University of Groningen, Faculty of Economics and Business

Master's thesis - MSc Supply Chain Management

Injecting hydrogen in the natural gas network: The extent to which hydrogen injection opportunities reduce the required size of a supplementary hydrogen storage

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ABSTRACT

Purpose: The purpose of this study is to investigate the role hydrogen injection could fulfil as a form of flexibility to reduce a supplementary required hydrogen buffer size. Otherwise, an excessive buffer capacity is required to capture the whole of excess power supply. Injecting hydrogen within natural gas networks can be seen as a relatively novel method to relieve excess power supply in the form of hydrogen.

Methodology: A simulation study was conducted on a local power distribution grid. Several experiments were considered for scenarios in which either 0%, 3%, 10%, or 20% of the hourly natural gas load can be injected. These experiments are sorted according to wind and PV capacity penetrations, hourly allowed export quantities, and the allowance to inject indirectly from the buffer or not. As a result, insight is obtained on the extent to which injection reduces the required supplementary buffer size by analyzing the absolute and relative flows of hydrogen towards either injection or the buffer.

Findings: The results show that for each hydrogen injection threshold, injection causes most relative buffer size reduction for power systems with increased penetrations of wind power. However, increasing the threshold to 10% or 20% causes a marginal decrease to required buffer size reduction for the 8.4 MW wind capacity experiment. Then, for the hourly allowed export experiments, small changes in buffer size reduction compared to the base case were observed for each injection threshold. Lastly, removing the option to inject indirectly raises the required buffer size most extensively in the 10% injection scenario.

Implications: Concerning the extent to which injection causes required buffer size reduction, raising the injection threshold towards 3% would be most applicable to power systems with additional wind penetration, although not too excessive. A stepwise increase towards 10% is recommended for most systems, except for those with large penetrations of PV capacity or those lacking indirect injection opportunities. Lastly, an increment towards 20% injection is recommended for systems with large penetrations of wind power or ones in which indirect injection from the buffer is not allowed.

Originality: This study contributes to the literature on the flexibility benefits of hydrogen injection in the natural gas network. It differentiates itself by considering the effect of changes in the system configuration for multiple injection scenarios.

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1. INTRODUCTION

Due to the scarcity of fossil fuel resources and ever-growing concerns about the consequences of climate change, the last decade saw a massive diffusion of variable and intermittent Renewable Energy Sources (RES). Specifically, the year 2020 experienced an unprecedented boom as the growth rate of RES jumped 45 percent (IEA, 2021). They are often sited in locations in which they have the most generation potential, e.g., the large penetrations of wind energy in the wind-rich North of Germany (Kroniger & Madener, 2014). Unfortunately, as this is not necessarily in accordance with the spread of energy demand, power often must travel long distances to reach its destination. This is problematic as current electricity infrastructures become overloaded (congested), and consequentially part of RES supply must be curtailed to avoid such overloading.

Fortunately, a possible solution to avoid curtailment is the utilization of excess power for hydrogen production using an electrolyzer, also called power-to-gas (P2G). Subsequently, the produced hydrogen can either be stockpiled or injected partially towards the natural-gas system. Furthermore, the technology contains the ability to store large amounts of power for longer periods of time, thereby suiting the seasonal supply and demand mismatches of RES power systems (Mazloomi & Gomes, 2012; Peng, 2013; Braun, 2008; Jørgensen & Ropenus, 2008). So far, research contributions on the flexibility benefits of hydrogen production are mainly focused on the use of hydrogen storage for later reconversion towards electricity (Hajimiragha, Canizares, Fowler, Geidl & Andersson, 2007), or the use of P2G to supply hydrogen powered vehicles (Maroufmashat, Fowler, Khavas, Elkamel, Roshandel & Hajimiragha, 2016), instead of flexibility benefits that could be achieved with injection.

Hydrogen created by surplus RES generation, - which is subsequentially injected into natural-gas pipelines through direct blending to form hydrogen-enriched natural gas (HENG) -, does possess great potential, however. It has been established for instance, that direct hydrogen blending of up to 10 and 12 percent of HENG for respectively Germany and The Netherlands does not cause major consequences to end-use equipment or the existing natural-gas infrastructure (Scamman & Newborough, 2016). On top of this, injection also brings about benefits in terms of RES curtailment reductions by providing additional flexibility (Qadrdan, Abeysekera, Chaudry, Wu, & Jenkins, 2015)

However, due to the maximum percentages of hydrogen that can be injected, DSOs cannot rely solely on this option to abolish curtailment issues and thereby integrate more RES in their networks. Therefore, an interesting option to consider is the combination of hydrogen storage and a fuel cell for reconversion towards electricity, and hydrogen injection. On top of that, as the addition of storage is characterized by decreasing marginal curtailment as storage capacity increases (Strbac et al., 2012), hydrogen injection could reduce the required hydrogen storage size significantly. The extent of this size reduction through the addition of injection as an extra flexibility option is however unclear. This is problematic for DSOs that wish to implement both hydrogen injection and storage to mitigate RES curtailment, while minimizing the required hydrogen buffer size.

Therefore, this research establishes the effectiveness of hydrogen injection in reducing the required hydrogen storage size to mitigate RES curtailment caused by congestion on the higher-voltage grid. This is investigated considering a handful of scenarios in which different thresholds on hourly hydrogen injection rates are investigated for a variation of unique experiments. These are generated through alterations in the RES generation capacities, the maximum allowed hourly export of power to the higher-voltage grid, or the option to inject hydrogen indirectly after it has already reached the hydrogen buffer. Hereby, clarity arises on the extent of hydrogen injection causing hydrogen buffer size reduction in different circumstances. This brings forward the following research question:

To what extent does the option to inject hydrogen into the natural gas network reduce the required size of supplementary hydrogen storage to avoid renewable energy curtailment?

So far, literature on injection’s flexibility advantage has established a curtailment reduction of 2.3% and 6.1% by including respectively the opportunity to inject without and with complementary storage (Mukherjee, Elsholkami, Walker, Fowler, Elkamel & Hajimiragha, 2015). On top of that, Qadrdan et al. (2015) established that blending natural gas flows with 5% hydrogen diminishes wind curtailment by 62 and 27 percent for respectively a low-demand and high-demand day. This work uniquely positions itself as it analyses different maximum injection rates, and measures injection’s flexibility benefit in terms of its effect on the reduction of a supplementary required hydrogen buffer size.

The organization of the paper is as follows. The upcoming section will clarify the theoretical framework of the study using existing literature, thereby reemphasizing the research objective and question. Afterwards, the research methodology is elaborated upon, followed by an overview of the most interesting results. Finally, a discussion is given on these results after which the research is concluded.

2. THEORETICAL BACKGROUND

So far, the literature on hydrogen injection has discovered flexibility benefits for a 5% maximum injection percentage of the natural gas load. Mukherjee et al. (2015) established a reduction of net power exports by 2.3% and 6.1% for respectively a system with solely injection, and one in which a supplementary buffer is added. Besides, Qadrdan et al. (2015) found a curtailment reduction of 62% and 27% for respectively a low-demand and high-demand day.

2.1 The challenge of integrating RES

Since the end of the earlier days in which electricity markets shifted from being owned and controlled by regulated monopolies towards deregulated markets, a significant number of challenges have come to the surface. One of these challenges is standing out in present research and is the one of congestion management (Pillay, Karthikeyan & Kothari, 2015). Congestion comes about when the required amount of power is unable to flow through the lines as certain limits have already been reached (Nandini, Suganya & Lakshmi, 2014; Tumuluru and Tsang, 2016). These limits are categorized as thermal limits, voltage limits and stability limits. Staying within these limits means the system is secure and is of vital importance, as failing to adhere to these limits can cause blackouts and thereby bring about severe economic consequences (Dutta & Singh, 2008).

Problematically, the large-scale deployment of RES has brought along an increasing amount of grid congestion, and subsequently a larger amount of generation from such resources that is curtailed (Gu & Xie, 2013). Specifically, RES is not necessarily sited in areas where the potential of satisfying local demand is large, thereby creating significant proportions of energy feedback to the main grid. To exemplify this, within the United States RES is located often based on what state offers the best incentives (Hitaj, 2013), while within Germany wind farms are generally located in the north of the country due to favorable wind conditions (Kunz, 2013).

2.2 Flexibility through storage

Luckily, a relatively novel method to tackle this geographical imbalance has introduced itself. Power systems have become more automated over the years thanks to the use of information management, communications, and automated monitoring technology, and have given rise to the so-called smart grid (Mohammadi, Noorollahi, Mohammadi-Ivatloo & Yousefi, 2017). This provides the possibility to interact with the net, store energy, and make further decisions on the energy flow. Hereby, an increased level of demand supply and efficient use of the existing energy infrastructure is accomplished, which reduces the dependency on infrastructure upgrades and facilitates the integration of distributed RES (Tuballa & Abundo, 2016). Besides, smart energy systems incorporate the complete mix of elements of the energy supply chain as production, transmission, storage, and distribution of energy towards end-users is considered. This is specifically done through the assistance of energy storage and energy conversion technologies e.g. battery storage, hydrogen storage, vehicle-to-grid, power-to-gas, and power-to-heat, as complements to the generation and load (Gondal, 2019).

Therefore, plenty of research has been conducted on both types of technologies. Specifically, the literature on storage requirements has either established required sizes with the objective of matching generation and demand or acquiring the lowest cost (Bertsch, Growitsch, Lorenczik, & Nagl, 2016; Bussar et al., 2016), or the most cost-effective choice between storage options (Palzar & Henning, 2014; Weitmeyer, Kleinhans, Vogt & Agert, 2015), both for a given set of system boundaries. However, the addition of storage to acquire flexibility benefits faces competition. Plants characterized by the option to generate flexibly such as biomass, or load shifting through demand response can have similar effects at lower cost (Budischak, Sewell, Thomson, Mach, Veron & Kempton, 2013).

Moreover, this is partially caused by the fact that different authors have confirmed decreasing marginal curtailment reductions to the addition of extra storage capacity (Strbac et al., 2012; Sioshansi, Denholm, Jenkin & Weiss, 2009; De Sisternes, Jenkins & Botterud, 2016; Bradbury, Pratson & Patiño-Echeverri, 2014). Specifically, the most significant benefits in terms of flexibility are observed for the first additions of capacity. This is brought about by the fact that eventually the addition of storage capacity would only capture the larger peaks over the period of generation. Some studies explicitly capture this within their results, as storage represents their main source of flexibility, thereby overstating its required quantity (Steinke, Wolfrum & Hoffman, 2013; Heide, Greiner, Von Bremen & Hoffman, 2011; Rodriguez, Becker, Andresen, Heide & Greiner, 2014).

2.3 Diversification to other end uses

One option that could be added is the use of excess generation in different energy sectors using one of the earlier mentioned power conversion technologies. This implies a coupling of different energy sectors, such as with the heating or hydrogen demand sectors. It should be noted that the use of excess power in the heating sector could only produce benefits if a low demand for electricity does not coincide with a simultaneous low demand for heating. Luckily, heating embodies a much larger share of the global primary energy consumption, representing 50% of it, compared to 20% for electricity (IEA, 2015). Although seasonal mismatches could occur as PV generation output and heating demand do not occur at the same time, the sector should still retain the capability to capture most of the electricity surplus. In line with this, Schaber (2014) established that thanks to power-to-heat’s functioning as a relief for excess power supply, total RES generation captures more economic value and thereby its price is reduced.

This reemphasizes the importance of technologies that facilitate an integration between the power and heating sector. A promising option in this regard is by power-to-gas (P2G). This technology has received ample attention thanks to its massive energy storage and absorption capabilities. Specifically, the technology enables the coupling of the electricity, mobility, and heating sector (Buttler & Spliethoff, 2018). In this regard, Scamman and Newborough (2016) examine the use of excess nuclear power for electrolyzers to satisfy demand for both mobility and natural gas. For the latter, 5% maximum hydrogen blending is allowed in the natural gas network. Likewise, Li, Gao and Ruan (2019) investigated the quantification and sensitivity of the investment decision and potential of P2G in increasing the RES utilization rate. They discovered that this is largely affected by the structure of the combination of wind and PV capacity, the electrolyzer conversion efficiency, and the price of hydrogen.

So far, literature on using P2G for the integration of the power and heating sector has mostly considered the conversion of excess power to methane for subsequent injection into the natural gas network (Vandewalle, Bruninx & D’haeseleer, 2015; Mesfun et al.; Sveinbjörnsson; Estermann, Newborough & Sterner, 2016; Simonis & Newborough, 2017). This research on the other hand, brings about novel evidence on the way hydrogen injection could be integrated to reduce RES curtailment, of which only several studied have made a first attempt in considering this benefit (Qadrdan et al., 2015; Qadrdan, Ameli, Strbac & Jenkins, 2017; Mukherjee et al., 2015).

2.4 The role of hydrogen injection

The practicability of using P2G to inject large concentrations of hydrogen depends on a paradigm shift in which a trade-off between natural gas and hydrogen takes place, thereby partly ruling out the viability of such a scenario. Luckily, in current natural gas supply chains hydrogen concentrations of up to 20% could be realized as current compression stations would still be able to handle such quantities (Gondal, 2016). Similarly, opting for this threshold would not cause a serious deleterious effect on modern gas-based appliances (Hodges, Geary, Graham, Hooker & Goff, 2015).

Furthermore, a handful of pieces of research solely occupied with pure hydrogen blending within natural gas networks have been conducted. On this subject, Mukherjee et al. (2015) established that net power exports can be diminished by 2.3% and 6.1% for respectively a case where only hydrogen injection is possible, and one in which a hydrogen buffer is added as supplement. In their work, hydrogen concentrations within the natural gas network of up till 5% are allowed. Similarly, Qadrdan et al. (2015) opted for two scenarios differentiated by a 5% and an unlimited injection threshold. They found that the former brings forward the possibility to shrink wind curtailment by 62% on a day where electricity demand is low, and 27% on one where electricity demand is high. Not surprisingly, when no barrier was posed to gas network hydrogen concentrations, wind curtailment abolished completely.

A complete removal of this barrier is however unimaginable, as 20% is currently considered the upper bound on injection (Gondal, 2016; Hodges et al., 2015). The literature considering hydrogen injection has hence opted for a 5% threshold on natural gas and hydrogen admixtures. What's missing though, is a consideration of hydrogen injection's flexibility advantage for larger percentages up till 20%.

2.5 Flexible resources

Lastly, the combination of injection as an extra source of flexibility to reduce a hydrogen inventory buffer, is in line with the theory on Buffer Flexibility (Hopp, 2008). Hereby, hydrogen injection serves as a form of flexible capacity which reduces the inventory buffer required within a supply chain or production system. Thus, they serve as a source against the combination of upstream (RES generation), and downstream (electrical load) variability (Tachizawa & Thomsen, 2007).

2.6 Contribution to the literature

To summarize, it is established that the addition of hydrogen storage comes with a decreasing marginal reduction to curtailment for each increase in capacity (Strbac et al., 2012; Sioshansi et al., 2009; De Sisternes et al., 2016; Bradbury et al., 2014). Hereby, it seems imperative that excessive quantities of storage capacity would be required to capture the whole of excess RES supply. Hence, it seems logical to incorporate a supplementary option for obtaining flexibility.

The coupling of the electricity and natural gas networks using P2G technology could be one such option. Specifically, it offers potential in capturing large portions of excess RES generation (IEA, 2015). Nonetheless, the use of P2G to produce hydrogen for subsequent injection into the natural gas network has received relatively little attention. Specifically, only a handful of studies have addressed its benefits in terms of curtailment reduction, while adhering to a maximum injection rate of 5% (Simonis & Newborough, 2017; Mukherjee et al., 2015; Qadrdan et al., 2015). This threshold could be increased to 20% however, as within this bound gas compression stations would still be able to process the hydrogen-enriched natural gas without major infrastructural alterations (Gondal, 2016).

Hence, this research is the first in examining the causal effect of different possible hydrogen injection scenarios in reducing a supplementary required hydrogen buffer size to mitigate RES curtailment. Hereby, a novel insight is obtained on the most efficient combination of hydrogen injection and storage possibilities to capture a certain degree of excess power generation.

3. METHODOLOGY

3.1 Problem description

The main problem addressed in this paper is concerned with the extent to which the required size of hydrogen storage to capture excess RES supply, is reduced if part of this excess is injected as hydrogen within the natural gas network. This is investigated considering a regional distribution grid in which excess power generation is prohibited (or largely prohibited) from being exported to the higher-voltage grid due to the issue of congestion.

To accomplish this, a reconstruction of this grid is modelled which combines electricity generation from wind and PV, with a local electricity load as its eventual destination. In line with the problem, an electrolyzer and fuel cell are included to convert respectively excess power or hydrogen. Moreover, the model incorporates the natural gas network for injection purposes, and a hydrogen buffer for storage purposes. On top of this, the natural gas load is modelled to determine the hourly permitted quantity of hydrogen that could be injected. Lastly, the higher-voltage grid is incorporated for several experiments in which small quantities of export are allowed. Figure 3.1 furthermore schematizes the modelled system.

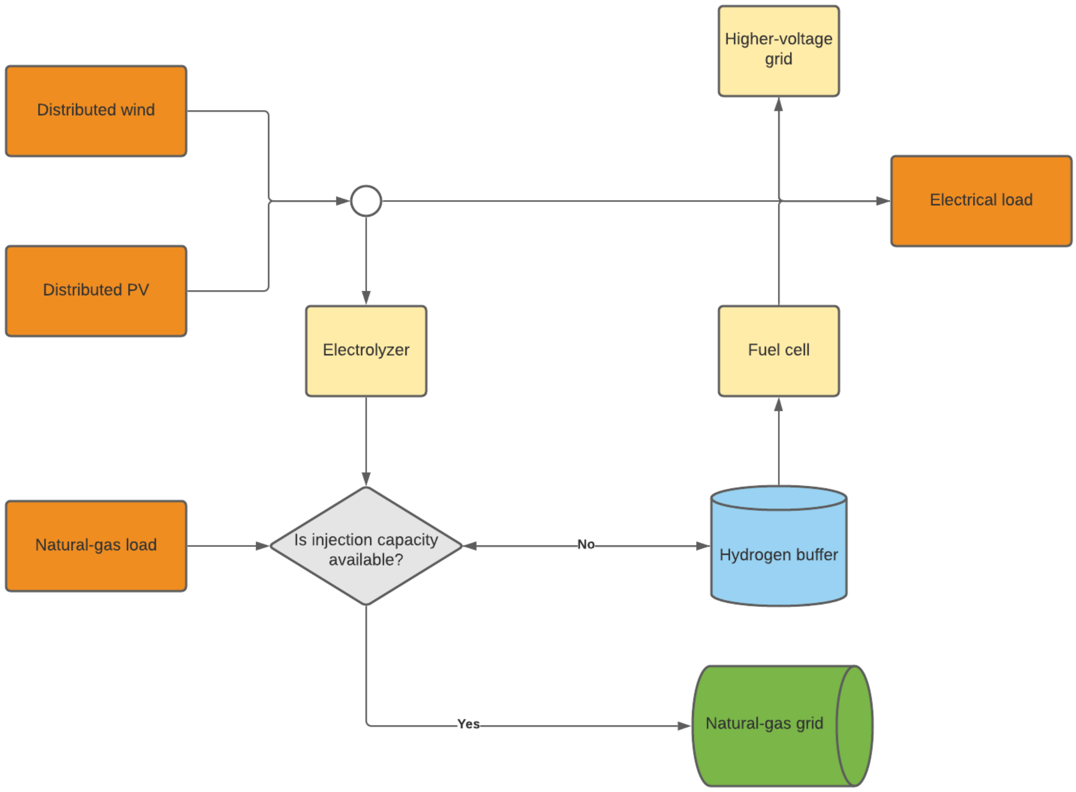

Figure 3.1: conceptual configuration of the system under investigation

3.2 System decisions

Furthermore, the flows between the different components of the depicted system are determined according to a sequence of decisions. Figure 3.2 depicts this complete sequence within a flowchart. The most important observation from this, comes from the two main decision pathways that follow from the first decision that ought to be taken. These are, the set of decisions taken if the combination of wind and PV generation is large enough to suffice the electrical load, and the set of decisions taken if the opposite is true.

