. The reference prices shown are based on an estimated 2050 crude oil price and natural gas price (including carbon tax). It shows that hydrogen is the least costly to produce and that the estimated synthetic hydrogen cost (year 2050) is lower than the natural gas cost and lower than the crude oil price. Levelized cost of other synthetic fuels seem to approach the carbon-taxed crude oil price.

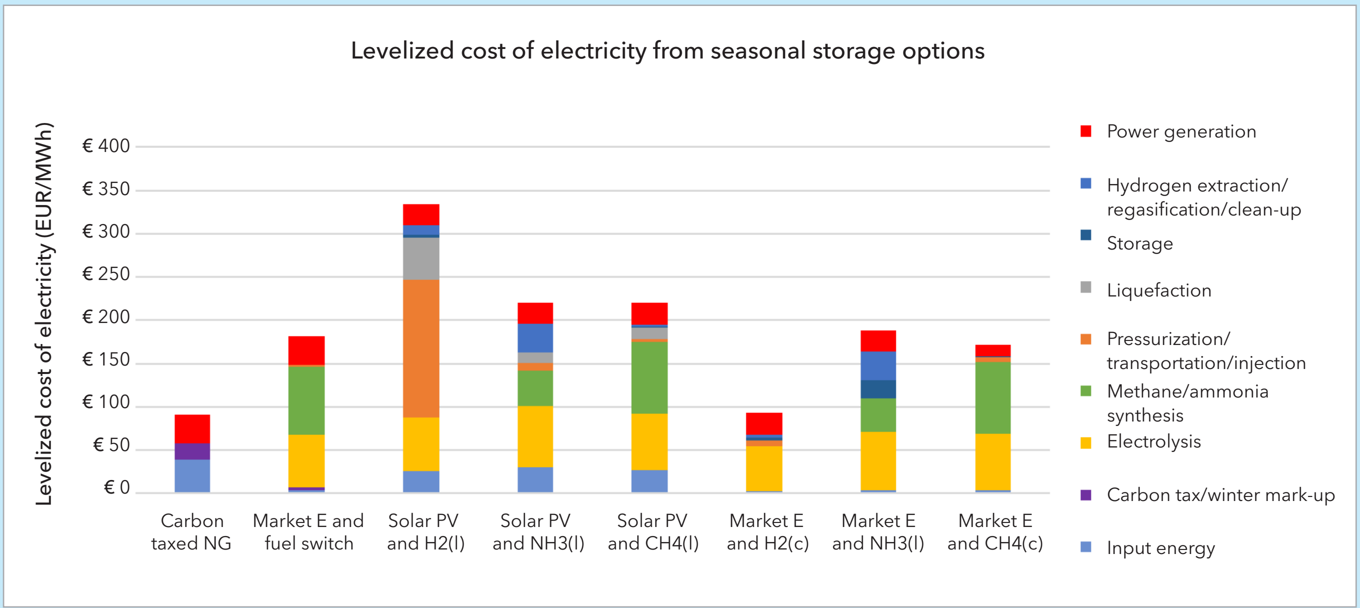


Figure 16 - Levelized cost of electricity different seasonal storage options[4]

