RAPPORT

Hydrogen Fuel Station

Province of Drenthe, The Netherlands

Klant: Province of Drenthe

Referentie: BE1656-RHD-ZZ-XX-RP-Z-0001

Status: S0/P01.01

Datum: Monday, 30 March 2020

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Auteur(s):	Marin Epema, Anish Bosch, Bastian Knoors

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Classificatie
Alleen voor intern gebruik

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1 Summary

This report provides a qualitative as well as quantitative analysis for realization of a hydrogen fuel station. The quantitative part of this study contains an analysis of four scenarios regarding a hydrogen fuel station, running on locally produces hydrogen.

The produced hydrogen will fuel 10 hydrogen busses in the province of Drenthe. Results are presented in levelized cost of hydrogen by using current investment costs. The cost breakdown using the LCOH of the baseload scenario (scenario 4) is shown in . The main cost drivers are investment costs in both the electrolyser and the fuel station (compression, buffers, etc). Electricity costs and energy tax are the main operational costs.

Table 1: LCOH breakdown of scenario 4

Investment fuelstation	€	4,00
O&M fuel station	€	0,78
Electricity costs	€	0,16
Energy tax	€	0,10
subtotal fuel station	***€***	***5,04***
Investment electrolyser	€	3,07
Electricity costs (incl cert)	€	3,42
Energy tax	€	2,17
O&M electrolyser	€	1,10
subtotal electrolyser	***€***	***9,77***
Subsidie	***€***	***-0,84***
Totaal LCOH	***€***	***13,96***

The results per scenario are summarized in Table 2

. The lowest price is realized when the system is designed as small as possible in scenario 4. This results in a full load operation and does not allow for flexibility. Scenario 1 and 2 have some flexibility to respond to local energy production and scenario 3 represents an off-grid system.

Table 2: Scenario results LCOH and amount of direct green electricity

Scenarios	LCOH	Green electricity
1: Local solar	16 €/kg H_2	62%
2: Local solar and wind	16 €/kg H_2	72%
3: Only green electricity	19 €/kg H_2	100%
4: High full load hours	14 €/kg H_2	54%

The main conclusions of the quantitative analyses are:

- Local produced hydrogen in the current market will cost at least 14€/kg;
- Dedicated (off grid) hydrogen production for a fuel station is very expensive due to large buffers needed.

This study also includes a qualitative analysis, focusing on legal aspects. Several permits will have to be requested to obtain permission for realization of a hydrogen fuel station. The duration of the permitting process normally varies between 9 months to over a year, depending on the necessary procedures to follow.

The northern region of The Netherlands already acquainted knowledge on legal procedures regarding the realization of hydrogen fuel stations.
Legal and safety experience is easily transferrable between regions, provinces and institutions. Realization of a hydrogen fuel station will most likely not be subjected to any constraints regarding permitting, due to high political ambitions on hydrogen.

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2 Introduction

The strive to restrain climate change increased importance to replace conventional fuels by sustainable fuels such as hydrogen. Hydrogen, in association with a fuel cell, enables both passenger vehicles and heavy-duty vehicles such as trucks, buses and special vehicles to drive electrically without locally emitting any CO_2.

On several locations in Europe hydrogen fuel stations have been realized out of which two have been realized in the northern part of The Netherlands in order to allow several special vehicles and two buses to fuel. Yet, more vehicles are to come. The public transport office (OV-Bureau) of Groningen and Drenthe have recently announced to deploy a total 20 hydrogen buses in the Dutch provinces of Groningen and Drenthe (northern provinces of The Netherlands).