Hence, if the total of wind and PV generation is large enough to suffice the load, the pathway is as follows:

1. A decision is made if a certain quantity (kWh) of wind and PV generation is allowed to be exported towards the higher-voltage grid.
    a. If this is the case, this will occur before going to the next decision.
    b. If this is not the case, the decision process moves forward to the next decision.
2. The remaining excess is now converted to hydrogen by the electrolyzer. Then, it is checked if a certain amount (kg hydrogen) of injection within the natural gas network is permitted. This is done by using the natural gas load of that specific hour.
    a. If this is the case, the permitted quantity of hydrogen will be injected within the natural gas network, and any remaining excess supply is sent to the hydrogen buffer.
    b. If this is not the case, the whole of excess supply is sent to the buffer.
3. Now, if the hourly injection capacity is fulfilled by the whole of created hydrogen in the same hour, this implies that within this hour injection can still occur. Hence, a decision is made if this remaining number can be fulfilled by injecting hydrogen indirectly from the buffer. This implies that enough hydrogen should reside within the buffer for this to occur.
    a. If this is the case, hydrogen is injected indirectly from the buffer before moving to the next decision.
    b. If this is not the case, the decision process moves forward to the next decision.
4. Finally, the decision process asserts if the complete year of analysis is finalized.
    a. If this is the case, the decision process ends.
    b. If this is not the case, the decision process moves to the next hour.

Moreover, if the total of wind and PV generation is insufficiently large to suffice the load, the pathway is as follows:

1. A decision is made if the hourly maximum injection capacity can be fulfilled by injecting hydrogen indirectly from the buffer. This implies that enough hydrogen should reside within the buffer for this to occur
    a. If this is the case, hydrogen is injected indirectly from the buffer before moving to the next decision.
    b. If this is not the case, the decision process moves forward to the next decision
2. Now, it is decided if the remaining electrical load can be fulfilled by reconverting hydrogen to electricity from the buffer. This implies that enough hydrogen needs to reside within the buffer for this to occur.
    a. If this is the case, hydrogen is reconverted towards electricity to fulfil the remaining electricity load.
    b. If this is not the case, the remaining electrical load is satisfied by importing the required quantity of electricity from the higher-voltage grid.
3. Finally, the decision process asserts if the complete year of analysis is finalized.
    a. If this is the case, the decision process ends.
    b. If this is not the case, the decision process moves to the next hour.

3.2.1 Rationale behind the decisions

The complete sequence of events does contain a couple of assumptions, however. Specifically, the electrolyzer and fuel cell are set to process an amount of respectively power to hydrogen or hydrogen to power depending on the state of the system. This contrasts power systems in which their production capacity is set at a constant amount. However, the currently used manner is considered as it allows injection’s flexibility advantage in buffer size reduction to be analyzed to its full potential.

Moreover, it was opted for to prioritize indirect injection from the buffer before hydrogen reconversion to satisfy the remaining electrical load for those hours of excess load. In this case, the same type of reasoning holds. Ultimately, this raises the extent to which injection causes required buffer size reduction due to those occasions where the quantity of hydrogen residing in the buffer is unsatisfactory to allow both inject and reconvertion.to perform both indirect injection and reconversion.

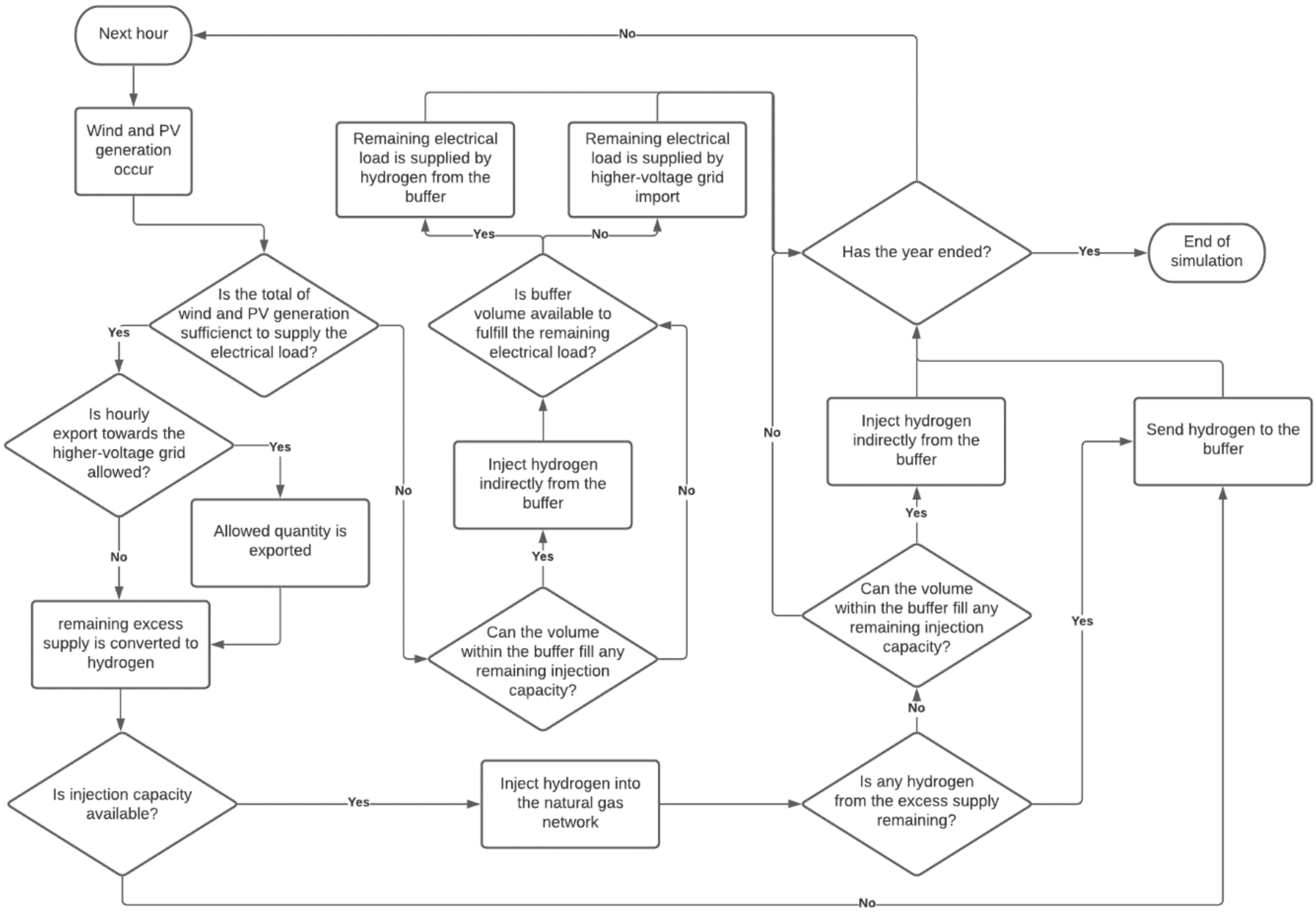

Figure 3.2: Flowchart of the system's decision process

3.3 The simulation model

To address the main problem of this research, a simulation model is built. The combination of parameters used, and output variables obtained from this are revealed in figure 3.3. A distinction is made between fixed and experimental parameters. This originates from the fact that the experimental parameters are altered for the purpose of creating several unique experiments. The most crucial of these is the maximum hourly injection rate of hydrogen within the natural gas network, as the remaining experimental parameters are varied for each maximum injection rate. This effectively generates a set of similar experiments for each possible future injection scenario. Hereby, the extent to which injection causes required buffer size reduction can be compared between these scenarios. Furthermore, the remaining experimental parameters are the generation capacities of wind and PV, the maximum hourly allowed quantity of export towards the higher-voltage grid, and the ability to inject indirectly from the buffer. By their usage, the cause-effect relationship between hydrogen injection and the corresponding decrease in the required hydrogen buffer size is analyzed for numerous unique power system configurations. This allows to obtain implications on the most suitable injection threshold for such configurations.

3.3.1 Experimental parameters explanation

Different upper bounds are placed on hourly allowed hydrogen injection into the natural gas network. The natural gas load is correspondingly used to determine these, by allowing a percentage of its hourly value to be fulfilled with hydrogen. These opted for percentages are grounded on the technical capabilities of diverse parts of the natural gas transmission network in transporting different hydrogen methane admixtures.

Specifically, hydrogen injection scenarios of 0%, 3%, 10%, and 20% are examined within the model. The first step in which 3% is maximally injected, allows current Dutch household gas appliances to retain proper functioning (Rendo, 2021). Therefore, this can be regarded as an undemanding application of injection. Moreover, the second step of 10% maximum injection can be regarded as the turning point at which gas volume meters start to reveal incorrect information. (Altfeld & Pinchbeck, 2013). Then, the upper value of injection considered in this work is one in which 20% of the natural gas load can be fulfilled with hydrogen. Below this value, gas compression stations would still be able to function properly, thereby causing no problems for distributing the admixture through the gas transmission network (Gondal, 2016).

Moreover, the RES capacity level experimental parameter is constructed by changing either the wind or PV capacity in steps of 4.2MW. Ultimately, this is done for two steps of wind, and two steps of PV. As the base case corresponds to 4.2MW wind capacity, and 4.2MW PV capacity, this implies a total of 5 unique configurations of wind and solar capacities.

Then, the maximum export quantity [kWh] experimental parameter is set in the bound of 0 till 500 kWh export. Although the objective of this paper depicts a system where export of excess supply is not permitted, small amounts of hourly export could still cause interesting results on the behavior of injection in required buffer size reduction. Specifically, as export functions as the first destination of excess RES supply, it essentially fulfils the role of a primary source of flexibility. For the base case, a value of 0 is opted for, and this value is increased twice by steps of 250 kWh. These values are opted for, as the combined wind and solar capacity of the base case system is approximately 375 kW. Hence, the first step would therefore be positioned on the lower end of this, while the second step would be on the higher end.

Finally, the last experimental parameter corresponds to a change in the permittance to inject indirectly from the buffer. As a base value the option is allowed, while it is disallowed otherwise. Its inclusion is done to assess whether the disallowance of indirect injection would severely affect total injection causing required hydrogen buffer size reduction. Hereby, the option to integrate injection is assessed for systems in which the locations of hydrogen creation, injection, and storage are decoupled.

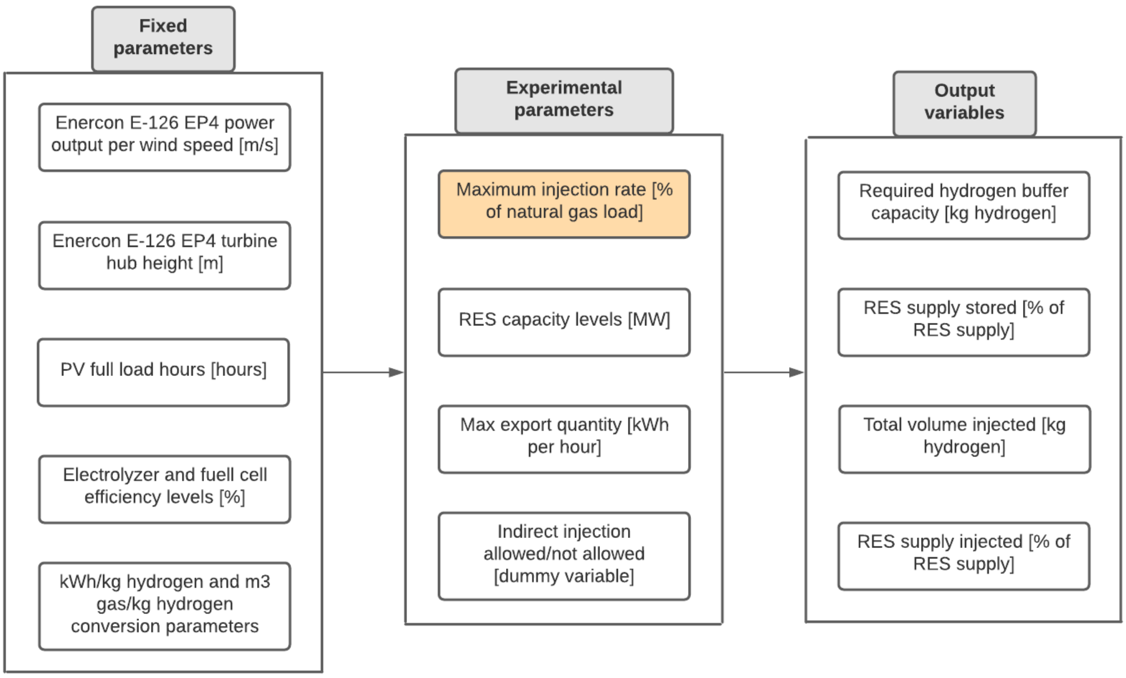

Figure 3.3: Overview of the simulation parameters and output variables

3.3.2 Output variables explanation

As observed from the figure, four output variables are retrieved to answer the research question. These are:

- The required hydrogen buffer size, measured in kilograms of hydrogen. This implies the maximum amount of simultaneous hydrogen within the buffer over the whole of the analyzed time period.
- The percentage of RES supply that reaches the buffer. Even if the corresponding hydrogen is subsequently injected indirectly from the buffer, this portion is still counted for the calculation of the percentage.
- The total volume of hydrogen that is injected, measured in kilograms of hydrogen. This value also includes the total volume that is injected indirectly from the buffer.
- The percentage of RES supply that is injected.

In this way, the first two output variables provide an indication of the behaviour of hydrogen flows towards the buffer. Similarly, the last two output variables do this for hydrogen that is injected. As the combined generation of wind and PV may differ drastically per experiment, e.g., through those experiments in which the generation capacities of wind and solar (RES) are altered, it is imperative to review the hydrogen flows relatively to their respective RES capacities. Therefore, the flows towards wither the buffer or injection are measured on an absolute and relative basis.

3.3.3 Fixed parameters explanation

Ultimately, the use of the first three fixed parameters is explained hereafter in the model inputs section. Moreover, the electrolyzer and fuel cell efficiency levels are set at 70%, and the kWh/kg hydrogen and m3 gas/kg hydrogen parameters are set at respectively 40 and 11.126. The kWh/kg hydrogen conversion parameter is used to convert a certain amount of kWh excess electricity supply to kg hydrogen by the electrolyzer, or to convert a certain amount of kg hydrogen within the buffer to kWh electricity to supply a portion of the electricity load by the fuel cell. Besides, the m3 gas/kg hydrogen conversion parameter is used to calculate the maximum allowed hourly injection quantity [kg hydrogen] from the hourly natural gas load [m3/h natural gas].

3.4 Model inputs

For a comprehensive understanding of the way the simulation model is constructed, an explanation of the input variable calculations is described in this section. As discussed, these are: distributed wind generation, distributed PV generation, the natural-gas load, and the electrical load.

3.4.1 Wind generation

For the calculation of the hourly kWh output level, the simulation model opts for the use of the Enercon E-126 EP4 wind turbine. This is a novel turbine and has been used in several onshore wind projects within The Netherlands within the near past. Correspondingly, the wind generation output calculation combines the power curve of this turbine with the hourly average wind speed at turbine height. A depiction of the power curve is found in Figure 3.4, which displays the power output (kWh) for every wind speed figure (m/s). From this, one observes a cut-in wind speed of 3 m/s, a rated wind speed of 13.5 m/s (the minimal wind speed at which maximal power output is obtained), and a cut-out wind speed of 34 m/s.

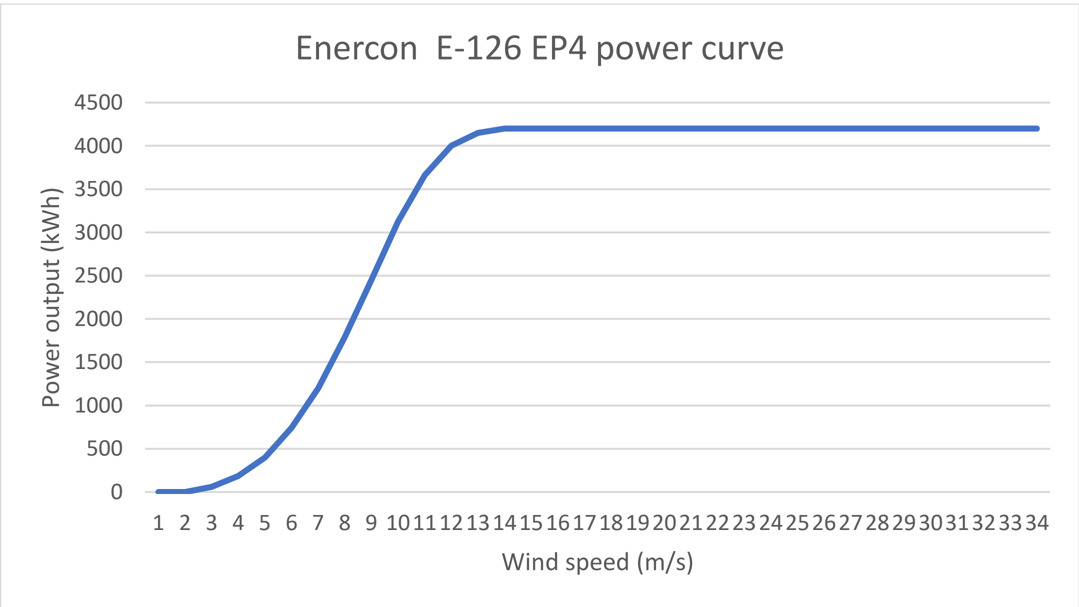

Figure 3.4: power curve of the selected wind turbine

Furthermore, hourly wind speed at turbine height (m/s) is obtained by combining the hourly average 2020 wind speed data of the KNMI Marknesse weather station (KNMI, 2021) with the logarithmic wind profile formula. This data was opted for as it is measured closest to the city of investigation. As wind speeds generally decline due to surface roughness and obstacles, larger altitudes cause wind speeds to be larger. The logarithmic wind profile formula is as follows:

$$v_2 = v_1 \frac{\ln\left(\frac{h_2}{z_0}\right)}{\ln\left(\frac{h_1}{z_0}\right)}$$

Hereby, a reasonable conversion of wind speeds towards different heights for places characterized by flat terrain such as The Netherlands can be obtained. Within this formula, v is the wind speed for both heights, h is the height in meters, and z is a corrective measure for the roughness surface of the ground named the roughness length. For grasslands, the typical range of the roughness length lies between 0.01 and 0.05, hence 0.03 is opted for in this research. Eventually, the formula is used to converse wind speeds from 10 meters of height (the height at which the KNMI Marknesse wind speeds were measured), towards 99 meters of height, which corresponds to the turbine hub height of the Enercon E-126 EP4.

Ultimately, the wind generation output (kWh) is retrieved for every hour of the simulation period. As the Enercon E-126 EP4 operates at 4.2MW capacity per turbine, the wind generation output is generated by adjusting the selected amount of wind turbines within the simulation model. Hence, wind generation capacity is adjustable in steps of 4.2MW. Figure 3.5 depicts the wind generation output for a single turbine over the analyzed time period.