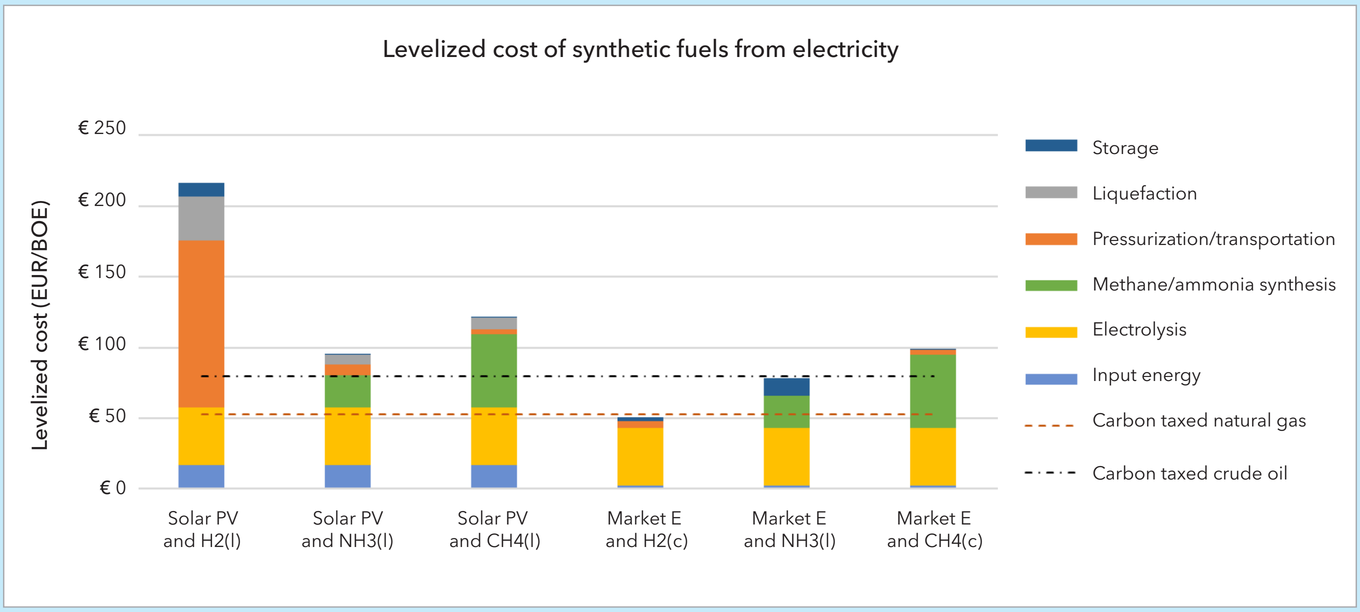
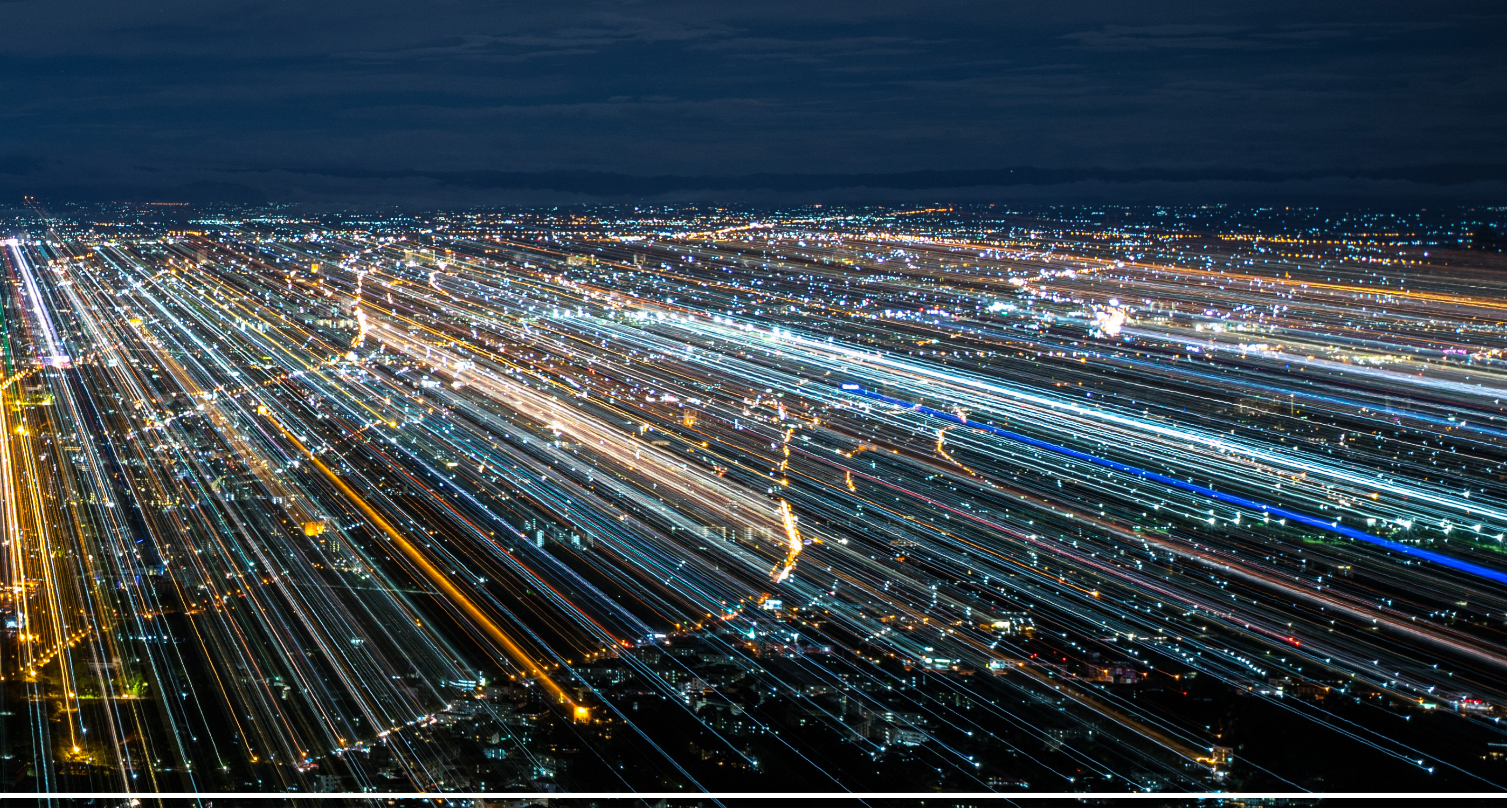


Figure 17 - Levelized cost of fuels for seasonal storage compared to a fossil fuel reference[4]

5 DISCUSSION AND MAIN INSIGHTS

- The idea of seasonal storage of electricity has great appeal as it seems to solve two problems:
  1. Using surplus electricity that might be curtailed otherwise (typically in the summer season)
  2. Decarbonize electricity generation when demand is high and VRES production is low (typically in the winter season).
- However, a significant part of the variability in electricity load and consumption is solved with short-term (daily and weekly) storage (for example, batteries, EV vehicle-to-grid, and pumped hydro). Short-term storage, therefore, significantly decreases the 'long spread', the average summer-winter electricity price spread.
- The most viable option for seasonal storage with the lowest levelized cost for electricity is compressed hydrogen combined with subsurface storage.
- Variability in demand and VRES electricity generation between years blur the distinction between seasonal storage and adequacy capacity.
- Seasonal storage is not a single-company business and needs a market for synthetic fuels to develop first (for example, for mobility or industrial use).



This paper presents the results of a case study to gain insight into the need and options for seasonal storage of electricity. This case study is based on modelling electricity generation and demand for 58 different climate years. The top 5 insights are summarized below:

1. **Seasonal storage must compete with other applications for low-priced electricity**
   We assume that in a future energy system, ample short-term storage capacity is available to accommodate daily and weekly cycles in VRES generation and demand. This storage capacity will be available as dedicated batteries for the electricity grid, electric vehicle batteries (vehicle-to-grid applications) and pumped hydro. This short-term storage accommodates a large part of the variability in electricity load and generation. This will significantly decrease the long spread (average summer-winter price spread), adversely affecting the business case for seasonal storage. Short-term storage also decreases the electricity volume available for seasonal storage. Other applications for use of low-priced electricity, such as electric heating, will amplify this effect.