The Province of Drenthe joined research as part of the Interreg project ‘HyTrec2’ on the development of hydrogen-based infrastructure, technologies and skills, focusing on an analysis of scenarios for hydrogen production, transport and consumption as a fuel for buses. In this report, several scenarios are presented, based on the answers on the following questions which were proposed by HyTrec2:

Questions for analysis of scenarios for hydrogen production, transport and consumption as a fuel for buses:

- Costs of investment
- Costs for management
- Technical specifications: pressure, refueling time, number of vehicles, storage capacity and speed of hydrogen production
- Origin of (green) electricity and costs of electricity
- Costs of hydrogen and price at which hydrogen is sold at
- Is oxygen sold?
- Synergies with electric or gas grid (storage, pumping and reforming, etcetera)
- Other customers and expected growth of vehicle fleet
- Experiences from management and urban planning, permits and risks
- Local/national financial benefits and/or incentives

2.1 Reading guide

First, in chapter 3, technical and financial figures and assumptions which are used as input for the model that was composed are presented. In chapter 4, four scenarios are briefly explained. Each scenario consists of an overview of assumptions, sources of hydrogen, the required transport and storage of hydrogen and specifications of capacities. Each scenario will also contain a business case, including levelized costs of hydrogen.

In chapter 5, a regional and national perspective on development of hydrogen as a fuel will be described, focusing on synergies with the electricity grid, potential oxygen users, potential growth of vehicle fleet and legal and management matters. Also, the chapter will provide an overview of local and national financial benefits or incentives. The last chapter provides the conclusion of the analysis.

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3 Technical and financial assumptions

For this feasibility study, cost estimates and technical parameters are based on interviews with market parties and a variety of researches, including the IEA "Future of Hydrogen". Findings from these studies were checked in cooperation with market parties. This chapter provides the sources of used parameters and technical and financial assumptions.

3.1 Technical aspects and volumes

Electrolyser technology
Different types of technologies can be used for producing hydrogen from electricity. Best known are Alkaline, PEM and SOEC electrolysers. This study will be based on PEM electrolyzer, a technology which was also used in a comparable project in Pau (France). The main advantage of this technology is the high pressure at which the stack can operate, saving investment costs of compressors and energy. Nevertheless, the investment costs, and efficiency are not (yet) as attractive as alkaline electrolysers.
Because SOEC technology is still at an early stage of development, the technology was not considered in this study.

Electrolyser efficiency
The efficiency used in the model is 56%(LHV). This is the lower margin of the IEA Future of Hydrogen report for PEM electrolysis. The lower margin is used because the small scale of this project will lead to a relatively high energy use for auxiliary systems.

	Alkaline electrolyser			PEM electrolyser			SOEC electrolyser		
	Today	2030	Long term	Today	2030	Long-term	Today	2030	Long term
Electrical efficiency (%, LHV)	63–70	65–71	70–80	56–60	63–68	67–74	74–81	77–84	77–90

Figure 1 IEA Future of hydrogen, electrical efficiency

Other hydrogen related studies often claim a much higher efficiency for three reasons:

1. The study assumes advances in technology and uses the year 2030 or other long-term figures;
2. Because of the scale, the upper range of the efficiency is applicable;
3. The efficiency percentage is a bit tricky. There is difference in LHV and HHV efficiency. An efficiency using the higher heating value (HHV, 140 MJ/kg) will always be higher compared to the lower heating value (LHV, 120 MJ/kg) efficiency. The difference between LHV and HHV is the heat of condensation from water in flue gasses and results in a ~10% difference in efficiency. In this study the LHV efficiency is applied.

Compressor energy
In this study the electrolyser process generates hydrogen at a pressure of 20 Bar. This is compressed to 550 Bar for the fuel station. We assume an energy use of 2.8 kWh/kg based on vendor information.

Hydrogen for buses
The fuel economy of a hydrogen powered bus is assumed to be 10 km/kg. This number is based on experience from other projects.

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Amount and average distance of the busses

This study assumes a traveling distance of 360 km per bus per day for a total of 10 buses. Information is provided by the province of Drenthe. The buses will only operate from Monday to Friday and the total fueling time is spread out over 5 hours a day, 3 hours in the morning and 2 hours in the evening.

3.2 Investment and maintenance costs

Electrical connection

Because the project will be realized in the province of Drenthe, prices of the local grid operator ‘Enexis’ are applied. The investment costs are € 24,567 for a 1750 kVA connection with an additional € 64.55 for every meter from the nearest connection point. We assume 50 meter resulting in the connection costs of € 27,795.