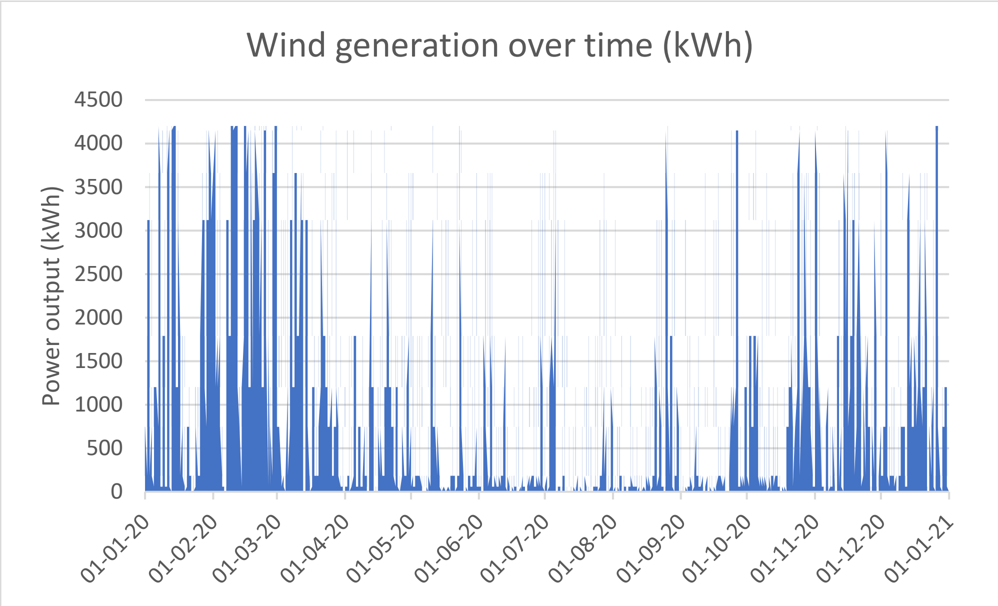

Figure 3.5: Wind generation output of a single 4.2MW Enercon E-126 EP4 turbine

3.4.2 PV generation

Then, for the calculation of the hourly kWh PV output level, a calculation is made which multiplies relative hourly fractions of the total yearly solar radiation (J/m2) with a specified number of full load hours and the opted for solar capacity.

Again, the KNMI Marknesse weather station data is consulted to obtain data on the solar radiation (J/m2) for the year 2020. For each hour, the relative fraction of the total of solar radiation over the whole year is calculated. This is hence a fraction of a yearly solar radiation of 404,126 J/m2. Furthermore, each hourly fraction is multiplied by the total yearly number of PV full load hours to obtain the solar output per MW PV capacity for each specific hour. The amount of full load hours for solar generally lies approcimately between 900 and 1000 hours (Rendo, 2021), hence 950 hours is opted for in this study. Ultimately, the calculated figure is multiplied with the selected MW PV capacity, which is an input parameter within the simulation model itself, to retrieve the PV generation output (kWh) for every hour of the selected time period.

Figure 3.6 illustrates the distribution of the relative hourly shares of solar radiation for every hour of the simulation. In accordance with the differences in seasonal climate, it is observed how the summer months encounter larger relative shares of radiation. Correspondingly, more solar generation output is produced in these months, and less in winter.

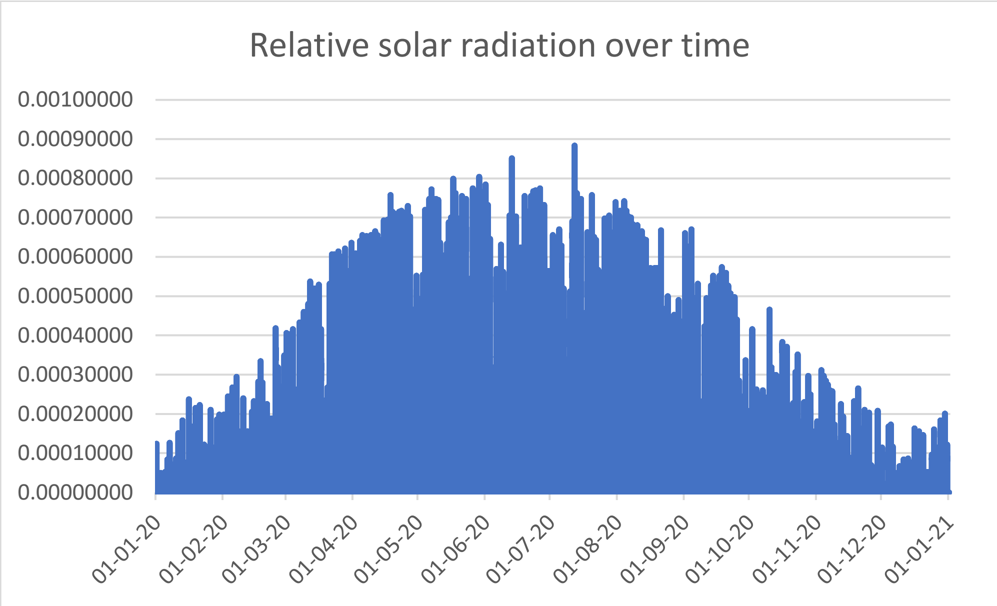

Figure 3.6: Distribution of solar radiation over the year 2020

3.4.3 Electricity load

In addition to hourly generation output levels, the model also incorporates hourly electricity load as input to the model. This is done by multiplying the total yearly electricity load of the city under investigation, by each hourly fraction of this total load.

For the calculation of the total electricity load, the standard annual 2020 electricity consumption of the 8,664 households under investigation (Rendo, 2021) is summed to receive a total of 28,170 MWh. Then, the E1C demand fraction profile of electricity (NEDU, 2021) for every hour of the same year is used for the eventual hourly electricity load calculations. Figure 3.7 displays the distribution of this demand. As expected, a large discrepancy of different demand levels is observed for each day of the year, as electricity load is known to vary largely on a given day. Besides, relative seasonal differences are also observed, and play their respective part in the total variation of electricity load over the examined time period.

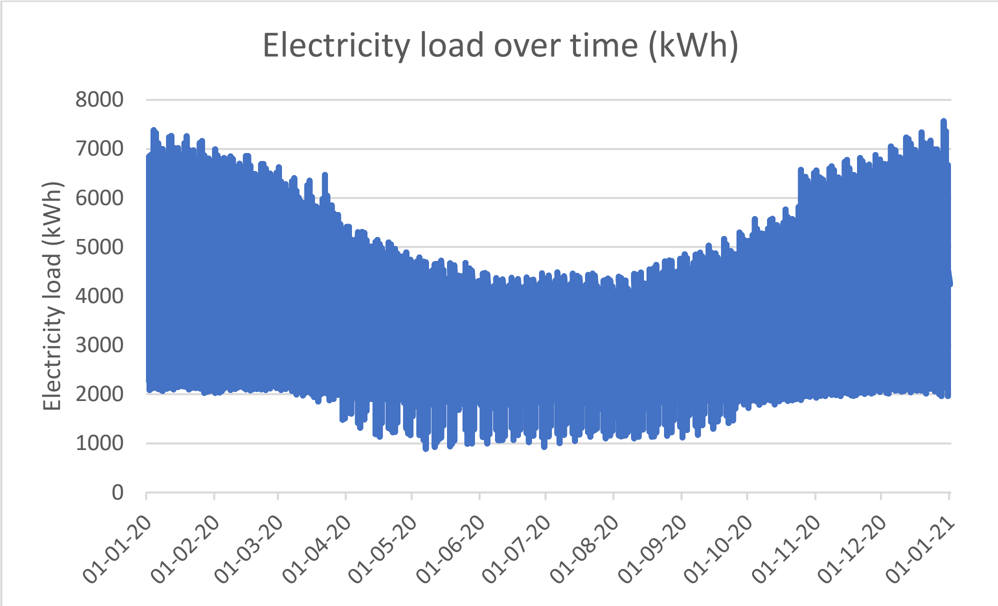

Figure 3.7: Distribution of the electricity load over the year 2020

3.4.4 Natural gas load

Finally, the natural-gas load is opted for as an input to the model to determine the hourly maximum injection capacity. As explained, this number is determined as a fraction of the natural gas load itself, and this fraction can be interpreted as a threshold to the amount of hydrogen that is allowed to be injected on an hourly basis. Moreover, the hourly load profiles were obtained from Rendo (2021), and are measured in m3/h. To perform calculations between the unit for electricity (kWh) and natural-gas (m3/h), both are converted to kilograms (kg) hydrogen through their respective conversion parameters.

Figure 3.8 presents the distribution of the natural-gas load over the investigated time period. Again, variation in the hourly levels is observed on both a daily and seasonal basis. These levels subsequently affect the maximum injection capacity, and hence injection's effectiveness in reducing the required hydrogen buffer size. As most natural-gas load occurs during the colder half of the year, it seems evident that injection will play a key role in required buffer size reduction during this period.

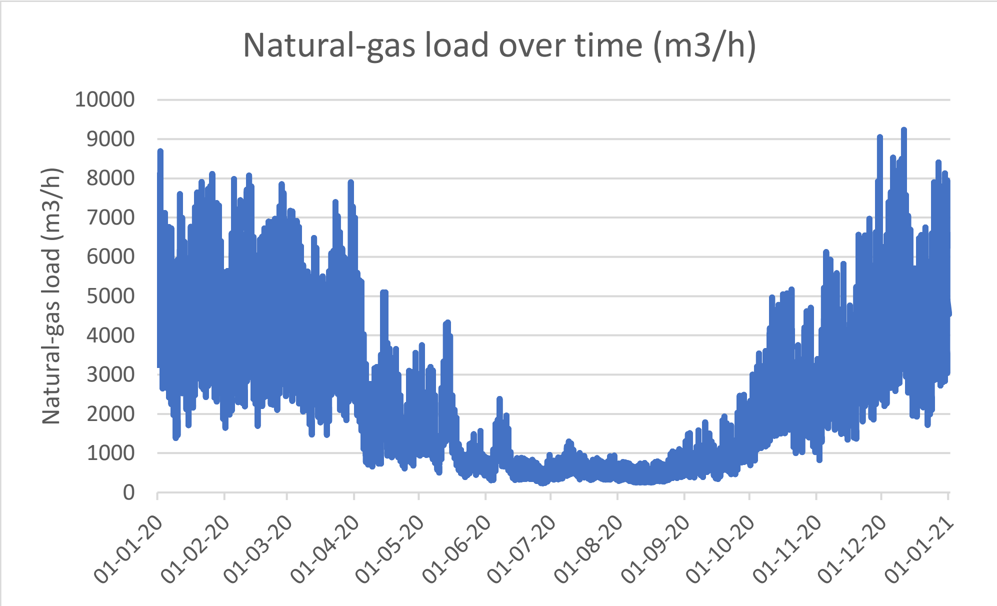

Figure 3.8: Distribution of the natural-gas load over the year 2020

3.5 Experimental design

To achieve a clear picture of the way hydrogen injection opportunities relieve the required hydrogen buffer size, two kinds of analyses will be conducted with each containing several unique scenarios. In the first one, the complete set of output variables are examined for different unique experiments. Hereby, it becomes apparent how and to what extent different injection scenarios cause required hydrogen buffer size reduction for systems characterized by the differing experimental parameters. Then, the second analysis performs a sensitivity analysis on the required hydrogen buffer size reduction when increasing the maximum injection rate for the same experimental parameter changes as before. In this way, the focus is moved towards the main output variable, namely the required hydrogen buffer size. Consequently, the insights from the first analysis are used to assist in explaining the observed sensitivities, and to compare them. Ultimately, this paves the way to provide sound recommendations for the selection of the most suitable injection thresholds in different system configurations.

3.5.1 First analysis: output variables analysis

First, the provided set of output variables will be examined for several different scenario groups. Each group is uniquely separated by the fact that one experimental parameter varies between a given bound that is specified in the table itself. Moreover, the different scenario groups and their composition are depicted in Table 3.1. Within the first column, those experiments in which only the maximum injection rate varies while maintaining the base case value of the remaining experimental parameters, is depicted. This implies that each injection rate effectively receives its own specific base case experiment. Moreover, the remaining experiments are developed by varying the experimental parameter of the specific scenario group for each maximum injection percentage. Eventually, one arrives at a total of 32 experiments.

Experiment number:	1-4	5-20	21-28	29-32
Scenario group name	**Injection capacity scenarios**	**RES generation scenarios**	**Max export scenarios**	**Indirect injection scenarios**
Injection rate [% of hourly natural gas load]	0% - 20%	0% - 20%	0% - 20%	0% - 20%
Wind generation capacity [MW]	4.2 MW	4.2 MW - 12.6 MW	4.2 MW	4.2 MW
PV generation capacity [MW]	4.2 MW	4.2 MW - 12.6 MW	4.2 MW	4.2 MW
Maximum hourly export quantity [kWh]	0 kWh	0 kWh	250 kWh & 500 kWh	0 kWh
Indirect injection allowed [Yes/No]	Yes	Yes	Yes	No

Table 3.1: Summary of the first analysis

3.5.1 Second analysis: Sensitivity analysis

After insight is obtained the extent to which injection causes required buffer size reduction within each system configuration, a sensitivity analysis is performed that captures the relative change in the required hydrogen buffer size for the same combination of experimental parameters as in analysis 1. Hereby, the possibility arises to zoom in on the output variable that is directly related to the research aim. Again, keeping future injection scenarios in mind, the sensitivities per experiment are analyzed for each stepwise raise in the maximum injection rate. At the end, the possibility arises to suggest the most effective maximum hydrogen injection threshold for the different system configurations.

3.5 Summary of assumptions

To simulate a real-life local electricity grid, numerous assumptions are made due to the non-existence of the actual system under investigation. Although some of these have already been discussed, the complete list of assumptions is as follows:

1. The maximum hourly injection capacity is determined as a fraction of the natural gas load of that specific hour.
2. A maximum upper bound of excess supply may be allowed to be exported to the higher-voltage grid per hour.
3. No threshold is placed on the maximum size the hydrogen buffer can maintain.
4. The Enercon E-126 EP4 wind turbine is used to calculate hourly wind generation output.
5. A hub height of 99 meters is considered in calculating wind speeds.
6. The logarithmic wind profile formula is used for converting wind speeds towards this height.
7. 950 PV full load hours are divided over the total of solar radiation (J/cm2) to calculate the hourly PV generation output.
8. An efficiency level of 70% for the electrolyzer and fuel cell is opted for.
9. A kWh/kg parameter of 40 for converting between kWh electricity and kg hydrogen is opted for.
10. A m3/kg parameter of 11.126 for converting between m3 natural-gas and kg hydrogen is opted for.

Ultimately, the first two assumptions could cause the produced output to be biased. Within a real-life local distribution grid for example, it would be unlikely that a constant upper bound is placed on hourly export, as export quantities would normally depend on the capacity of the higher-voltage power lines at each moment of time. Similarly, the assumption of a maximum injection percentage over the hourly local natural gas load is also not fully reasonable. It may for instance still be the case that hydrogen could be injected, even though the natural gas load is already satisfied. The fact that these assumptions still had to be considered, stems from the time-consuming efforts in modelling this accordingly.

4. RESULTS

The current section will elaborate on the output of the set of different experiments. In this fashion, the opportunity arises to observe how and the extent to which hydrogen injection causes required buffer size reduction. As explained, the “Required hydrogen buffer size [kg]” is the main output variable as it directly relates to the objective of this work. Complementary to this, the “RES supply stored [%]”, “Total volume injected [kg]”, and “RES supply injected [%]” output variables function as means of acquiring the necessary insight on the dynamics behind the altering causal effect for different parameter settings. Hereby, it is deduced if different local power system configurations have their respective influence on the causal relationship itself.

Furthermore, this section contains two different types of analyses. In the first it becomes clear in what manner each experiment group affects injection’s cause in a lower buffer requirement. This is moreover executed with the assistance of graphs and charts that provide clarity on the observed output. Then, a sensitivity analysis is performed on the relative change in the required hydrogen buffer size. The same parameter changes are made here as in this first analysis, though the focus is on the relative change for each increment in the maximum allowed injection percentage. Hereby, clarity is received on the ability of injection to reduce the buffer size between the different system configurations.

4.1 Analysis 1: Experiment groups analysis

This section depicts the most essential output changes between each experiment group and the base case. As noticed in the methodology section, three different scenario groups will each receive their respective analysis. These constitute: the RES generation scenarios, the maximum allowed hourly export scenarios, and the indirect injection scenarios. This is furthermore accompanied by graphs and charts that assist in understanding these. For a complete overview of every experiment’s results in this analysis, one is referred to Appendix B.

4.1.1 RES generation scenarios

Most important insights from this section:

- The required hydrogen buffer reaches a significantly larger volume when adding wind capacity compared to PV capacity. Specifically, wind power generation is characterized by short-duration peaks, thereby causing a larger raise in required buffer size for each 4.2 MW stepwise increase in its capacity. This effect drops when larger maximum injection percentages are maintained.
- Whenever the percentage of maximum injection is enlarged, the decrease in required hydrogen buffer size becomes more substantial for systems containing relatively more wind capacity

This section analyzes the extent to which the inclusion of hydrogen injection causes a reduction in the required hydrogen buffer size, and why these alterations occur. To manage this, certain experiments are conducted in which either the wind or PV capacity is expanded with 4.2 MW or 8.2 MW. Tables 4.1 and 4.2 depict the output of each conducted experiment within this group for the 3% and 20% injection scenario. In addition, it is imperative to examine the fraction of RES supply that reaches the buffer (“RES supply stored [kg]”) alongside the required hydrogen buffer size for the specified experiments. Hereby, a clear picture of the role that wind and PV generation patterns perform regarding the research goal is retrieved. In this regard, the 3% and 20% injection scenario will each receive a graph portraying exactly these output variables for the given rise in the wind and PV capacity parameters. On top of that, the fraction of RES supply that is injected (“RES supply injected [kg]”) is compared between the experiment where 8.4MW wind capacity, and 8.4MW PV capacity is added for each injection scenario. These same capacity experiments then each receive their own graph that displays the kg amount of hydrogen injected over time.

Experiment	*Required hydrogen buffer capacity [kg]*	*RES supply stored*	*Total volume injected [kg]*	*RES supply injected*
Base case	*1,149*	*16.81%*	*13,180*	*5.58%*
8.4 MW wind & 4.2 MW PV	*7,597*	*33.59%*	*30,714*	*7.63%*
12.6 MW wind & 4.2 MW PV	*32,821*	*46.24%*	*43,358*	*7.62%*
4.2 MW wind & 8.4 MW PV	*2,413*	*29.19%*	*17,366*	*5.67%*
4.2 MW wind & 12.6 MW PV	*4,060*	*38.94%*	*20,776*	*5.53%*

Table 4.1: Results of the RES generation experiments for the future 3% injection scenario

Experiment	*Required hydrogen buffer capacity [kg]*	*RES supply stored*	*Total volume injected [kg]*	*RES supply injected*
Base case	*503*	*7.60%*	*36,535*	*15.46%*
8.4 MW wind & 4.2 MW PV	*3,789*	*17.20%*	*111,041*	*27.57%*
12.6 MW wind & 4.2 MW PV	*8,411*	*28.11%*	*187,750*	*32.99%*
4.2 MW wind & 8.4 MW PV	*1,046*	*18.15%*	*58,259*	*19.03%*
4.2 MW wind & 12.6 MW PV	*2,252*	*27.50%*	*75,592*	*20.11%*

Table 4.2: Results of the RES generation experiments for the future 20% injection scenario

First, the lower the maximum hydrogen injection percentage, the larger the required hydrogen buffer size grows if wind capacity is added compared to PV capacity. Figures 4.1-4.4 provide both the change in the percentage of RES supply that reaches the buffer (RES supply stored [%]), and the actual change in the required hydrogen buffer size for the 3% and 20% maximum injection threshold. The remarkable observation here, comes from the fact that when maintaining a 3% maximum injection percentage, the RES supply stored output variable does not rise proportionally to the absolute value of the buffer. Specifically, in the 12.6 MW wind capacity experiment, the RES supply stored output variable reaches 46.24% while the required buffer size jumps all the way to 32,821 kg storage. Contrarily, in the 12.6 MW PV capacity experiment, theese numbers correspond to 38.94% and 4,060 kg.

At first glance, it seems peculiar that the difference in the quantity of RES that reaches the buffer ("RES supply stored") between the wind and PV experiments is not as large as the difference in required hydrogen buffer size for the 3% injection scenario. Nevertheless, as wind generation is renowned for its generation patterns in which occasional peaks occur, the required buffer size can increase to a much larger extent than the RES supply stored output variable for an extensive peak supply moment. As the injection threshold rises however, injection enables to capture these peaks, and thereby limits the buffer size from rising too extensively. For a clear observation of this phenomenon, one is referred to Appendix C and D. Appendix C reveals a depiction of the kg buffer size over time for the base case, the 12.6 MW wind experiment, and the 12.6 MW PV experiment, while maintaining a maximum injection upper bound of 3%. Moreover, Appendix D reveals similar graphs, though the maximum injection rate is raised to 20%.