2. **Compressed hydrogen is the first viable option for seasonal storage**
   The viability of seasonal storage of electricity depends on the availability of low-cost, large-volume storage of energy. Therefore, an intermediate step to generate a synthetic fuel is a necessary part of the options we explore in this paper. Based on our LCOE analysis, storage of compressed hydrogen in the subsurface (salt caverns or depleted hydrocarbon fields) seems the most viable option for synthetic fuel for seasonal storage. Storing hydrogen in salt caverns or a depleted hydrocarbon field has the lowest cost. Conversion of hydrogen into another synthetic fuel has the advantage of relative straightforward storage and transporting over longer distances, using existing infrastructure and experience. It has the disadvantage of an additional conversion step incurring additional cost and losses. This increases the LCOE.

3. **Variability in demand and VRES generation between years blur the distinction between seasonal storage and adequacy capacity**
   The weather patterns that determine electricity generation by wind and solar generation, as well as demand for heating, vary considerably between the 58 climate years that we analysed, and so does the amount of energy that needs to be stored to overcome the seasonal difference.
   This means that the physical distinction between seasonal storage and adequacy – i.e., the capacity that is dispatched each year vs. the capacity that is needed as a reserve – is very thin at best. The economical distinction between seasonal storage and adequacy – i.e., the long spread between average summer prices and average winter prices can cover the levelized cost vs. does it need to be covered collectively through system fees – is virtually non-existent. Just like the distinction between seasonal storage and adequacy, the distinction between seasonal storage and short-term storage is not clear. Both will charge at low prices and both will discharge at high prices. The difference is that the energy capacity compared to the power capacity of seasonal storage is much higher, giving it a longer charge/discharge duration. However, given enough short-term storage, charging and discharging it at full power will be suboptimal as it influences prices negatively and thus also the 'staying power' or duration of both charging and discharging of short-term storage (including demand response and vehicle-to-grid applications) will increase significantly as its capacity increases.

4. **Seasonal storage is not a single-company business**
   Seasonal electricity storage differs fundamentally from short-term (daily and weekly) electricity storage. Short-term storage (for example, batteries and pumped hydro) consists of a single installation that converts electricity to a storable form (chemical energy, potential energy) and converts it back when needed. Seasonal electricity storage requires conversion to a transportable synthetic fuel that is stored in large volumes for multiple months. Conversion from and to electricity are decoupled in time and space.

   Seasonal storage is, therefore, not a single-company business. Given the LCOE options for seasonal storage of electricity, it is unlikely that seasonal storage will develop as a single business on its own. A two-step development is more likely. Firstly, a market for synthetic fuels will develop, for example, based on hydrogen produced locally from offshore wind. The market for synthetic fuels will also serve other users and uses (industrial, commercial, domestic). As discussed in our previous paper[12], these uses may be price setting for synthetic fuels.

   Secondly, it depends on the willingness-to-pay to fully decarbonize the electricity production, whether these carbon-free synthetic fuels will be used to serve seasonal and multi-year power shortages. If the estimated carbon price in 2050 reflects the willingness-to-pay for carbon-free electricity, using natural gas and accepting the carbon fine may still be the most viable option.

   The difference between the LCOE of the most viable seasonal storage option and of electricity from carbon taxed natural gas is less than 5%. While this may prevent seasonal storage to be developed, a 10% increase of the carbon price will make seasonal storage competitive, provided that it is small enough that it does not affect market prices.

5. **Seasonal storage is both an opportunity and need**
   Comparing load duration and residual load duration curves for multiple climate years provides valuable insight in variability and adequacy of electricity load and generation. It shows that for the weather data used in the case study there is a consistent oversupply in summer and undersupply in winter, that — if combined — would solve a major issue in the decarbonization of the electricity supply by variable renewables. Hence, the idea of seasonal storage has great appeal.

   This appeal comes from both sides: the availability of surplus electricity on the one side and the need for carbon free dispatchable power on the other side. However, as discussed in this chapter, both sides come with competition. On the supply side, only part of the potential of surplus electricity is economically available for long-term storage. Competitive uses are economically more viable with fewer operating hours. These other uses both reduce the available electricity volume and increase the electricity price.

   On the demand side, seasonal storage must compete with other options too, most notably carbon-taxed natural gas. This option is, based on current assumptions, still more cost-effective. The difference between the next-best alternative (seasonal storage of compressed hydrogen), however, is small and maybe not significant given a forecast period of 30 years. If the need for fully decarbonized, fossil-fuel free electricity supply is high enough, this will reflect in a significantly higher carbon price, making seasonal storage a viable option. And when the need is high enough, seasonal storage transfers to a business opportunity.

APPENDIX A
ANALYSIS OF WEATHER AND LOAD DATA

As discussed in section 1.2, we see storage in general, and seasonal storage especially, as an option to accommodate cycles in production of energy from VRES and cycles in electricity demand. It is clear that these cycles are related to daily and yearly weather patterns and daily and weekly demand patterns (working days and weekend days). This assumption is substantiated by using a frequency spectrum analysis[23] of weather data and load data.

We use load data and weather data for the Netherlands, as this is the base of our case study. Hourly weather data is available from 1961[24], hourly load data from 2004[25].

Figure 18 shows the power spectrum for Dutch total load data. The spectrum shows how much a certain frequency contributes to the total load. This contribution is normalized to a value of 1 for the contribution of the yearly cycle. The contribution per frequency is calculated based on a pure sinusoidal shape. Load patterns that deviate from a sinusoidal shape produce higher harmonics, i.e., contributions at frequencies of two times, three times, etc., of the fundamental frequency.

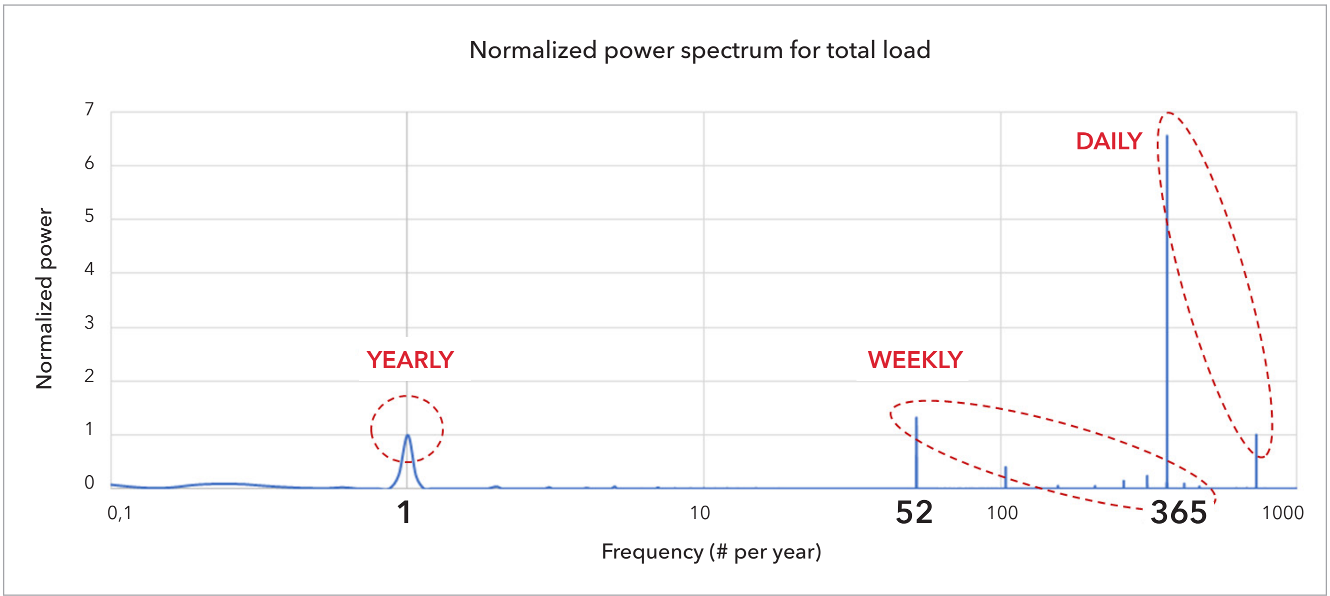


Figure 18 - Frequency spectrum analysis of Dutch total load data for 2004 - 2018[4]

Keeping the higher harmonic effect in mind, the total load clearly illustrates three types of cyclic behaviour:

1. Yearly (once every year)
2. Weekly (approximately 52 times every year)
3. Daily (approximately 365 times every year).

The magnitude of each peak is a measure for the contribution of this frequency to the total variation. Roughly, the daily load cycle contributes for 70% to the total cyclic behaviour, the weekly load cycle for 20% and the yearly cycle for 10%.

The same analysis is done for weather data. Relevant weather data are the solar irradiance (solar PV production), wind speed (wind turbine production) and temperature (space heating demand). The results are summarized in Figure 19 through Figure 21. The spectrum analysis emphasizes the obvious that weather patterns only show clear daily and yearly cycles. The difference in contribution to the daily cycle and the yearly cycle is interesting. The yearly temperature cycle is much larger than the daily cycle suggesting that accommodating the electrified space heating demand pattern will be much more of a challenge on a yearly basis than on a daily basis. For the wind speed, the yearly cycle and the daily cycle are comparable and for the solar irradiation, the daily cycle is much larger than the yearly cycle.

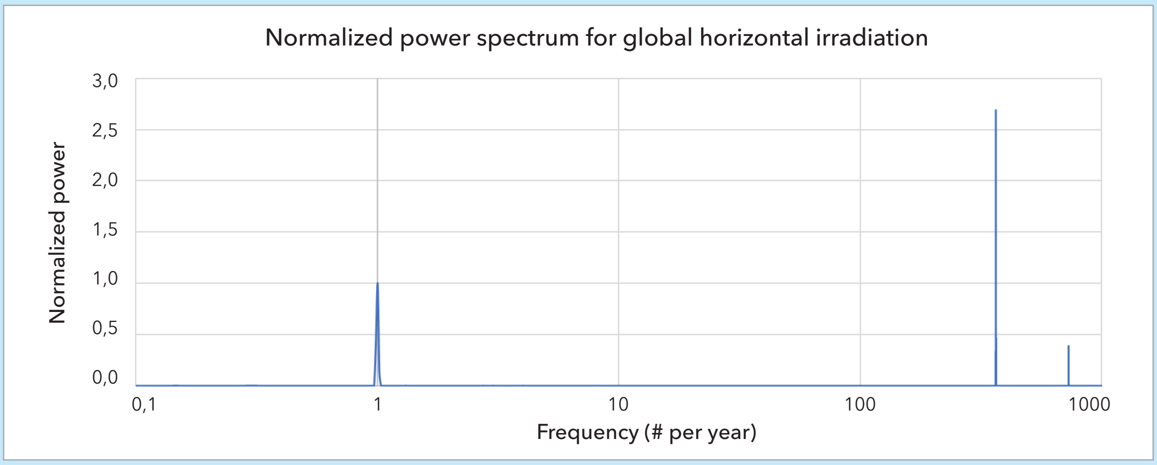


Figure 19 - Frequency spectrum analysis of Dutch global horizontal irradiation for 1961 - 2018[4]