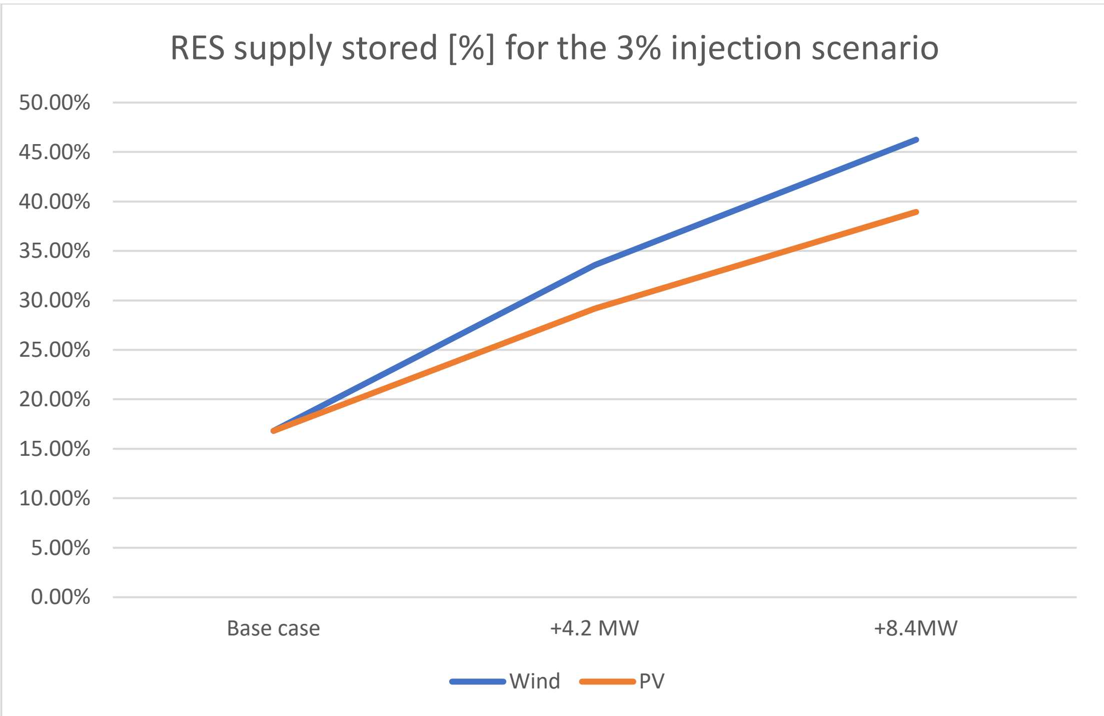

Figure 4.1: The fraction of RES supply that reaches the buffer for the 3% injection scenario

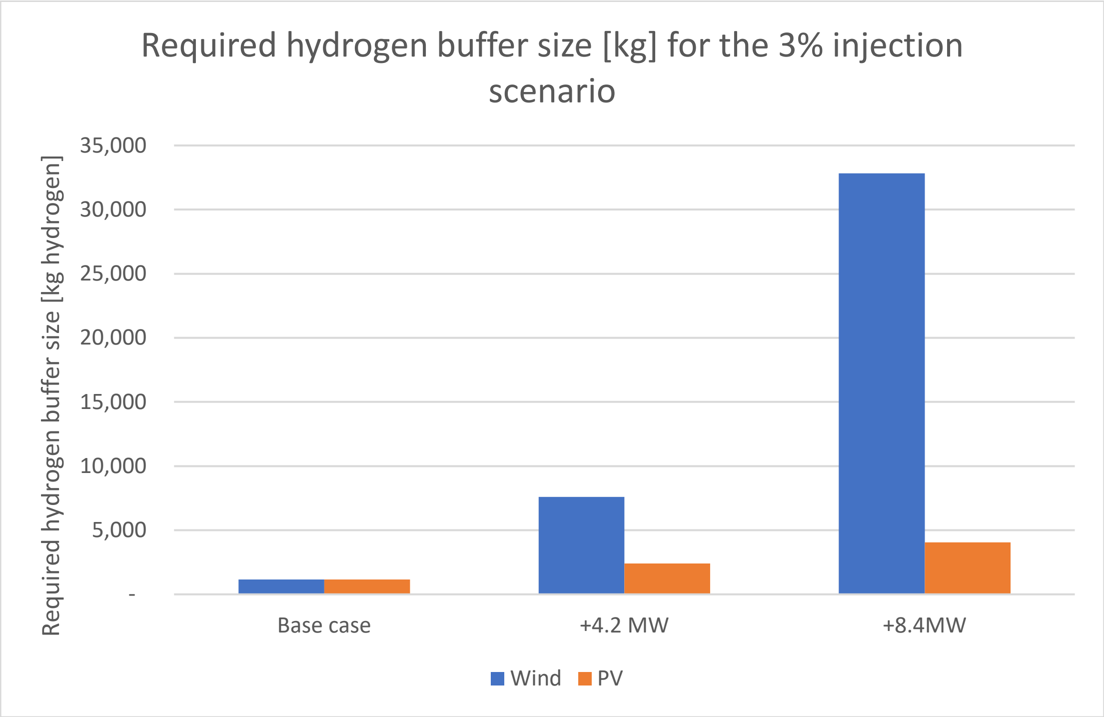

Figure 4.2: The required hydrogen buffer size for the 3% injection scenario

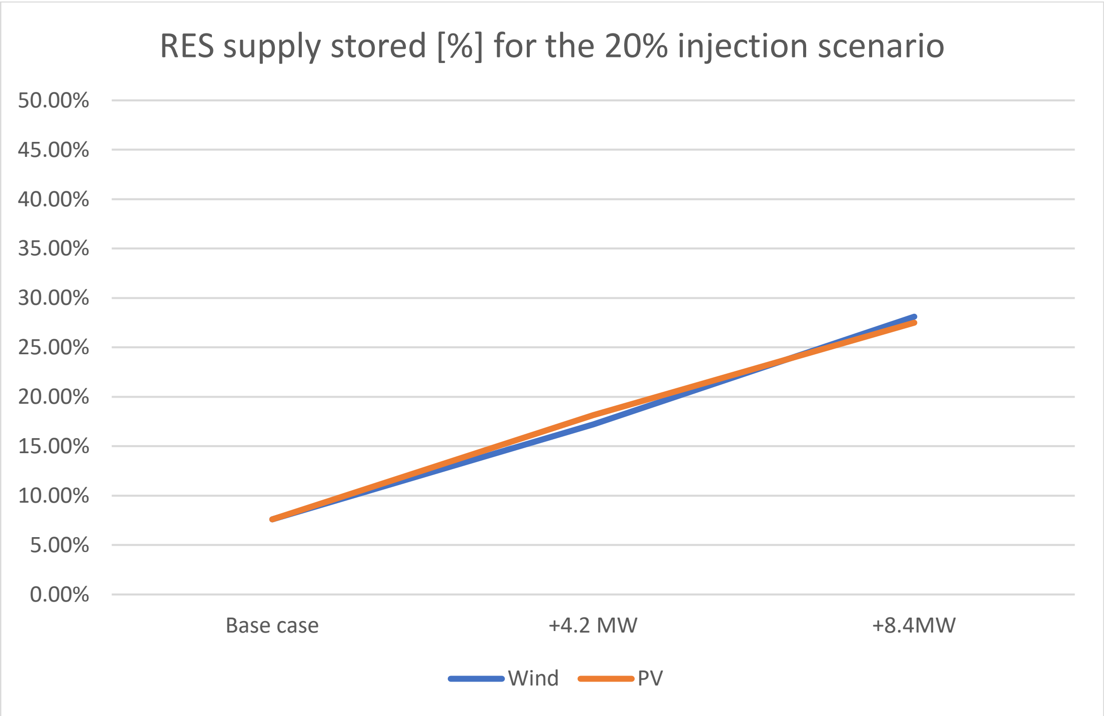

Figure 4.3: The fraction of RES supply that reaches the buffer for the 20% injection scenario

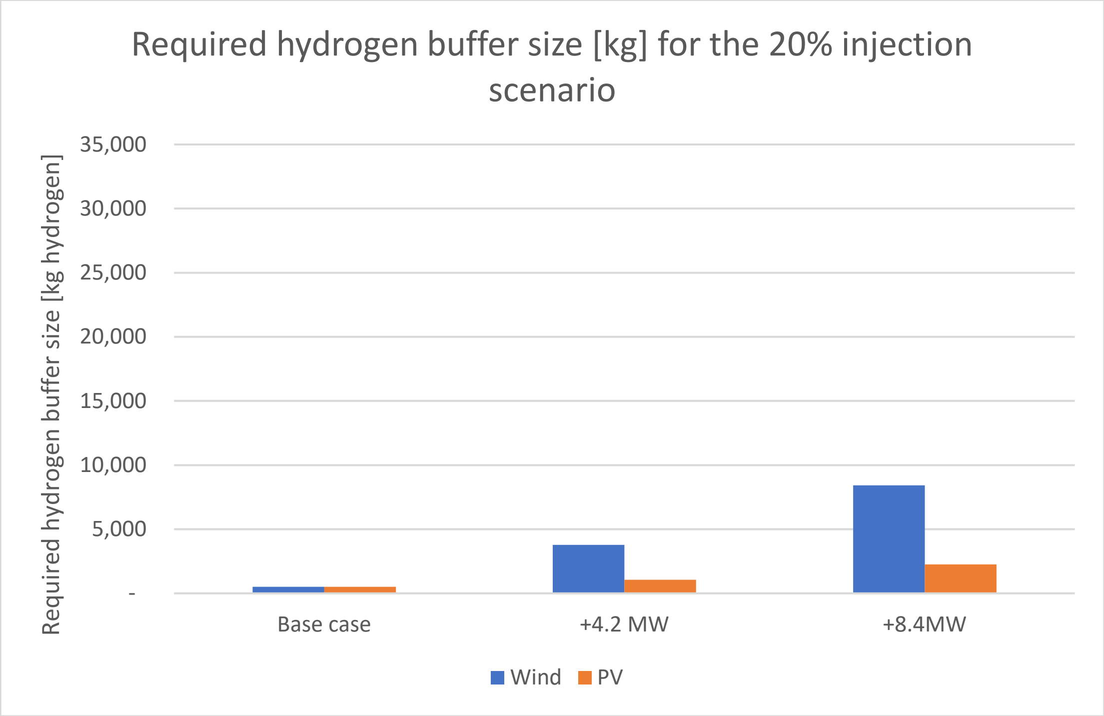

Figure 4.4: The required hydrogen buffer size for the 20% injection scenario

Then, if the maximum hydrogen injection percentage is raised, it correspondingly causes hydrogen injection to decrease the required hydrogen buffer more substantially for those scenarios with mostly wind power penetration. Specifically, most potential for hydrogen injection is found within the winter season, thanks to the overall larger values of the natural gas load within this period (Figure 7). As most wind power is generated within the same period (Figure 4), a raise in the maximum injection threshold will cause most required buffer reduction for power systems dominated by wind power penetration.

Figure 4.5 captures this well, as it compares the percentage of RES supply that is injected for situations where wind capacity is added, compared to situations where PV capacity is added. It is observed that the larger the maximum allowed injection percentage, the larger the difference in the output variable between both experiments. For the 20% threshold on hydrogen injection, one can witness this difference by comparing Figures 4.6 and 4.7. Both figures display respectively the amount of kg hydrogen injected over time for the 12.6 MW wind, and the 12.6 MW PV experiment.

Contrarily, if one compares exactly these experiments while maintaining a 3% threshold on hydrogen injection, both curves reveal a similar pattern of injection for the complete examined year. One is moreover referred to Appendix E to observe this.

Thus, hydrogen injection causes most buffer size reduction and thereby flexibility benefits within local power distribution systems that contain a large capacity of wind power. Besides, for each stepwise increase in the maximum hydrogen injection threshold, this effect becomes more substantial. This implies that when considering the integration of hydrogen injection opportunities to reduce RES curtailment, injection could be considered a more valuable option if the system is characterized by much wind power generation.

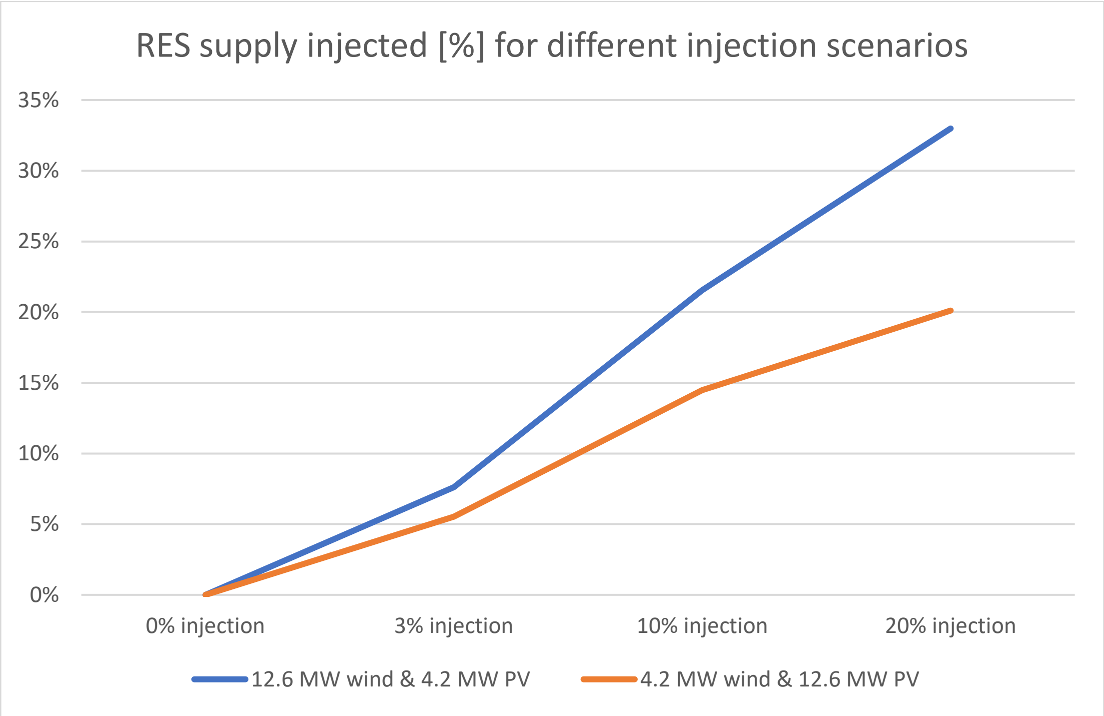

Figure 4.5: The fraction of RES supply that is injected for each injection scenario

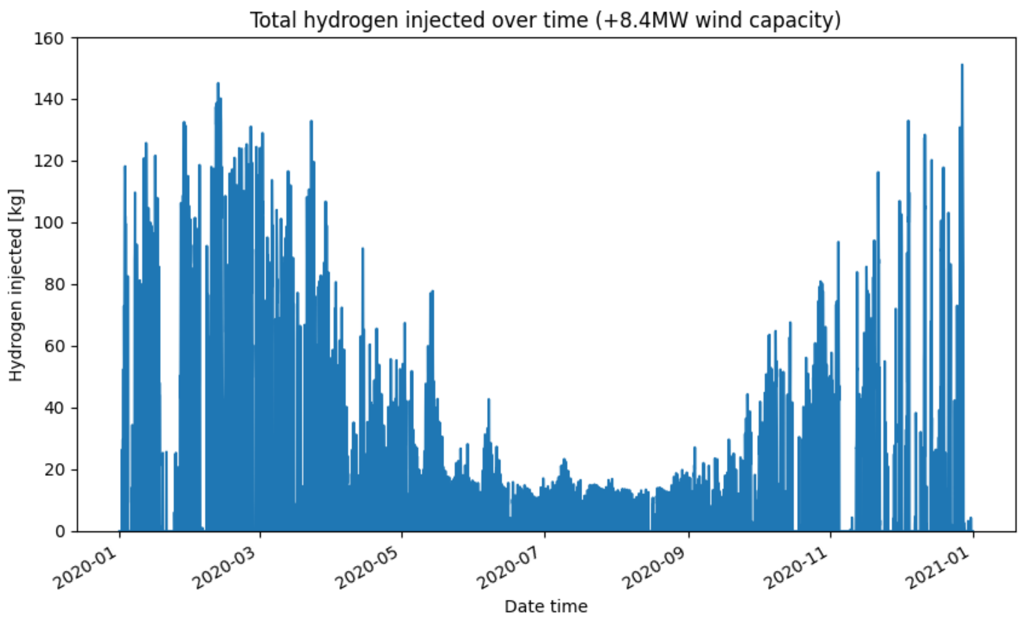

Figure 4.6: Total hydrogen injected over time for the +8.4MW wind capacity experiment while maintaining a 20% injection threshold

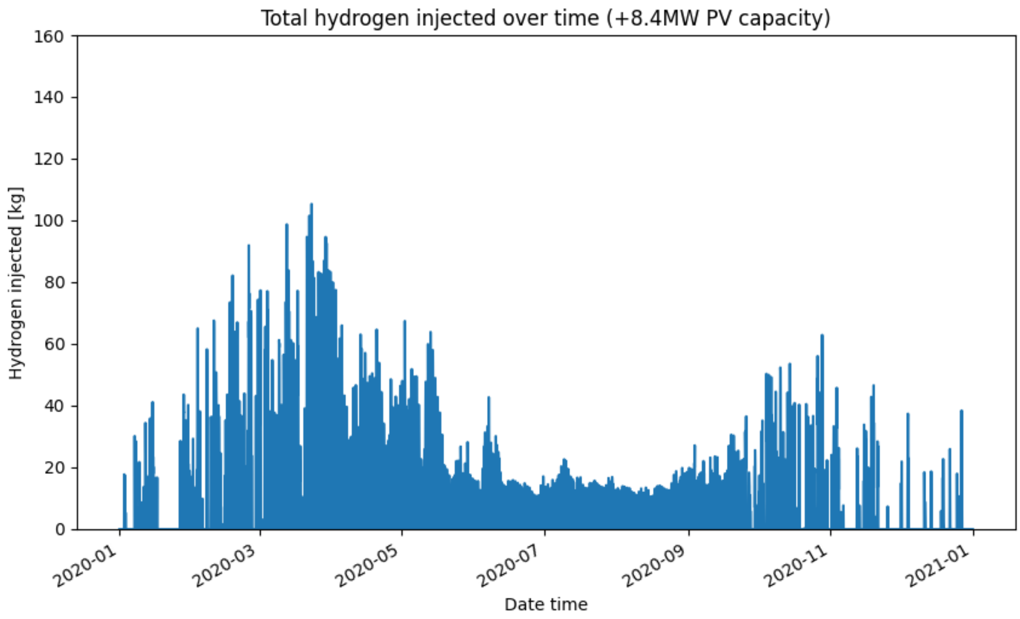

Figure 4.7: Total hydrogen injected over time for the +8.4MW PV capacity experiment while maintaining a 20% injection threshold

4.1.2 Max export scenarios

Most important insight from this section:

- For each step in hourly volume [kWh] increment of permitted export towards the higher-voltage grid, hydrogen injection will cause less required hydrogen buffer size reduction for the 10% and 20% injection scenario

This section analyzes the behavior of injection opportunities in reducing the required hydrogen buffer size for experiments in which a maximum allowed quantity of export towards the higher-voltage grid [kWh] is permitted on an hourly basis. This is done in two increments of 250 kWh export. Tables 4.3 and 4.4 again summarize the output of the respective experiments for both the 3% and 20% injection scenarios. Moreover, these tables are accompanied by Figure 4.8 that depicts the change in the main output variable ("Required hydrogen buffer size [kg]") for both increments of maximum export. On top of that, Figures 4.9-4.11 are used to explain the witnessed buffer size alterations by examining the flow of generated hydrogen. The first two graphs do this for 3% and 10% injection, by depicting the fraction of total RES supply that reaches the buffer ("RES supply stored [%]") and the fraction of total RES supply that is injected ("RES supply injected [%]"). The reason why these two output variables are used in this case is explained hereafter. Finally, Figure 4.11 displays the difference in the total kg hydrogen volume injected between the different injection scenarios when export quantities are allowed.