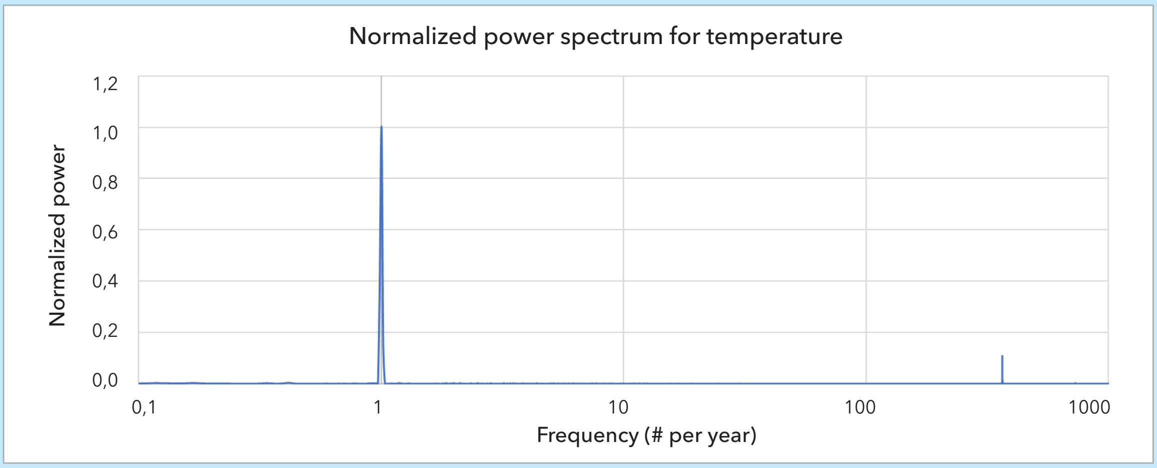


Figure 20 - Frequency spectrum analysis of Dutch temperature for 1961 - 2018[4]

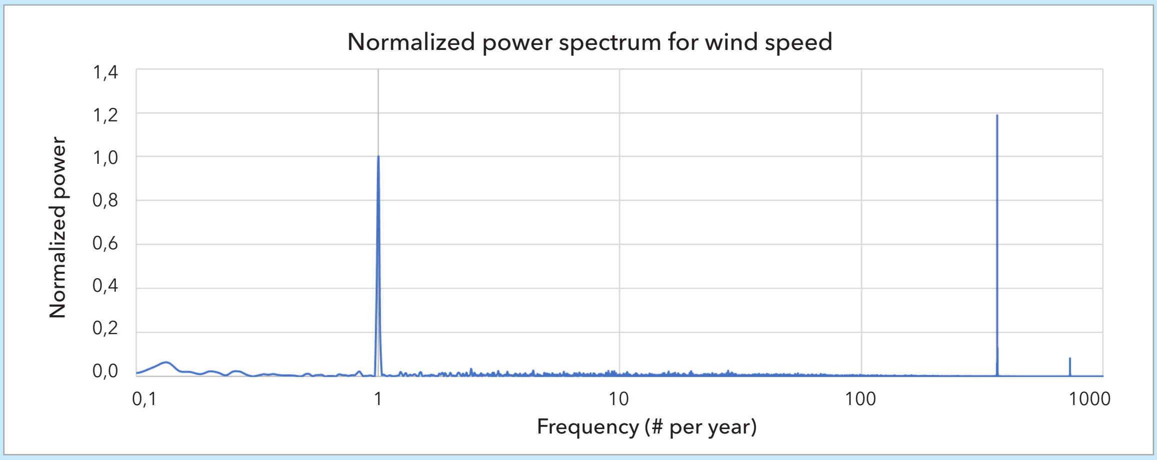


Figure 21 - Frequency spectrum analysis of Dutch wind speed 1961 - 2018[4]

APPENDIX B
SEASONAL STORAGE TECHNICAL DATA

The tables below summarize the technical data used to evaluate the seasonal storage options. Data is based on review of publications and reports and on DNV GL's ExplEnergy tool[26].

1 Carbon taxed natural gas

idx	Option	Param1	Value1	Param2	Value2	Param3	Value3
1	Natural gas from natural gas market	Power [MW]	100	Rate [%]	5%		
2	Carbon tax						
3	Combined Cycle	Lifetime [yr]	25	Loss [%]	40,0%	CAPEX [€/W]	€ 0,800

1 Carbon taxed natural gas

idx	Option	Param4	Value4	Param5	Value5	Param6	Value6	Param7	Value7
1	Natural gas from natural gas market	CoE [€/GJ]	6,57	Oper. [h/yr]	2200				
2	Carbon tax	CoE [€/GJ]	3,05	Oper. [h/yr]	2200				
3	Combined Cycle	OPEX [€/GJ]	2,02	Oper. [h/yr]	2200				

2 Market electricity and fuel switch

idx	Option	Param1	Value1	Param2	Value2	Param3	Value3
1	Electricity from electricity market	Power [MW]	100	Rate [%]	5%		
2	Electrolysis (60 bar)	Lifetime [yr]	20	Loss [%]	19%	CAPEX [€/W]	€ 0,610
3	Methane synthesis	Lifetime [yr]	25	Loss [%]	20%	CAPEX [€/W]	1,32
4	Injection in NG-grid	Lifetime [yr]	35	Loss [%]	0,0%	CAPEX [€/W]	0,05
5	Natural gas winter mark-up						
6	Combined Cycle	Lifetime [yr]	25	Loss [%]	40,0%	CAPEX [€/W]	€ 0,800

2 Market electricity and fuel switch

idx	Option	Param4	Value4	Param5	Value5	Param6	Value6	Param7	Value7
1	Electricity from electricity market	CoE [€/GJ]	0,39	Oper. [h/yr]	2200				
2	Electrolysis (60 bar)	OPEX [€/GJ]	€ 1,93	Oper. [h/yr]	2200				
3	Methane synthesis	OPEX [€/GJ]	1,22807	Oper. [h/yr]	2200				
4	Injection in NG-grid	OPEX [€/GJ]	0,0003	Oper. [h/yr]	2200				
5	Natural gas winter mark-up	CoE [€/GJ]	0,66	Oper. [h/yr]	2200				
6	Combined Cycle	OPEX [€/GJ]	2,02	Oper. [h/yr]	2200				

3 Solar PV and liquefied hydrogen

idx	Option	Param1	Value1	Param2	Value2	Param3	Value3
1	Electricity from dedicated solar field	Power [MW]	100	Rate [%]	5%		
2	Electrolysis (60 bar)	Lifetime [yr]	20	Loss [%]	19%	CAPEX [€/W]	€ 0,610
3	Pipeline transport	Lifetime [yr]	40	Loss [%/km]	0,006%	CAPEX [€/MW.km]	658
4	Liquefaction	Lifetime [yr]	25	Loss [%]	20,0%	CAPEX [€/W]	0,789
5	Liquefied transport by ship	Lifetime [yr]	40	Loss [%/day]	0,001%	CAPEX [€/GJcap]	351
6	Liquefied tank storage	Lifetime [yr]	25	Loss [%/day]	0,1%	CAPEX [€/GJ]	439
7	Regasification	Lifetime [yr]	25	Loss [%]	0%	CAPEX [€/W]	0,175
8	PEM Fuel Cell	Lifetime [yr]	20	Loss [%]	40%	CAPEX [€/W]	0,500

3 Solar PV and liquefied hydrogen

idx	Option	Param4	Value4	Param5	Value5	Param6	Value6	Param7	Value7
1	Electricity from dedicated solar field	CoE [€/GJ]	2,78	Oper. [h/yr]	2200				
2	Electrolysis (60 bar)	OPEX [€/GJ]	€ 1,93	Oper. [h/yr]	2200				
3	Pipeline transport	OPEX [€/GJ.km]	0,000526	Oper. [h/yr]	2200	Distance [km]	100		
4	Liquefaction	OPEX [€/GJ]	0,88	Oper. [h/yr]	2200				
5	Liquefied transport by ship	OPEX [€/GJ.km]	0,002114	Oper. [h/yr]	8760	Distance [km]	11653	Avg. speed [km/h]	24
6	Liquefied tank storage	OPEX [€/GJ.yr]	0	Oper. [h/yr]	8760	Days [day]	7		
7	Regasification	OPEX [€/GJ]	0,175	Oper. [h/yr]	2200				
8	PEM Fuel Cell	OPEX [€/GJ]	1,894	Oper. [h/yr]	2200				

4 Solar PV and liquefied ammonia

idx	Option	Param1	Value1	Param2	Value2	Param3	Value3
1	Electricity from dedicated solar field	Power [MW]	100	Rate [%]	5%		
2	Electrolysis (60 bar)	Lifetime [yr]	20	Loss [%]	19%	CAPEX [€/W]	€ 0,610
3	Ammonia synthesis	Lifetime [yr]	25	Loss [%]	15,000%	CAPEX [€/W]	0,526
4	Pipeline transport	Lifetime [yr]	40	Loss [%/km]	0,0%	CAPEX [€/MW.km]	149
5	Liquefaction	Lifetime [yr]	25	Loss [%]	5,000%	CAPEX [€/W]	0,175
6	Liquefied transport by ship	Lifetime [yr]	40	Loss [%/day]	0,0%	CAPEX [€/GJcap]	69,298
7	Liquefied tank storage	Lifetime [yr]	25	Loss [%/day]	0,08%	CAPEX [€/GJ]	19,30
8	Hydrogen extraction	Lifetime [yr]	25	Loss [%]	15%	CAPEX [€/W]	0,526
9	PEM Fuel Cell	Lifetime [yr]	20	Loss [%]	40%	CAPEX [€/W]	0,500

4 Solar PV and liquefied ammonia

idx	Option	Param4	Value4	Param5	Value5	Param6	Value6	Param7	Value7
1	Electricity from dedicated solar field	CoE [€/GJ]	2,78	Oper. [h/yr]	2200				
2	Electrolysis (60 bar)	OPEX [€/GJ]	€ 1,93	Oper. [h/yr]	2200				
3	Ammonia synthesis	OPEX [€/GJ]	0,737	Oper. [h/yr]	2200				
4	Pipeline transport	OPEX [€/GJ.km]	4,386E-05	Oper. [h/yr]	2200	Distance [km]	100		
5	Liquefaction	OPEX [€/GJ]	0,175	Oper. [h/yr]	2200				
6	Liquefied transport by ship	OPEX [€/GJ.km]	7,02E-05	Oper. [h/yr]	8760	Distance [km]	11653	Avg. speed [km/h]	24
7	Liquefied tank storage	OPEX [€/GJ.yr]	0	Oper. [h/yr]	8760	Days [day]	7		
8	Hydrogen extraction	OPEX [€/GJ]	0,737	Oper. [h/yr]	2200				
9	PEM Fuel Cell	OPEX [€/GJ]	1,894	Oper. [h/yr]	2200				

5 Solar PV and liquefied methane

idx	Option	Param1	Value1	Param2	Value2	Param3	Value3
1	Electricity from dedicated solar field	Power [MW]	100	Rate [%]	5%		
2	Electrolysis (60 bar)	Lifetime [yr]	20	Loss [%]	19%	CAPEX [€/W]	€ 0,610
3	Methane synthesis	Lifetime [yr]	25	Loss [%]	20,000%	CAPEX [€/W]	1,316
4	Pipeline transport	Lifetime [yr]	40	Loss [%/km]	0,0%	CAPEX [€/MW.km]	26,3
5	Liquefaction	Lifetime [yr]	25	Loss [%]	5,000%	CAPEX [€/W]	0,1096
6	Liquefied transport by ship	Lifetime [yr]	40	Loss [%/day]	0,00023%	CAPEX [€/GJcap]	36,8421
7	Liquefied tank storage	Lifetime [yr]	25	Loss [%/day]	0,12%	CAPEX [€/GJ]	87,719
8	Regasification	Lifetime [yr]	25	Loss [%]	0%	CAPEX [€/W]	0,044
9	PEM Fuel Cell	Lifetime [yr]	20	Loss [%]	40%	CAPEX [€/W]	0,500