Experiment	*Required hydrogen buffer capacity [kg]*	*RES supply stored*	*Total volume injected [kg]*	*RES supply injected*
Base case	*1,149*	*16.81%*	*13,180*	*5.58%*
250 kWh hourly allowed export	*983*	*13.89%*	*11,826*	*5.01%*
500 kWh hourly allowed export	*817*	*11.31%*	*10,296*	*4.36%*

Table 4.3: Results of the maximum export experiments for the future 3% injection scenario

Experiment	*Required hydrogen buffer capacity [kg]*	*RES supply stored*	*Total volume injected [kg]*	*RES supply injected*
Base case	*503*	*7.60%*	*36,535*	*15.46%*
250 kWh hourly allowed export	*468*	*6.18%*	*31,032*	*13.13%*
500 kWh hourly allowed export	*433*	*4.99%*	*26,081*	*11.04%*

Table 4.4: Results of the maximum export experiments for the future 20% injection scenario

With the assistance of figure 4.8, if the maximum allowed export volume rises, it seems noticeable that hydrogen injection causes less required hydrogen buffer size reduction when increasing from 3% to 10% maximum injection threshold. For a clear understanding of this trend, the behavior of the generated hydrogen flows from the remainder of excess supply after export ought to be analyzed. Figures 4.9 and 4.10 aid in this regard, as they depict and contrast this behavior for the 3% and 10% injection scenarios. Remarkably, when increasing the maximum export quantity, the RES supply stored output variable declines in the 3% case, while both RES supply stored and RES supply injected decline proportionally in the 10% case. Hence, after reaching the 10% maximum injection threshold, the quantity of excess supply going to export is an amount that would otherwise partly have flown towards injection. The effect of this is illustrated in figure 4.11, in which the total volume injected decreases more intensively for the 10% and 20% injection scenario.

Hence, in situations characterized by maximum injection percentages of 10% or 20%, hydrogen injection causes less hydrogen buffer size reduction when export towards the higher-voltage grid is permitted. On the contrary, the opposite effect holds for the 3% case. Hence, if hourly portions of export are permitted in a regional power grid constrained by higher-voltage grid congestion, one might want to consider a low injection threshold of 3% if injection is to cause more required buffer size reduction. If no export is permitted on the other hand, larger injection threshold could be opted for in this regard.

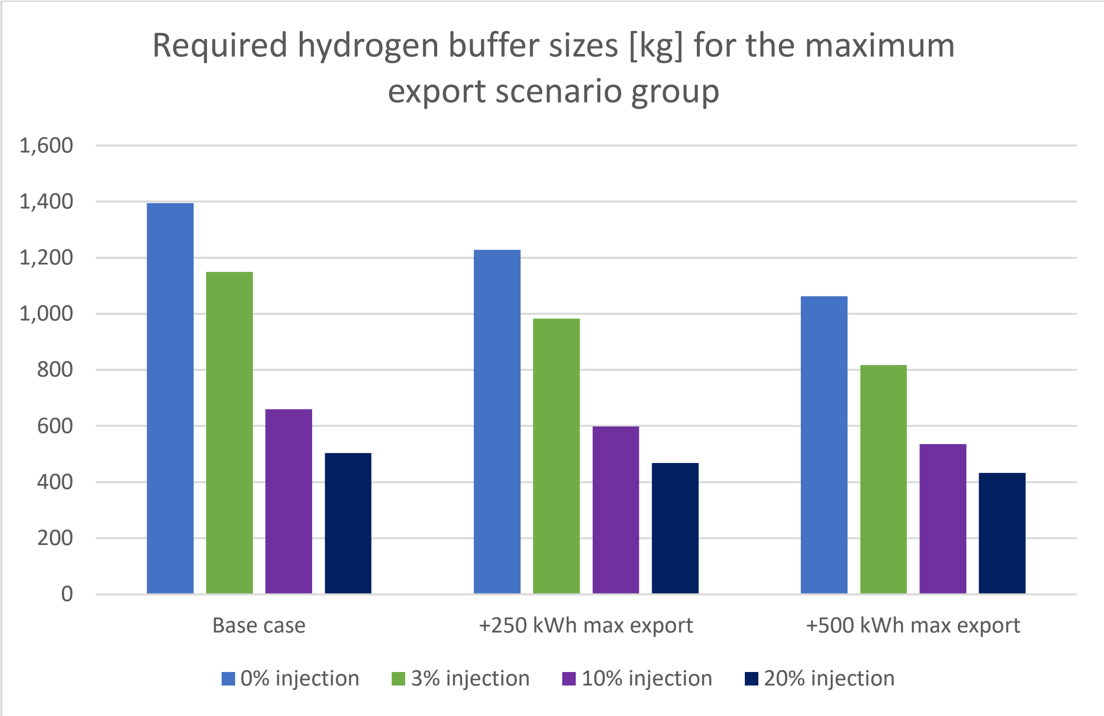

Figure 4.8: Required hydrogen buffer sizes for the maximum export scenario group

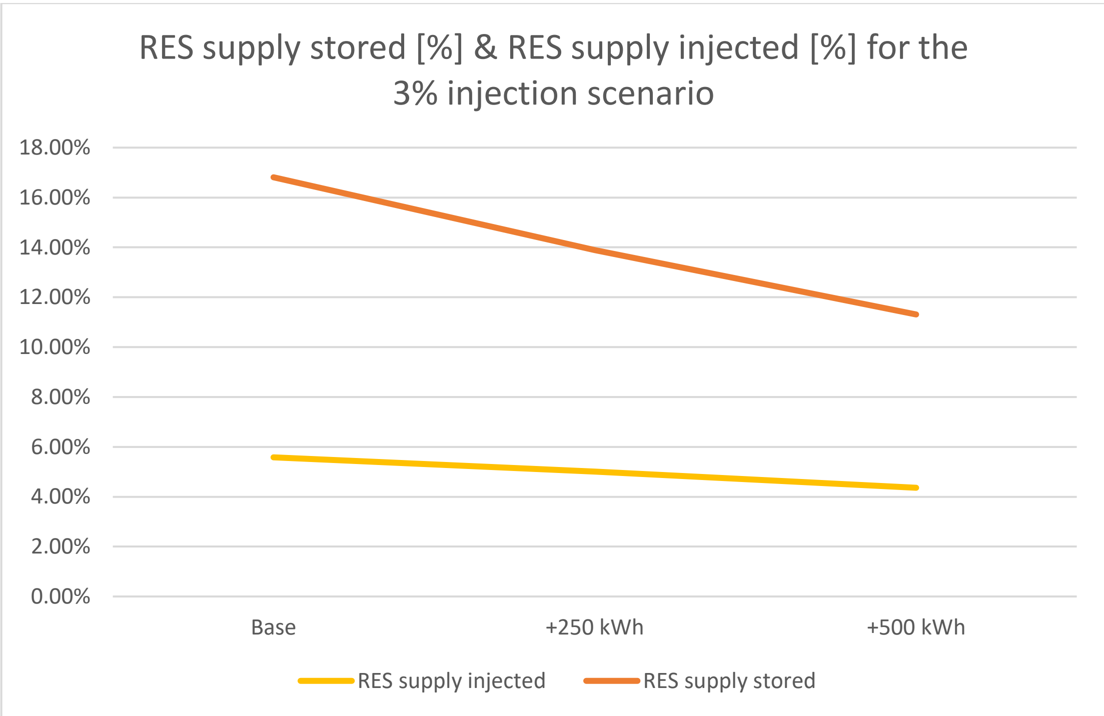

Figure 4.9: RES supply stored [% of total RES generation] & RES supply injected [% of total RES generation] for the 3% injection scenario

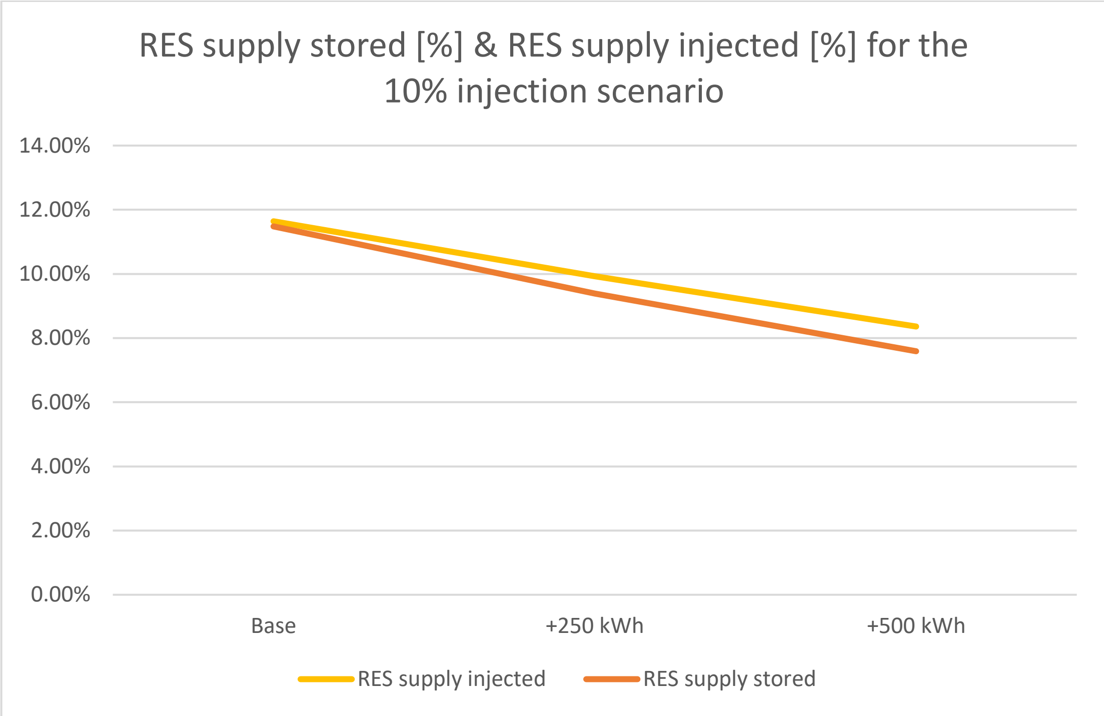

Figure 4.10: RES supply stored [% of total RES generation] & RES supply injected [% of total RES generation] for the 10% injection scenario

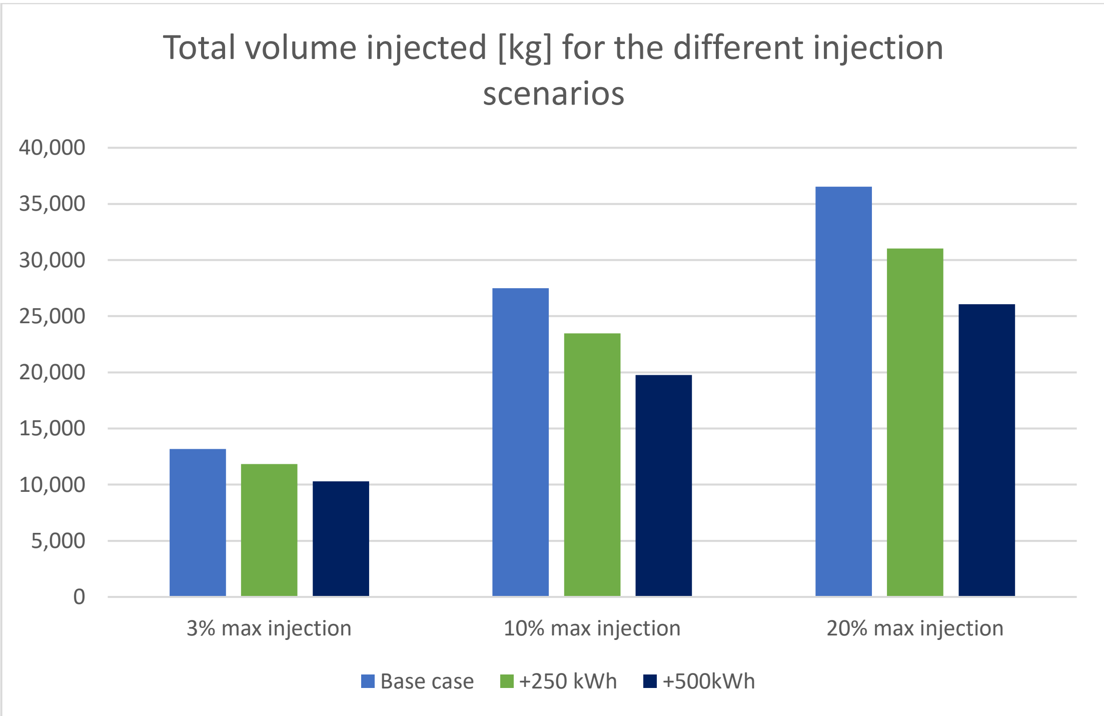

Figure 4.11: Total volume injected [kg hydrogen] for the different injection scenarios when different quantities of export towards the higher-voltage grid are allowed

4.1.3 Indirect injection scenarios

Most important insight from this section:

- The exclusion of indirect injection from the buffer brings about the largest decline in the cause-effect relationship between hydrogen injection and required hydrogen buffer size reduction for the 10% injection scenario

The last experiment conducted for each different injection scenario is one in which the option to inject indirectly from the buffer is excluded. This implies that injection can only occur directly after hydrogen is produced from excess RES supply. Tables 4.5-4.7 summarize the output of the respective experiments for both the 3%, 10%, and 20% injection scenarios. This is done as peculiarities in the main output variable of interest are mostly witnessed in the 10% case. The elaboration on this is included hereafter. Furthermore, Figures 4.12-4.17 are included as the collective of them assist in a holistic explanation of the buffer size alterations. Specifically, the first two display the kilogram hydrogen buffer size over the investigated time period in the 10% injection scenario. The first one does this when indirect injection from the buffer is allowed, and the second one does this for a situation without this option. Then, Figure 4.14 reveals the RES generation levels in kWh over the complete time period. Ultimately, Figures 4.15-4.17 display the exact same as the former three graphs, though they zoom in on the period between the 20th of April, and the end of the 23rd of April.

Experiment	*Required hydrogen buffer capacity [kg]*	*RES supply stored*	*Total volume injected [kg]*	*RES supply injected*
Base case	*1,149*	*16.81%*	*13,180*	*5.58%*
No indirect injection	*1,222*	*16.81%*	*8,937*	*3.78%*

Table 4.5: Results of the indirect injection experiments for the future 3% injection scenario

Experiment	*Required hydrogen buffer capacity [kg]*	*RES supply stored*	*Total volume injected [kg]*	*RES supply injected*
Base case	*660*	*11.48%*	*27,506*	*11.64%*
No indirect injection	*830*	*11.48%*	*21,530*	*9.11%*

Table 4.6: Results of the indirect injection experiments for the future 10% injection scenario

Experiment	*Required hydrogen buffer capacity [kg]*	*RES supply stored*	*Total volume injected [kg]*	*RES supply injected*
Base case	*503*	*7.60%*	*36,535*	*15.46%*
No indirect injection	*517*	*7.60%*	*30,692*	*12.99%*

Table 4.7: Results of the indirect injection experiments for the future 20% injection scenario

For the 10% injection scenario, the rise in the required hydrogen buffer size is most significant if indirect injection from the buffer is prohibited. This seems peculiar at first sight, due to this scenario's central positioning between 3% and 20% maximum injection. However, by observing Figures 4.12 and 4.13, it is noticeable that the removal of the opportunity to inject indirectly from the buffer increases one peak, resulting in the required buffer capacity. Appendix F displays exactly these two graphs for the 20% injection scenario. From these, one can notice no difference between them for the same peak.

Furthermore, the peak in the 10% injection case is caused by a period of excessive RES generation levels as observed in Figure 4.14. This is the period of 20-23 April. In this period, one observes three short consecutive generation peaks as displayed in Figure 4.17. This is a unique phenomenon and only occurs in exactly this period of the year. Now, to receive a clear understanding of the difference in the required hydrogen buffer size between a situation with and without indirect injection from the buffer, one is referred to Figures 4.15 and 4.16. From these, it becomes clear that in situations without the opportunity to inject indirectly from the buffer, the buffer is not fully relieved of its quantity in the few short periods between supply peaks. Thus, after the third and final consecutive peak, the buffer size has reached 830 kg hydrogen, instead of 660 kg hydrogen if indirect injection from the buffer was permitted.

Ultimately, indirect injection functions as an extra form of flexibility to relieve the buffer of its capacity. Within the 10% injection scenario, this option is necessary to combat the three consecutive supply peaks, as the quantity of hydrogen in the buffer cannot be fully relieved with hydrogen-to-power reconversion alone. This differs from the 3% injection scenario, in which the aid of indirect injection is too little to fully relief the buffer before the next peak occurs. Hence, the large peak occurs regardless of the permittance of indirect injection. In contrast, for the 20% injection scenario a different explanation holds. Specifically, in this scenario the hydrogen quantity residing in the buffer after each peak will not have reached a size that significant for hydrogen-to-power reconversion not to be able to relieve it completely by itself. Hence, no difference is observed between the two peaks in Appendix F.

This implies that indirect injection plays an essential role in buffer size reduction whenever many consecutive peaks in generation supply occur for the 10% injection scenario. Removing this option has a detrimental effect on the required buffer size, as hereby injection causes less required buffer size reduction.