5 Solar PV and liquefied methane

idx	Option	Param4	Value4	Param5	Value5	Param6	Value6	Param7	Value7
1	Electricity from dedicated solar field	CoE [€/GJ]	2,7778	Oper. [h/yr]	2200				
2	Electrolysis (60 bar)	OPEX [€/GJ]	€ 1,93	Oper. [h/yr]	2200				
3	Methane synthesis	OPEX [€/GJ]	1,22807	Oper. [h/yr]	2200				
4	Pipeline transport	OPEX [€/GJ.km]	7,02E-05	Oper. [h/yr]	2200	Distance [km]	100		
5	Liquefaction	OPEX [€/GJ]	1,18	Oper. [h/yr]	2200				
6	Liquefied transport by ship	OPEX [€/GJ.km]	3,51E-05	Oper. [h/yr]	8760	Distance [km]	11653	Avg. speed [km/h]	24
7	Liquefied tank storage	OPEX [€/GJ.yr]	0	Oper. [h/yr]	8760	Days [day]	7		
8	Regasification	OPEX [€/GJ]	0,0439	Oper. [h/yr]	2200				
9	PEM Fuel Cell	OPEX [€/GJ]	1,894	Oper. [h/yr]	2200				

6 Market electricity and compressed hydrogen

idx	Option	Param1	Value1	Param2	Value2	Param3	Value3
1	Electricity from electricity market	Power [MW]	100	Rate [%]	5%		
2	Electrolysis (60 bar)	Lifetime [yr]	20	Loss [%]	19%	CAPEX [€/W]	€ 0,610
3	Pressurization (250 bar)	Lifetime [yr]	25	Loss [%]	3,500%	CAPEX [€/W]	0,07018
4	Long term storage	Lifetime [yr]	40	Loss [%/day]	0,014%	CAPEX [€/GJ]	17,5
5	Hydrogen extraction	Lifetime [yr]	25	Loss [%]	0,000%	CAPEX [€/W]	0,05
6	PEM Fuel Cell	Lifetime [yr]	20	Loss [%]	40%	CAPEX [€/W]	0,500

6 Market electricity and compressed hydrogen

idx	Option	Param4	Value4	Param5	Value5	Param6	Value6	Param7	Value7
1	Electricity from electricity market	CoE [€/GJ]	0,3889	Oper. [h/yr]	2200				
2	Electrolysis (60 bar)	OPEX [€/GJ]	€ 1,93	Oper. [h/yr]	2200				
3	Pressurization (250 bar)	OPEX [€/GJ]	0,4386	Oper. [h/yr]	2200				
4	Long term storage	OPEX [€/GJ.yr]	0,079	Oper. [h/yr]	8760	Days [day]	180		
5	Hydrogen extraction	OPEX [€/GJ]	0,05	Oper. [h/yr]	2200				
6	PEM Fuel Cell	OPEX [€/GJ]	1,894	Oper. [h/yr]	2200				

7 Market electricity and compressed ammonia

idx	Option	Param1	Value1	Param2	Value2	Param3	Value3
1	Electricity from electricity market	Power [MW]	100	Rate [%]	5%		
2	Electrolysis (60 bar)	Lifetime [yr]	20	Loss [%]	19%	CAPEX [€/W]	€ 0,610
3	Ammonia synthesis	Lifetime [yr]	25	Loss [%]	15,000%	CAPEX [€/W]	0,52631579
4	Long term storage	Lifetime [yr]	25	Loss [%/day]	0,0%	CAPEX [€/GJ]	85
5	Hydrogen extraction	Lifetime [yr]	25	Loss [%]	15%	CAPEX [€/W]	0,526
6	PEM Fuel Cell	Lifetime [yr]	20	Loss [%]	40%	CAPEX [€/W]	0,500

7 Market electricity and compressed ammonia

idx	Option	Param4	Value4	Param5	Value5	Param6	Value6	Param7	Value7
1	Electricity from electricity market	CoE [€/GJ]	0,3889	Oper. [h/yr]	2200				
2	Electrolysis (60 bar)	OPEX [€/GJ]	€ 1,93	Oper. [h/yr]	2200				
3	Ammonia synthesis	OPEX [€/GJ]	0,736842	Oper. [h/yr]	2200				
4	Long term storage	OPEX [€/GJ.yr]	0	Oper. [h/yr]	8760	Days [day]	180		
5	Hydrogen extraction	OPEX [€/GJ]	0,737	Oper. [h/yr]	2200				
6	PEM Fuel Cell	OPEX [€/GJ]	1,894	Oper. [h/yr]	2200				

8 Market electricity and compressed methane

idx	Option	Param1	Value1	Param2	Value2	Param3	Value3
1	Electricity from electricity market	Power [MW]	100	Rate [%]	5%		
2	Electrolysis (60 bar)	Lifetime [yr]	20	Loss [%]	19%	CAPEX [€/W]	€ 0,610
3	Methane synthesis	Lifetime [yr]	25	Loss [%]	20,000%	CAPEX [€/W]	1,31578947
4	Pressurization (250 bar)	Lifetime [yr]	25	Loss [%]	1,0%	CAPEX [€/W]	0,08
5	Long term storage	Lifetime [yr]	25	Loss [%/day]	0,028%	CAPEX [€/GJ]	3,509
6	Combined Cycle	Lifetime [yr]	25	Loss [%]	40,0%	CAPEX [€/W]	€ 0,800

8 Market electricity and compressed methane

idx	Option	Param4	Value4	Param5	Value5	Param6	Value6	Param7	Value7
1	Electricity from electricity market	CoE [€/GJ]	0,3889	Oper. [h/yr]	2200				
2	Electrolysis (60 bar)	OPEX [€/GJ]	€ 1,93	Oper. [h/yr]	2200				
3	Methane synthesis	OPEX [€/GJ]	1,22807	Oper. [h/yr]	2200				
4	Pressurization (250 bar)	OPEX [€/GJ]	0,2	Oper. [h/yr]	2200				
5	Long term storage	OPEX [€/GJ.yr]	0,0018	Oper. [h/yr]	8760	Days [day]	180		
6	Combined Cycle	OPEX [€/GJ]	2,02	Oper. [h/yr]	8760				

END NOTES

1 Variability of demand and generation is not the same as predictability. For example, heat pump demand can be reasonably well predicted based on the weather forecast but might still represent a variability challenge. When we use the term "variability" we refer to both predictable and unpredictable variations.