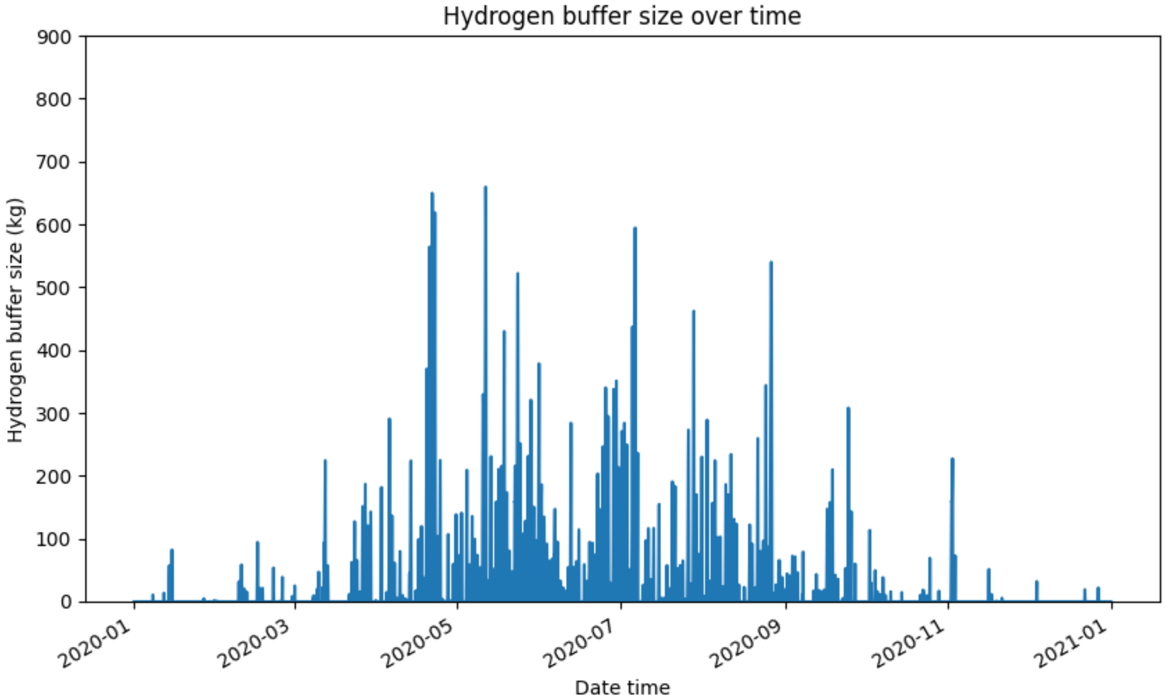

Figure 4.12: The hydrogen buffer size when indirect injection is allowed for the 10% future injection scenario

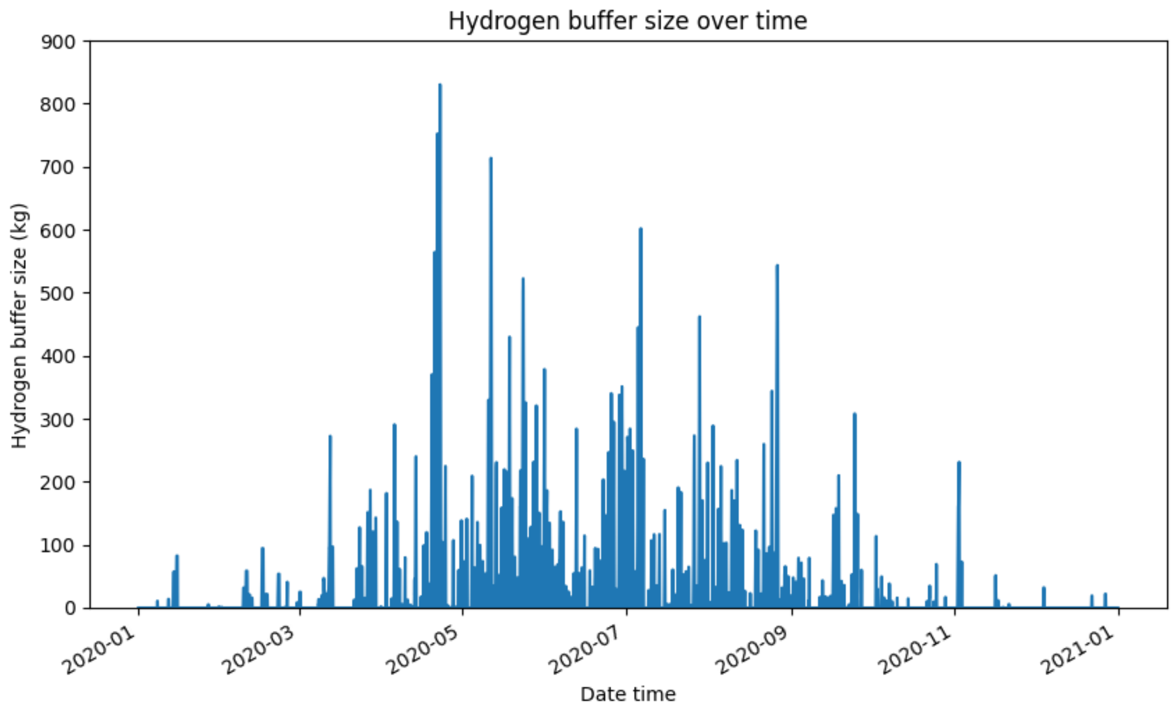

Figure 4.13: The hydrogen buffer size when indirect injection is disallowed for the 10% future injection scenario

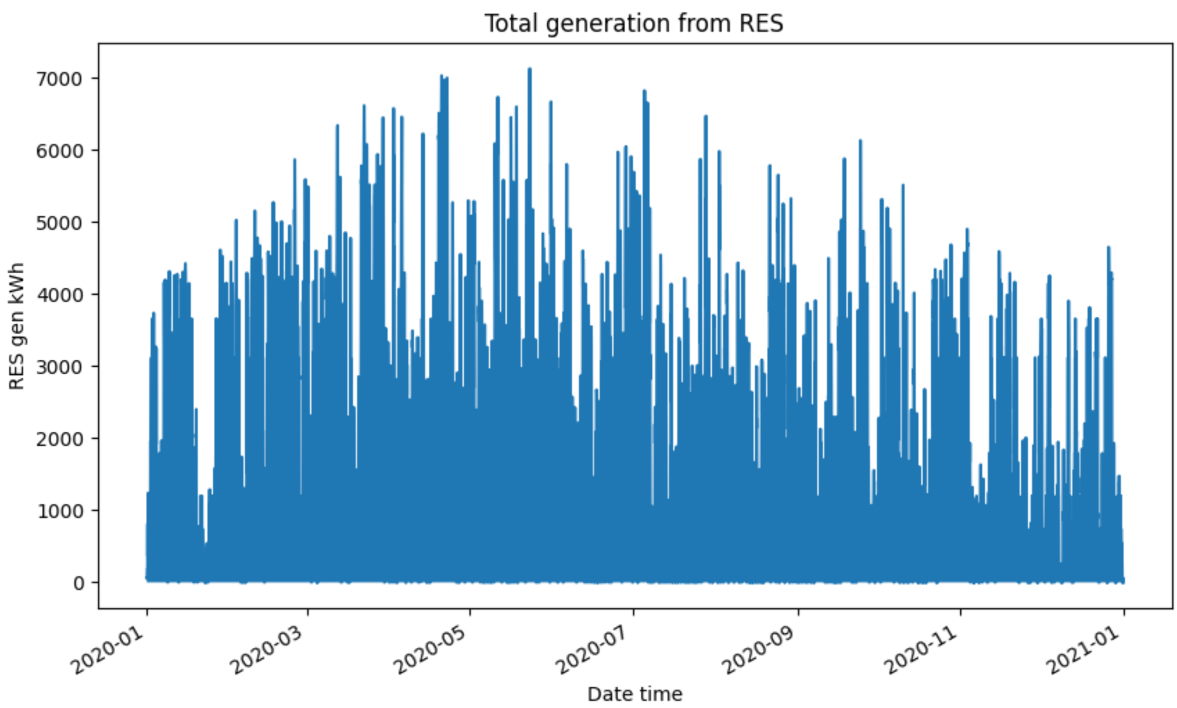

Figure 4.14: The total RES generation over the analyzed time period

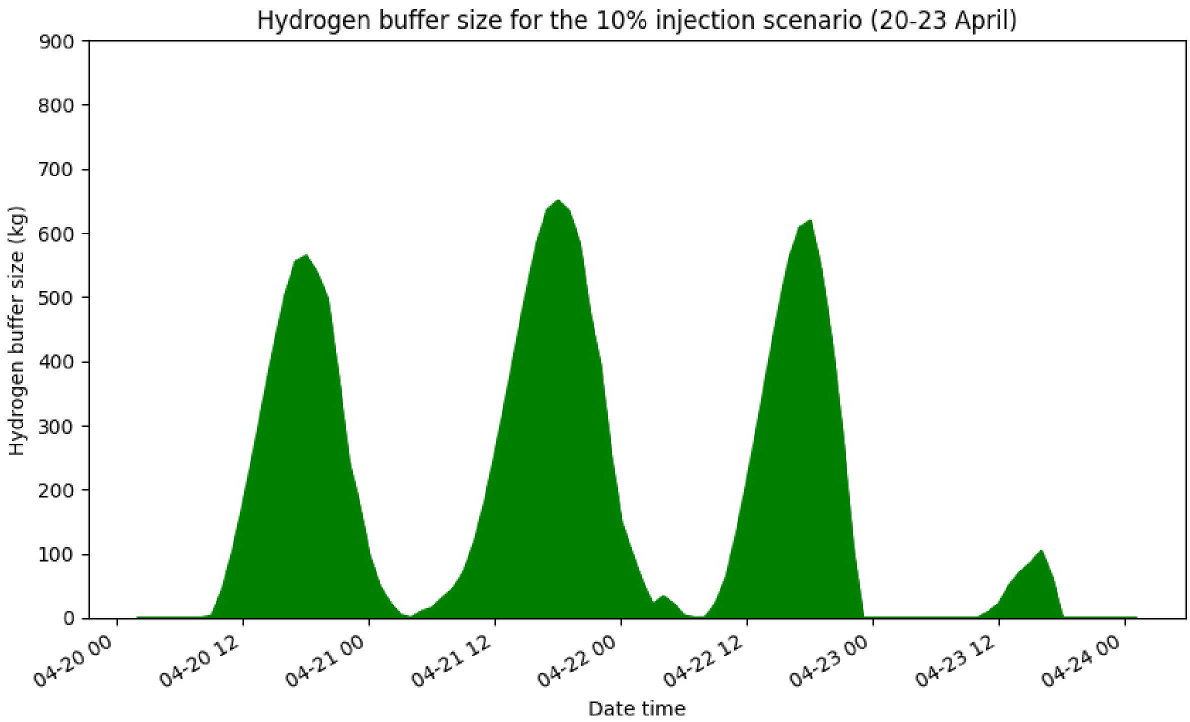

Figure 4.15: The hydrogen buffer size for the 10% injection scenario from 20-23 April (Indirect injection allowed)

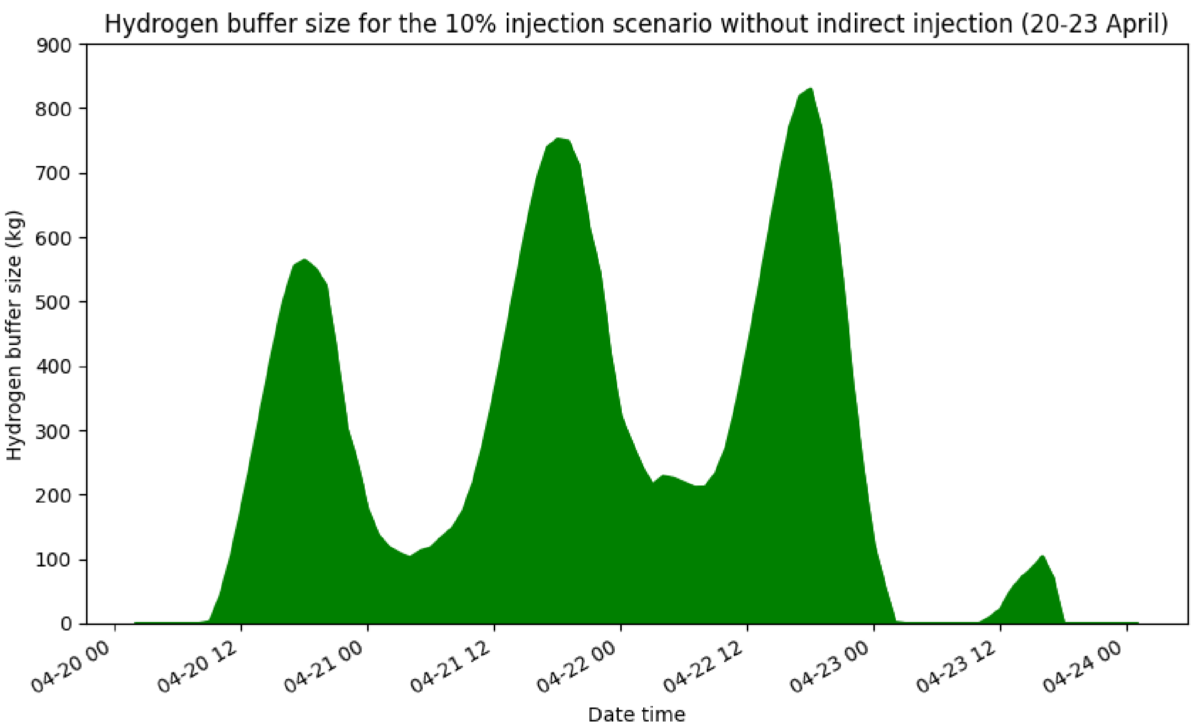

Figure 4.16: The hydrogen buffer size for the 10% injection scenario from 20-23 April (Indirect injection not allowed)

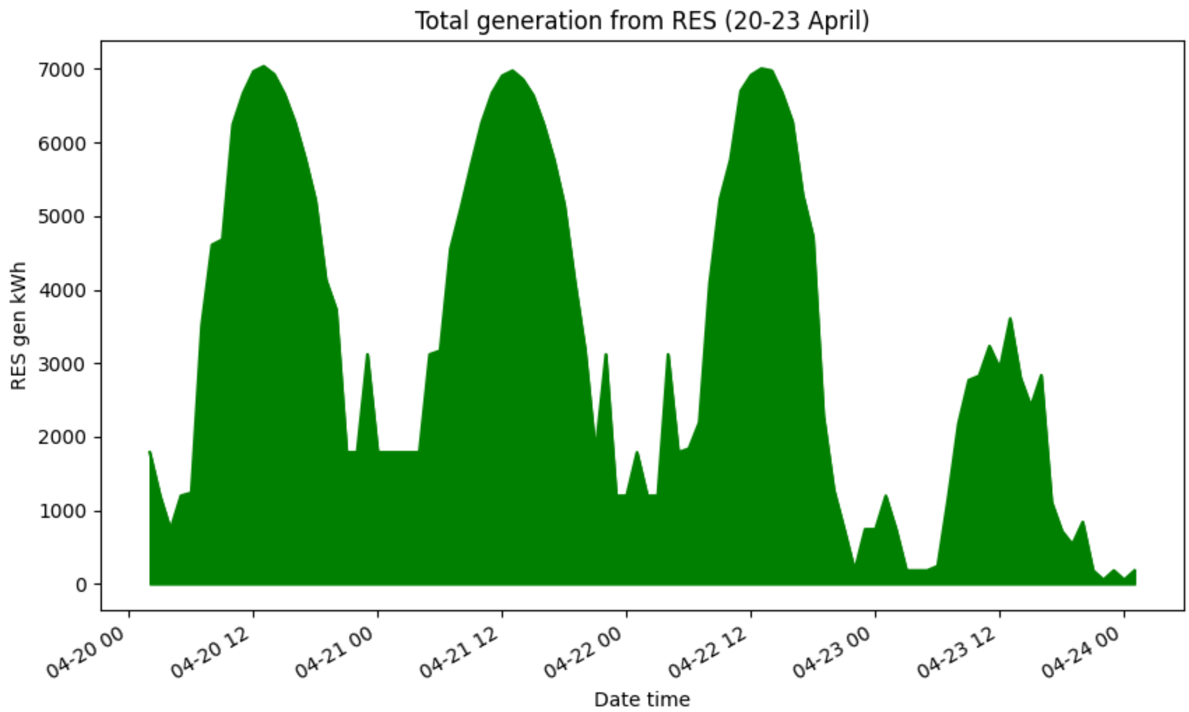

Figure 4.17: The total RES generation from 20-23 April

4.2 Analysis 2: Sensitivity analysis on the required hydrogen buffer size

Most important insights from this section:

- Hydrogen injection plays the most significant role in buffer size reduction for systems characterized by large penetrations of wind power, regardless of the maximum hydrogen injection percentage. On top of that, the larger the wind power capacity, the more influential become larger maximum injection threshold scenarios in increasing the extent to which the required buffer size is reduced by the opportunity to inject.
- Allowing the export of a certain amount of excess power towards the higher-voltage grid portrays little impact on hydrogen injection's cause in buffer size reduction compared to the base case.
- If the option to inject indirectly from the buffer is missing, hydrogen injection causes less buffer size reduction for the 3% and 10% injection scenario, especially in the latter one. Thus, if indirect injection is not allowed, an injection percentage of 20% should be opted for to balance out its negative effect.

As explained in the methodology section, this next analysis provides a sensitivity on the required hydrogen buffer size whenever the maximum injection percentage is enlarged. This is executed for a set of different experiments in which the RES generation capacities, the maximum hourly allowed export quantity, and the opportunity to inject indirectly are altered in a similar fashion as the experiments of the first analysis. Hereby, observations on the sensitivities of each experiment in the current section can be explained by assistance of the first analysis' findings. Moreover, Tables 4.8 and 4.9 represent respectively the required hydrogen buffer size [kg] and the change in the required hydrogen buffer size compared to the 0% injection scenario for each experiment. Besides, Figure 4.18 depicts the same sensitivities with a differently colored line for each experiment. In this graph, the highest positioned line for a specific injection scenario represents the experiment in which hydrogen injection's cause in buffer reduction is the smallest, while the lowest positioned line represents the exact opposite. Lastly, Figure 4.19 represents the RES supply injected [%] output variable to explain one of the observations from Figure 4.18. In this figure, the value is measured for the four different injection thresholds.

Experiment number	***Future injection scenario:***	*0%*	*3%*	*10%*	*20%*
33	Base case	1,395	1,149	660	503
34	8.4 MW wind & 4.2 MW PV	12,532	7,597	4,927	3,789
35	12.6 MW wind & 4.2 MW PV	45,708	32,821	18,321	8,411
36	4.2 MW wind & 8.4 MW PV	2,754	2,413	1,820	1,046
37	4.2 MW wind & 12.6 MW PV	4,406	4,060	3,263	2,252
38	250 kWh hourly allowed export	1,228	983	598	468
39	500 kWh hourly allowed export	1,062	817	536	433
40	No indirect injection	1,395	1,222	830	517

Table 4.8: Required hydrogen buffer size [kg] when increasing the maximum hydrogen injection threshold for different input parameter experiments

Experiment number	Future injection scenario:	0%	3%	10%	20%
33	Base case	0%	-17.63%	-52.69%	-63.94%
34	8.4 MW wind & 4.2 MW PV	0%	-39.38%	-60.68%	-69.77%
35	12.6 MW wind & 4.2 MW PV	0%	-28.19%	-59.92%	-81.60%
36	4.2 MW wind & 8.4 MW PV	0%	-12.38%	-33.91%	-62.02%
37	4.2 MW wind & 12.6 MW PV	0%	-7.85%	-25.94%	-48.89%
38	250 kWh hourly allowed export	0%	-19.95%	-51.30%	-61.89%
39	500 kWh hourly allowed export	0%	-23.07%	-49.53%	-59.23%
40	No indirect injection	0%	-12.40%	-40.50%	-62.94%

Table 4.9: Relative change in required hydrogen buffer size when increasing the maximum hydrogen injection threshold for different input parameter experiments

What comes to foremost attention is the more substantial decrease of those lines in which wind capacity is added. Hence, in comparison with the other experiments most buffer size reduction using injection is established for such power systems. Interestingly, for the 8.4 MW wind experiment, a decreasing marginal effect on buffer size reduction is observed when the injection threshold is raised. This is however not the case for a system containing 12.6 MW of wind capacity. Eventually, the 10% injection rate serves as the trade-off point, after which hydrogen injection causes more buffer size reduction for the 12.6 MW wind experiment. Figure 4.19 furthermore depicts the mechanisms behind this observation. As witnessed, both the 8.4 MW and 12.6 MW wind experiment reveal a similar percentage of hydrogen that is injected in the 3% injection scenario. If the threshold on injection is raised however, it is observed that relatively more RES supply is injected for the 12.6 MW experiment. This implies that when considering raising the maximum injection percentage to 20%, a power system ought to contain much wind power capacity for injection to cause a substantial amount of buffer size reduction. Otherwise, a lower percentage should be opted for

Moreover, for the base case, 250 kWh hourly allowed export, and 500 kWh hourly allowed export experiment lines, a similar pattern in their respective courses is observed. This implies that in systems in which hourly export quantities are permitted, a drastic change in hydrogen injection causing buffer size reduction is not established. Moreover, the little alterations to the base case are explained by the fact that export opportunities remove a portion of excess RES supply that would otherwise have reached either injection or storage. In the 3% injection scenario, this is mostly excess supply destined for the buffer, while in the 10% and 20% case, relatively more supply destined for injection is removed.

The last noticeable observation within the figure is one concerning the experiment in which indirect injection is not allowed. Specifically, in comparison to the base case it is observed that the removal of indirect injection from the buffer portrays a negative impact on buffer size reduction for the 3% and 10% injection scenario, especially for the latter.

This result is in accordance with the obtained insights of the indirect injection experiments of analysis 1. Specifically, during moments of excess power demand that occur between consecutive generation peaks, indirect injection plays a key role in relieving the buffer of its complete hydrogen volume before the subsequent generation peak occurs. This effect however disappears for the 20% injection case as hydrogen volumes within the buffer will never reach such excessive amounts where indirect injection is required to play its respective role in buffer relief. This implies that for systems in which the option to inject indirectly is missing, a large injection rate of 20% should be considered to balance out its negative effect on injection causing buffer size reduction.

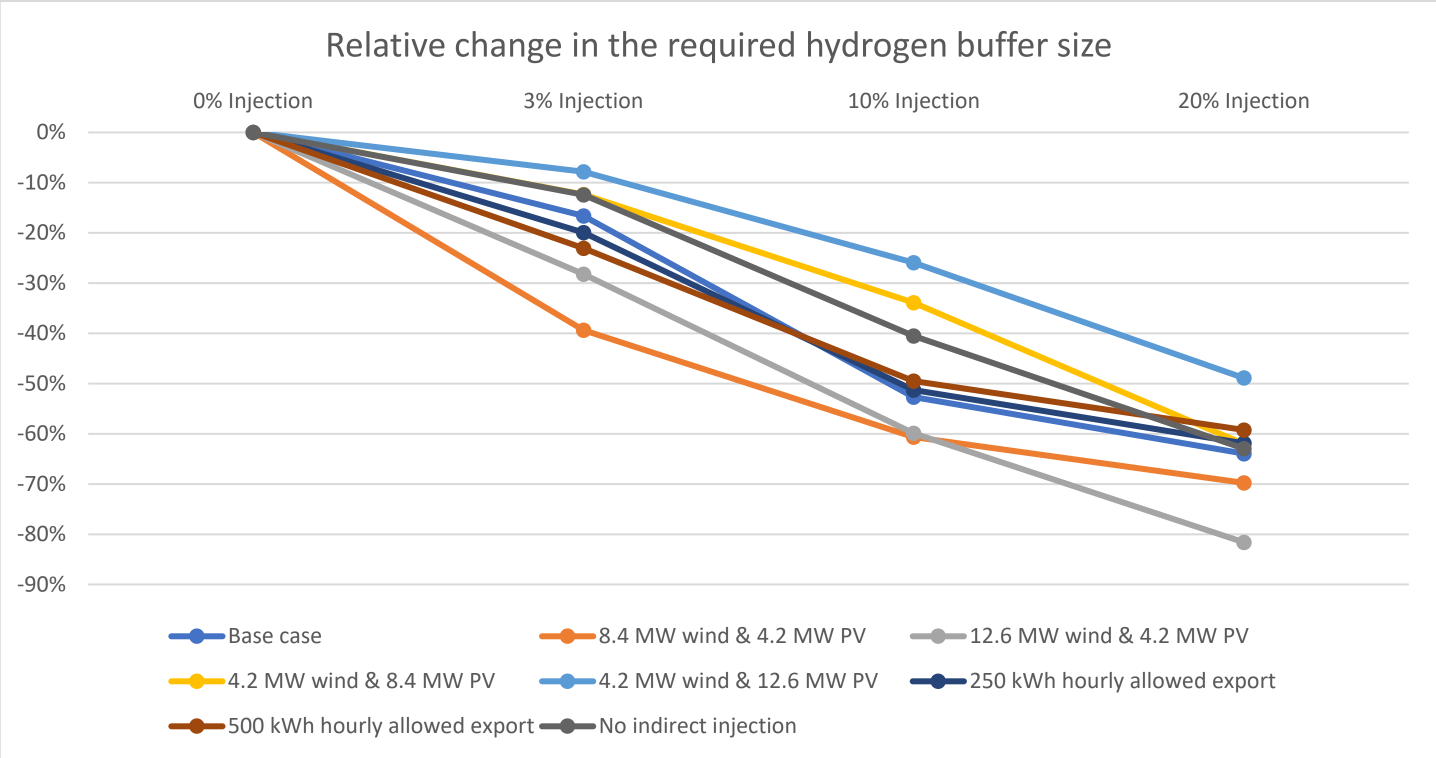

Figure 4.18: Relative change in the required hydrogen buffer size when increasing the maximum hydrogen injection threshold for different input parameter experiments

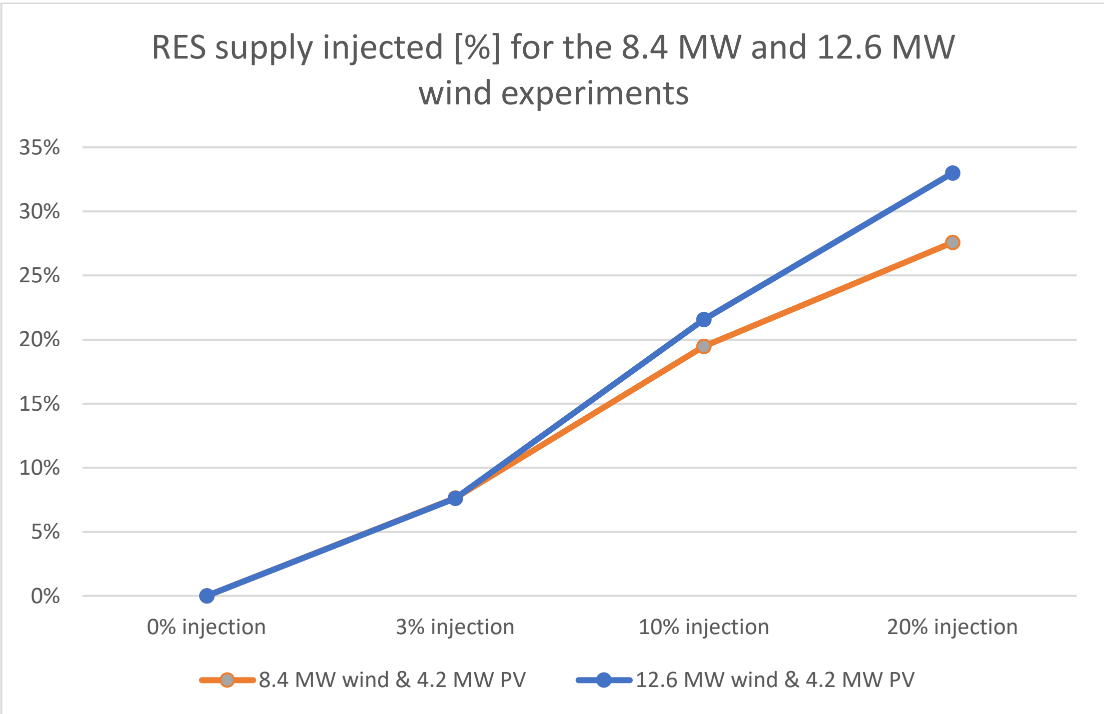

Figure 4.19: RES supply injected [%] for the 8.4 MW wind and 12.6 MW wind experiments

5. DISCUSSION

This section first summarizes and interprets the complete set of findings from the conducted analyses. These insights are then compared to the existing literature to either confirm, add to, or contrast earlier scientific work. Lastly, implications of the work for practice are stated.

5.1 Implications of the findings

First, it was established that a raise in the maximum threshold on hydrogen injection reveals differing buffer reduction quantities depending on the capacities of wind and PV within the system. It was shown that if wind power is the main choice of RES supply, larger quantities of hydrogen flow towards injection compared to situations where PV is the main source of power supply. Correspondingly, the required buffer size is reduced most significantly if injection is used in systems with much wind power capacity.

The cause for this was found in the similar pattern of hourly wind generation and hourly maximum permitted hydrogen quantities over the investigated time period. Specifically, hourly permitted injection quantities are higher in the winter season, due to most natural gas load occurring then. This overlaps furthermore with the period in which most wind generation occurs. For systems dominated by PV capacity however, the opposite holds. Such systems are namely characterized by periods of relatively large generation in the summer period.

Moreover, each specific injection scenario portrays a different effect on injection's buffer size reduction performance. Specifically, a large injection threshold of 20% is most effective in a system with an excessive amount of wind capacity, while a 3% scenario is more effective if the wind power capacity is large, but not as excessive. This implies that careful consideration must be given to the opted for injection threshold, where larger maximum injection percentages produce more buffer size reduction if wind penetrations are excessive enough.

Furthermore, in those systems where export towards the higher-voltage grid is allowed, hydrogen injection will cause more required hydrogen buffer size reduction if the injection threshold is set at 3% of the hourly natural gas load. Contrarily, the opposite is true if this threshold is set at 10% or 20%. It was shown that export opportunities to the higher-voltage grid remove a portion of excess supply otherwise destined for hydrogen injection or hydrogen buffer storage. In the 3% injection scenario, a larger proportion of this would have reached the buffer, while a more substantial part would have been injected if a larger maximum injection percentage was maintained. Eventually, this alters the cause-effect relationship between hydrogen injection and required buffer size reduction. It was witnessed in the second analysis however, that these effects are not as extensive as the effect of other experiments. Specifically, the export experiments revealed little change in the extent to which injection causes buffer size reduction compared to the base case, when comparing this with all other experiments. This implies that each stepwise increase in the injection threshold could be implemented in systems in which hourly export opportunities of excess power are permitted.

Then, it was established for the 3% and 10% injection scenario that hydrogen injection causes a smaller drop in the required buffer size if indirect injection is not permitted, with the biggest difference found for the 10% case. If on the other hand 20% injection is opted for as the upper bound on the hourly allowed hydrogen injection quantities, the total of direct and indirect injection causes the same required hydrogen buffer size decrease for systems with and without the option to inject indirectly.

Specifically, for the 3% and 10% injection case this is brought about by the fact that indirect injection is essential in required buffer size reduction if many consecutive power generation peaks occur in a short time. Specifically, if such peaks do not happen shortly after one another, hydrogen-to-power to supply excessive electricity load would already have emptied the buffer completely, hence ruling out the causal effect of indirect injection in buffer size reduction.

For the 20% scenario however, it was found that hydrogen-to-power would be capable of emptying the buffer on its own, as the buffer would not contain too much volume after each consecutive generation peak. Thus, if power generation displays many reoccurring excess power peaks in a short duration of time, injection will cause less required hydrogen buffer size decline for the 3% and 10% injection case if the option to indirect indirectly from the buffer is removed. This implies that for systems in which the opportunity to inject indirectly from the buffer is lacking, a consideration of a 20% injection threshold would be worthwhile. Specifically, this would mitigate the negative consequences of indirect injection on the extent to which injection causes buffer size reduction.

5.2 Implications for theory

Furthermore, the results of this work confirm a general flexibility advantage of directing hydrogen towards the natural gas network by the means of injection. In practice, this implies the use of smart-grid technology to facilitate this type of hydrogen flow. Tuballa and Abundo (2016) stated that smart-grid technology facilitates the integration of larger quantities of RES capacities within existing power networks. This work established that by properly using the smart-grid technology to inject hourly quantities of hydrogen within the natural gas network, excess RES supply converted to hydrogen can be captured. This subsequently raises the utilization rate of RES, and thereby facilitates its integration within power networks.

Besides, this work confirms the literature on the power efficiency and flexibility benefits from the coupling of the electricity and natural gas network using P2G technology. The literature considers such a decision worthful thanks to P2Gs massive energy storage and absorption capabilities, caused by the possibility to couple the electricity, mobility, and heating sector (Buttler & Spliethoff, 2018). Correspondingly, by establishing a causal relationship between indirect injection from the buffer and flexibility benefits, this study complements the work of Li, Gao and Ruan (2019), who discovered that the potential of P2G to improve the RES utilization rate is affected by the combination of RES capacity, the price of hydrogen, and electrolyzer conversion efficiency.

Moreover, in contrast to other works conducted within the field of hydrogen injection as a means of capturing excess supply to balance a network, this piece of research differentiates itself as it considers several maximum hydrogen injection thresholds within different power system contexts. Hereby, it has become evident that by raising hourly maximum allowed injection capacity, a different gain in flexibility benefits in terms of buffer size reduction is obtained for different system configurations. Specifically, systems altered by changing RES capacities, or ones by an extra injection pathway in the form of indirect injection from the buffer, portray their respective effects. Hence, the research contributes to the formation of a holistic understanding of the use of injection to capture excess power generation, as context matters.

5.3 Implications for practice

If the natural gas infrastructure becomes capable of transporting larger relative fractions of hydrogen on a technical and legislative basis, DSOs ought to investigate the context of their respective power systems before deciding on the fraction of hydrogen that will be injected within natural gas networks.

Specifically, an increment of the injection threshold to 3% is most recommended for regional power systems in which the supply of power is in favor of wind generation. This is represented by the 8.4 MW wind experiment in this work, in which most buffer size reduction was witnessed for an increment towards this threshold. However, this holds till a certain degree of wind penetration, as observed from the 12.6 MW wind experiment in Figure 4.18. Moreover, a stepwise increment of the maximum injection percentage from 3% to 10% would be suitable for most power systems except ones dominated by PV capacity, or ones in which the option to inject indirectly from the buffer is missing. Finally, a stepwise increase towards 20% injection is recommended for power systems dominated by excessive penetrations of wind supply, or ones without indirect injection. The latter of these is grounded on the fact that the negative consequences of lacking indirect injection opportunities on buffer size reduction, are mitigated for such a scenario.

Moreover, the legislative side could also benefit from the combination of insight retrieved in this research. Specifically, as the pressure on carbon emission reductions will most likely rise in the future, hydrogen injection may prove fruitful as an effective means to substitute the use of natural gas. On top of that, it may facilitate larger quantities of RES penetration thanks to its proven benefits in flexibility.

6. CONCLUSION

This study addressed the use of the opportunity to inject hydrogen within the natural gas network. This was conducted within a local electricity grid in which hydrogen injection functions as a means of capturing part of excess power supply generated by different capacities of intermittent wind and PV. Hereby, hydrogen injection could be utilized to provide flexibility to balance an electricity system characterized by reoccurring imbalances between generation and load. To obtain measurable insight into the flexibility advantage of injection, the addition of hydrogen storage was incorporated to observe the decline in its required size when injection opportunities come into existence. Correspondingly, the extent to which hydrogen injection causes a decline in the required size of a supplementary hydrogen buffer is established.

To obtain insight into the flexibility benefit of injection, and thereby the extent to which its inclusion could reduce the required size of a supplementary hydrogen buffer, a simulation model was built that incorporates both hydrogen injection and storage in a local residential power grid. Moreover, the model considers the hourly natural gas load as well. Hereby, this functions to determine the permitted hourly injection capacity by taking a maximum percentage of injection from this load.

Different experiments were conducted to capture the causal relationship between hydrogen injection and required hydrogen buffer size reduction for different power system contexts. These contexts differentiate themselves by varying wind and PV capacities, quantities of hourly allowed export of excess power towards the higher-voltage grid, or a change in the option to disallow indirect hydrogen injection after it has already reached the buffer.

It was established that local power systems characterized by much wind power penetration experience the largest drop in required buffer size, regardless of the maximum allowed hydrogen injection percentage. This is brought about by a similarity in the season in which most wind power and injection opportunities occur, namely the winter. During this season, relatively larger quantities are allowed to be injected. Nevertheless, increasing the injection threshold above 3% was found to have a decreasing marginal effect on buffer size reduction for systems with a larger penetration of wind, though inadequately large enough.

Furthermore, incorporating hourly allowed quantities of excess power that can be exported towards the higher-voltage grid, will have the opposite effect for small and large maximum hourly injection percentages. Specifically, if a 3% upper-bound on hourly injection is maintained, the extra flexibility option in the form of export causes power that would otherwise have largely reached the buffer, to flow towards the higher-voltage grid. Hereby, injection eventually causes relatively more buffer size reduction. For the 10% and 20% case, the opposite holds, and export removes power that would otherwise have flown towards injection. Hereby, injection causes relatively less buffer size reduction. These effects are however little in comparison with the injection's cause in buffer size reduction for the base case.

Ultimately, the option to indirect indirectly from the buffer was found to portray most effect in buffer size reduction for the 10% scenario, while no effect was found in the 20% scenario. It was established that in the former, indirect injection could assist significantly in complete relief of the buffer volume between short-term peaks of excessive supply. In the model, the combination of such periods causes the largest peaks in buffer volume, hence the required size. For the 20% scenario on the other hand, the option to inject indirectly from the buffer becomes redundant, as it is not necessary anymore for complete buffer capacity relief between short-term excessive generation periods.

The results were furthermore compared with a general base case power system for each injection scenario. Hereby, the general recommendation is to implement a 3% threshold to power systems in which the balance of power generation favors wind, though not too drastically. Then, a 10% injection scenario is recommended for most regional power systems, except ones dominated by PV penetration, or ones in which the option to inject indirectly from the buffer is not permitted. Finally, raising the injection threshold towards 20% is recommended for regional power systems with excessive penetrations of wind power, and ones in which indirect injection is not permitted.

This work does bring forward a handful of limitations, however. First, the scope of the research did not venture beyond a regional power grid compromised of a residential power and natural gas load for the year 2020. As the required buffer sizes were often obtained from wind power peak moments, a year with many or little reoccurrences of such events could bias the required buffer sizes. Besides, it was assumed for the higher-voltage grid export scenario group, that an absolute maximum quantity of export was permitted for each hour. Hence, different results on injection causing buffer size reduction for the export experiments might have been obtained. Presumably, this could alter the flows of excess supply which otherwise would have been destined for injection or the buffer, depending on the injection rate.

Moreover, the outcome of the research may only be useful for the short-term. Specifically, as the price of hydrogen storage is expected to drop over the coming years, it may become worthwhile to consider hydrogen storage as the sole flexibility option. Hence, injection as a second flexibility option may end up being redundant.

Finally, future research could investigate the flexibility benefit of hydrogen injection with the inclusion of extra hydrogen demand centres. Specifically, hydrogen for mobility or industry may be incorporated to examine injection's cause in flexibility improvements if such options are added to the system. Similarly, the scale of the work could be improved to a regional, national, or international level, as this may provide useful insight on the dynamics of the system in these considerations.