2 Future-proof renewables, DNV GL white paper, 2018, available at: https://www.dnvgl.com/publications/future-proof-renewables-103549

3 Based on a generation mix of approximately 33% solar, 33% wind and 33% dispatchable generation (capacity based)

4 Based on DNV GL calculations.

5 This general picture does not include the effect of grid constraints. This may lead to additional curtailing of renewables if there is insufficient grid capacity between areas with high renewable generation and areas with a matching demand.

6 Flexibility in the power system, the need, opportunity and value of flexibility, DNV GL white paper 2017, available at: https://www.dnvgl.com/publications/flexibility-in-the-power-system-103874

7 DNV GL 2019 Energy Transition Outlook, available at: https://eto.dnvgl.com/2019

8 Load data is only available from 2004, weather data is based on measurements from the national weather station De Bilt. The weather data we used is not harmonized and may include effects of, for example, urbanization.

9 We use a Student-t distribution to test the significance of the linear trend, assuming the residual errors are independent of each other. For the temperature and the solar irradiation, the linear trend is significant based on a confidence interval of 99%.

10 We use both a whole reference year or a shortened reference year, both based on historic weather data. Yearly weather data is translated into an 8-week shortened reference year by choosing representative weeks from each year according to the procedure described in European standard EN ISO 15927-4: Hygrothermal performance of buildings – Calculation and presentation of climate data – Part 4: Hourly data for assessing the annual energy use for heating and cooling. Using a shortened reference year reduces the required calculation time significantly.

11 For 2050, a vehicle fleet consisting of 1/3 of EV's is conservative. Each EV is assumed to have 80 kWh of capacity available on average that can be used for arbitrage and discharging to the grid, and on average is not reserved for driving. While this might seem ambitious, there is no technical hurdle. An average car in the Netherlands drives about 60 km/day, translating in a use of 10 kWh/day. Already, high end EVs have a battery capacity of 100kWh.

12 Hydrogen in the electricity value chain, DNV GL white paper, 2019, available at: https://dnvgl.com/publications/hydrogen-in-the-electricity-value-chain-141099

13 A load duration curve is basically a load curve sorted from high to low values. It conveniently shows for how long a certain load is exceeded. It provides quick insight the required power generation capacity at the cost of not knowing exactly when it is needed.

14 Other options like seasonal heat storage and conversion of stored energy to heat instead of electricity during wintertime is an option to avoid electricity use for electric heating but this option does not add to the insights we want to gain in this paper and is therefore not considered.

15 See for instance: Seasonal storage and alternative carriers: A flexible hydrogen supply chain model, Applied Energy 200 (2017) 290–302; Ammonia (NH3) Storage for Massive PV Electricity, Energy Procedia, Volume 150, September 2018, Pages 99-105.

16 We analysed monthly price data for Henry Hub, Louisiana natural gas (spot prices). We compared monthly prices with the yearly average for June, 1989 – May, 2019

17 We assume that the natural gas demand will be large enough to absorb this injection. This is not obvious, but this issue is outside the topic of this paper.

18 Although this makes it a sustainable solution, it does depend on the existence of a non-sustainable natural gas infrastructure, similar to guarantees of origin for wind and solar power depend on the existence of the (not-renewable) dispatchable power generation.

[19] A negative electricity price is possible, for instance when must-run power units or units with a long start-up and shut-down time are willing to pay to keep running. Also, subsidy schemes tied to renewable production may result in negative prices. These are special situations and hard to predict. Therefore, we assume a zero electricity price in the case of potential VRES overproduction.

[20] The price taker assumption provides a best-case electricity price ratio for seasonal storage.

[21] This price does not account for the effect of large-scale storage on the electricity price and the effect of sector coupling (for example, electric heating and hydrogen production). This may lead to a higher price. Sector coupling is the subject of a forthcoming position paper.

[22] A bid of 1.79 $cent/kWh (15.7 EUR/MWh) was given for a solar project in Saudi Arabia, see: https://www.thenational.ae/business/energy/world-s-cheapest-prices-submitted-for-saudi-arabia-s-first-solar-project-1.663842. Assuming some cost reduction in the future, a production price of 10 EUR/MWh is assumed.

[23] We use a standard Fast Fourier Transform (FFT) method for the power spectrum analysis. Data is de-trended, padded with zeros to obtain a power-of-two number of data and windowed using a Hann-function.

[24] Hourly weather data is available from the website of the Royal Dutch Meteorological Institute (https://projects.knmi.nl/klimatologie/uurgegevens/selectie.cgi). We use data from the national weather station De Bilt starting with year 1961. Earlier data is dismissed because of large deviations in the wind speed that could not be explained statistically.
Solar irradiation is the global irradiation in a horizontal plane, temperature is measured at 1.5 m height, wind speed is measured at 10 m height.

[25] Quarterly total load data is available from the website of the Dutch TSO TenneT (https://www.tennet.org/english/operational_management/export_data.aspx). It is based on the measured feed to the distribution grids and the balance of exchanges with other countries. Load and generation that is balanced within the distribution grids and that is not registered (for example, private PV-generation) is not visible. We use data starting with year 2004.

[26] ExplEnergy, understanding, configure and compare alternative energy value chains, available at: https://www.dnvgl.com/oilgas/contact/explenergy-2019-register-user.html

NOTES

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