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APPENDIX

Appendix A: Overview of each experiment conducted

APPENDIX A1: Overview of the experiments of analysis 1

	Maximum Injection rate			
	0%	**3%**	**10%**	**20%**
Base case	*1*	*2*	*3*	*4*
8.4 MW wind & 4.2 MW PV	*5*	*6*	*7*	*8*
12.6 MW wind & 4.2 MW PV	*9*	*10*	*11*	*12*
4.2 MW wind & 8.4 MW PV	*13*	*14*	*15*	*16*
4.2 MW wind & 12.6 MW PV	*17*	*18*	*19*	*20*
250 kWh hourly allowed export	*21*	*22*	*23*	*24*
500 kWh hourly allowed export	*25*	*26*	*27*	*28*
No indirect injection	*29*	*30*	*31*	*32*

APPENDIX A2: Overview of the experiments of analysis 2

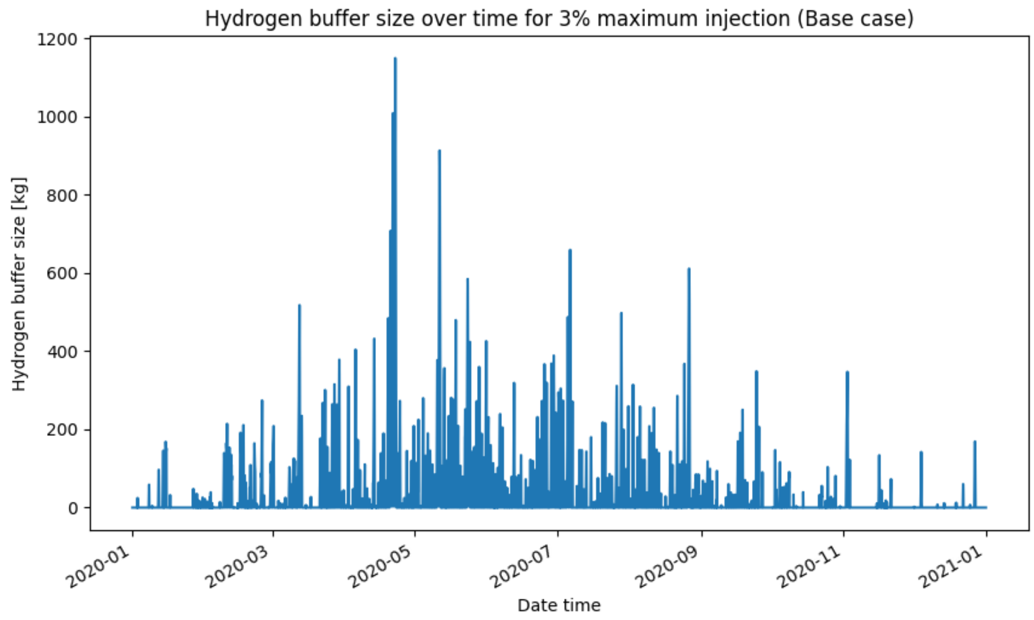
	Experiment number
Base case	*33*
8.4 MW wind & 4.2 MW PV	*34*
12.6 MW wind & 4.2 MW PV	*35*
4.2 MW wind & 8.4 MW PV	*36*
4.2 MW wind & 12.6 MW PV	*37*
250 kWh hourly allowed export	*38*
500 kWh hourly allowed export	*39*
No indirect injection	*40*

APPENDIX B: Overview of the output for every experiment of analysis 1

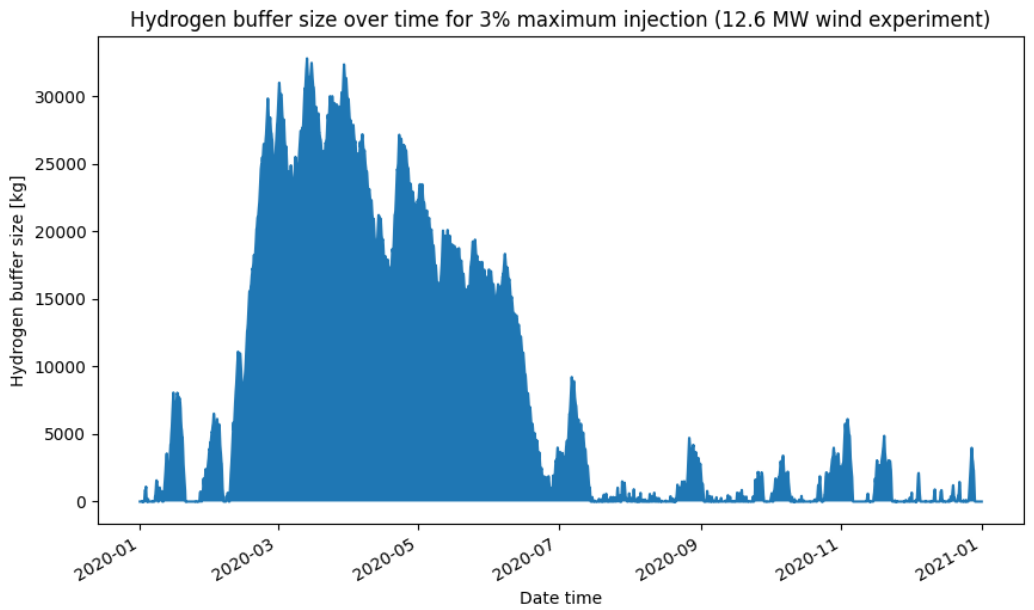
Scenario	*Required hydrogen buffer capacity [kg]*	*RES supply stored*	*Total volume injected [kg]*	*RES supply injected*
1	*1,395*	*20.59%*	*0*	*0%*
2	*1,149*	*16.81%*	*13,180*	*5.58%*
3	*660*	*11.48%*	*27,506*	*11.64%*
4	*503*	*7.60%*	*36,535*	*15.46%*
5	*12,532*	*38.28%*	*0*	*0%*
6	*7,597*	*33.59%*	*30,714*	*7.63%*
7	*4,927*	*24.93%*	*78,354*	*19.46%*
8	*3,789*	*17.20%*	*111,041*	*27.57%*
9	*45,708*	*50.55%*	*0*	*0%*
10	*32,821*	*46.24%*	*43,358*	*7.62%*
11	*18,321*	*37.65%*	*122,645*	*21,55%*
12	*8,411*	*28.11%*	*187,750*	*32.99%*
13	*2,754*	*32.98%*	*0*	*0%*
14	*2,413*	*29.19%*	*17,366*	*5.67%*
15	*1,820*	*23.20%*	*40,011*	*13.07%*
16	*1,046*	*18.15%*	*58,259*	*19.03%*
17	*4,406*	*42.50%*	*0*	*0%*
18	*4,060*	*38.94%*	*20,776*	*5.53%*
19	*3,263*	*32.95%*	*50,628*	*14.47%*
20	*2,252*	*27.50%*	*75,592*	*20.11%*
21	*1,228*	*17.17%*	*0*	*0%*
22	*983*	*13.89%*	*11,826*	*5.01%*
23	*598*	*9.39%*	*23,466*	*9.93%*
24	*468*	*6.18%*	*31,032*	*13.13%*
25	*1,062*	*14.14%*	*0*	*0%*
26	*817*	*11.31%*	*10,296*	*4.36%*
27	*536*	*7.59%*	*19,760*	*8.36%*
28	*433*	*4.99%*	*26,081*	*11.04%*
29	*1,395*	*20.59%*	*0*	*0%*
30	*1,222*	*16.81%*	*8,937*	*3.78%*
31	*830*	*11.48%*	*21,530*	*9.11%*
32	*517*	*7.60%*	*30,692*	*12.99%*

APPENDIX C: hydrogen buffer size [kg] over time for the 3% maximum injection scenario

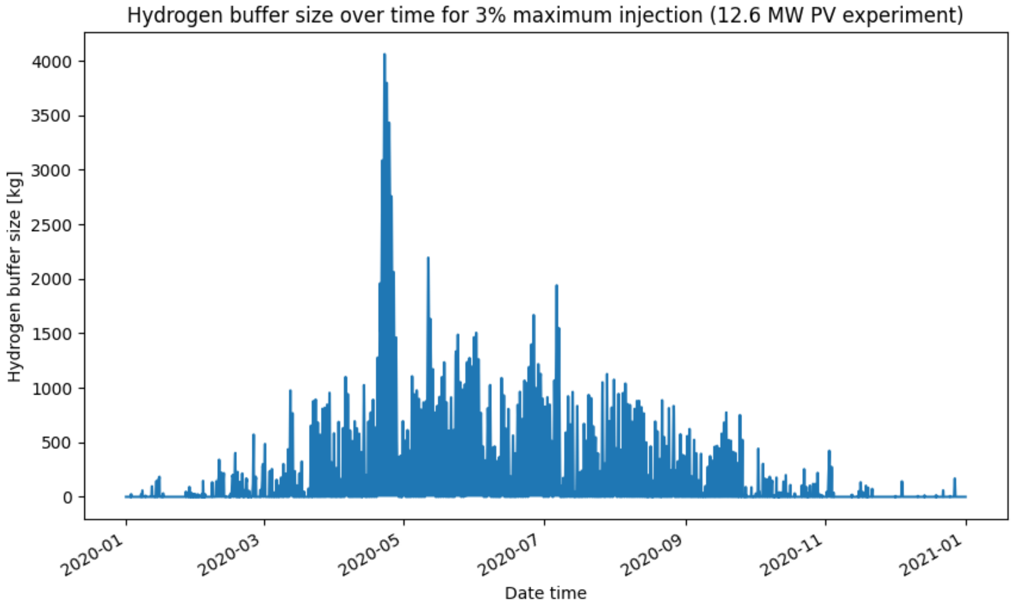
Appendix C1: Base case



Appendix C2: 12.6 MW wind capacity experiment

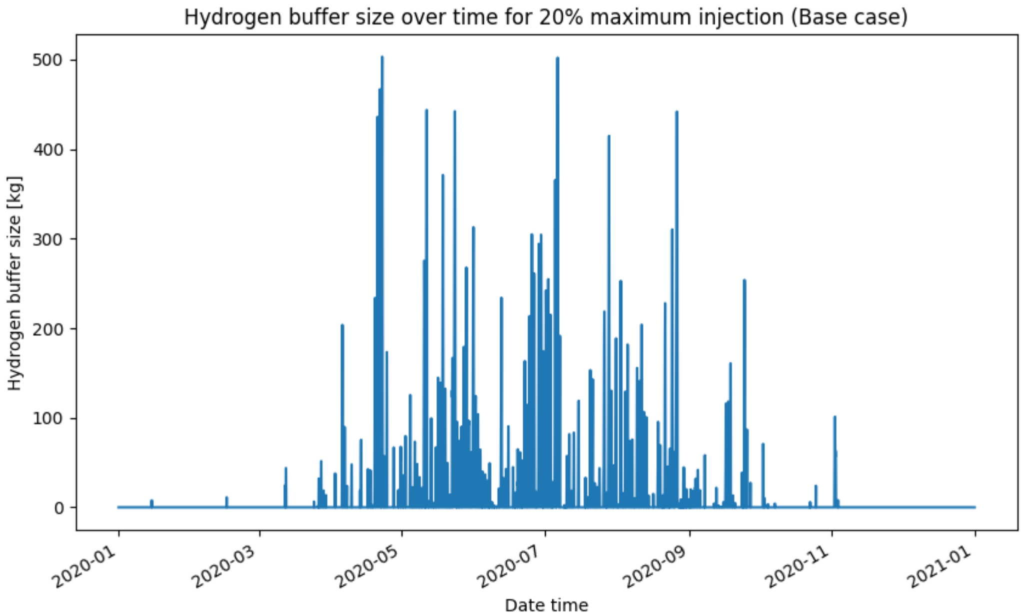


Appendix C3: 12.6 MW PV experiment

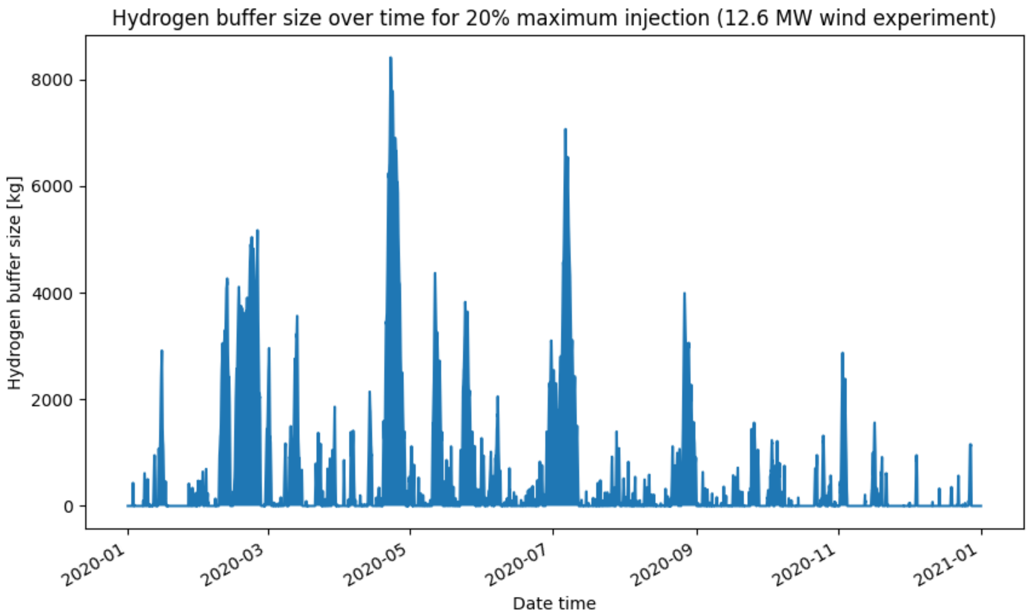


APPENDIX D: Hydrogen buffer size [kg] over time for the 20% maximum injection scenario

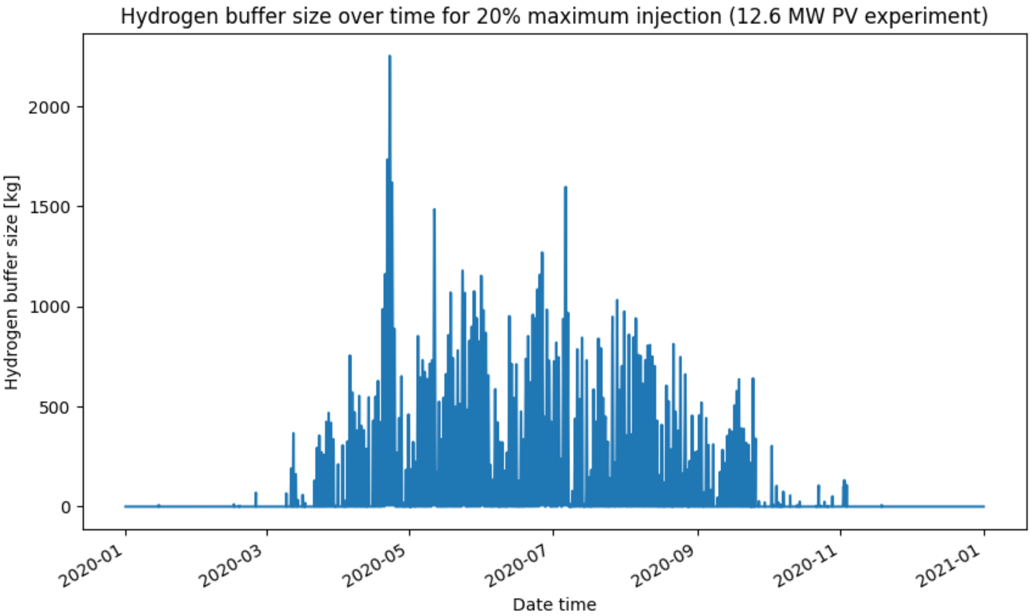
Appendix D1: Base case



Appendix D2: 12.6 MW wind experiment

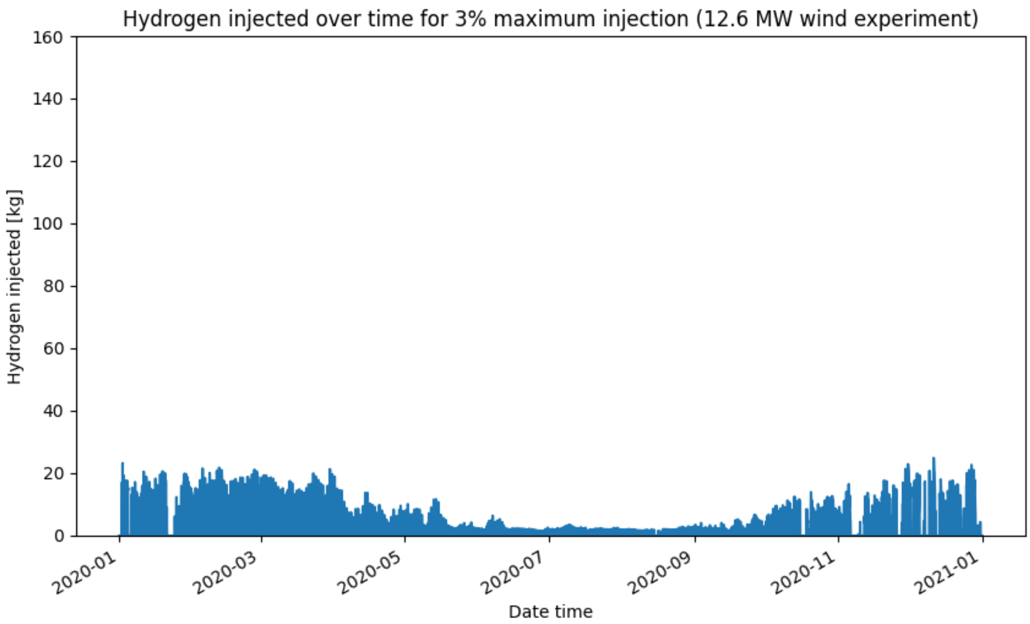


Appendix D3: 12.6 MW PV experiment

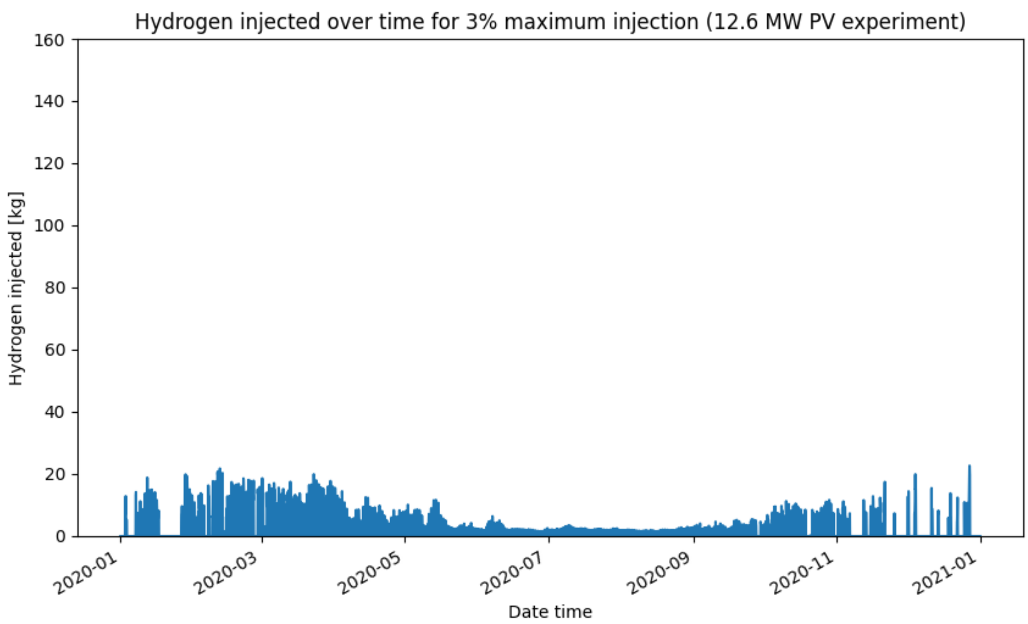


APPENDIX E: Total hydrogen injection for the 3% maximum injection scenario

Appendix E1: 12.6 MW wind experiment

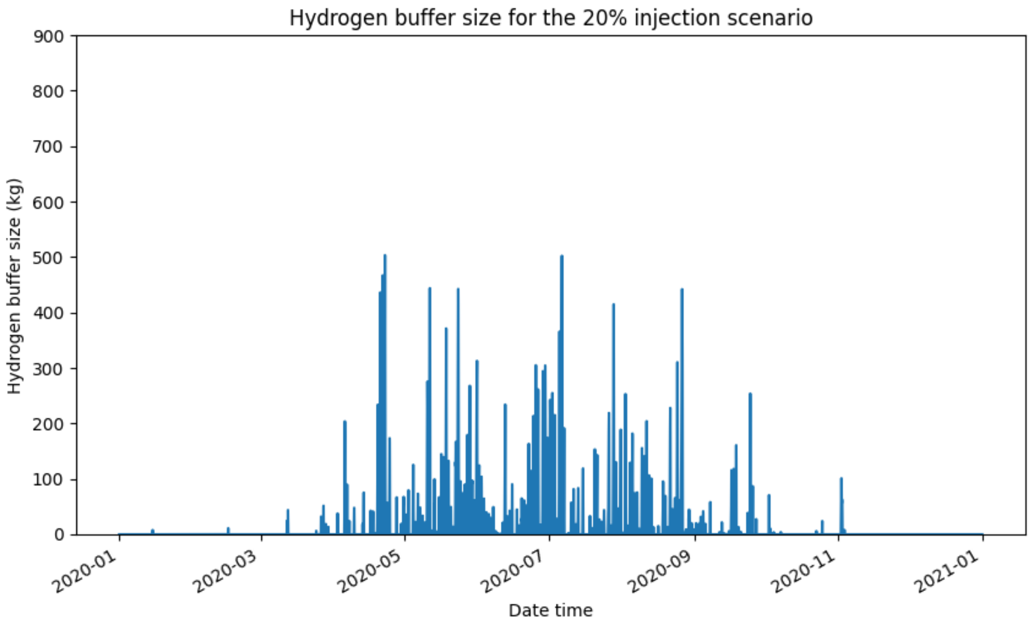


Appendix E2: 12.6 MW PV experiment



APPENDIX F: hydrogen buffer size [kg] over time for the 3% maximum injection scenario (with and without indirect injection from the buffer)

Appendix F1: With indirect injection



Appendix F2: Without indirect injection