Electrolyser

To take economies of scale into account we used fixed and variable cost to calculate total investment costs. Information is based on researches of market parties and results of the IEA study.

	Alkaline electrolyser			PEM electrolyser			SOEC electrolyser		
	Today	2030	Long term	Today	2030	Long-term	Today	2030	Long term
CAPEX (USD/kW$_e$)	500 – 1400	400 – 850	200 – 700	1 100 – 1 800	650 – 1 500	200 – 900	2 800 – 5 600	800 – 2 800	500 – 1 000

Figure 2 CAPEX of electrolysers, IEA Future of Hydrogen

The fixed costs are based on the difference in lower and upper range of the IEA results for a 1 MW unit. Converted to euro’s this is roughly € 500,000 per unit. Costs per MW are based on the lower range, resulting in € 1,000,000 €/MW. Based on research of market parties a maintenance percentage of 5% is applied.

Compressor

The compressor is a key component of the system. It is necessary step to compress produced hydrogen when the electrolyser is in operation and when the system is fueled using a tube trailer. For instance, in case of maintenance. Therefore, a redundant compressor is assumed in the system. The investment costs of the compressor are based on the NREL study “H2FIRST Reference Station Design Task” and adjusted to €500,000 for a 25 kg/hour unit (20 to 550 Bar), based on research of market parties. Based on the same sources, maintenance costs of 4% of CAPEX are assumed.

Buffer

The fuel station uses 3 types of buffers. One 20 Bar buffer directly after the electrolyzer and a second 50 Bar buffer for larger storage capacity. The last buffer consists of 550 bar storage in order to fuel the buses. Prices are based on the Dace Price Booklet and research of market parties. Maintenance costs are estimated on 3% of CAPEX for all buffers.

Table 3 Hydrogen storage prices

Pressure	Unit	Price
20 Bar	10 m^3 tank	€ 50,000
50 Bar	Cost per kg storage	€ 500
550 Bar	1.3 m3 cylinder	€ 30,000

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Fuel station dispenser
The costs for a hydrogen dispenser are based on the NREL H2FIRST study combined with research of market parties. The estimate used in the model is € 75,000 per dispenser.

Other costs
Several additional costs add up to the CAPEX of the individual components. A total of €75,000 for Piping and valves was added, based on the NREL H2FIRST study. Also, a general percentage of 40% was added on all investments for engineering costs, control systems and installation (based on the NREL H2FIRST study). Also, 10% contingency was included.

3.3 Energy costs

Electricity price
The Dutch electricity price development is estimated in the "Klimaat en Energieverkenning 2019" (KEV). Two estimates for 2020 (43 €/MWh) and 2030 (57 €/MWh) are used to calculate a year on year indexation of 2.86%.
Fluctuations or hourly energy prices during the year were not considered in this study. Therefore, electrical energy has the same price during periods of shortage and abundance of renewable energy.

Energy tax
The energy tax and the renewable energy surcharge (ODE) is used as published by the Dutch tax authority. An indexation equal to the general indexation rate of 2% is assumed and applied in this study.

Table 4 Energy tax and the renewable energy surcharge in The Netherlands 2020

Year 2020	0 - 10 MWh	10 - 50 MWh	50 – 10,000 MWh	From 10,000 MWh
Energy tax	97.7 €/MWh	50.83 €/MWh	13.53 €/MWh	0.55 €/MWh
Renewable energy surcharge (ODE)	27.30 €/MWh	37.50 €/MWh	20.50 €/MWh	0.40 €/MWh

Green electricity certificates
The price for green electricity certificates is based on information from the website www.wisenederland.nl. In this study the lower margin of Dutch wind certificates was assumed, because of the large quantities of electricity used in this project. The price is 7 €/MWh.

Total energy price
In this project ~6,000 MWh of electricity a year is assumed, resulting in an average total energy tax of 34 €/MWh (year 1). Subsequently an average total energy price of 84€/MWh (8.4 ct/kWh) is assumed.

- 51% of this price is the wholesale energy price;
- 41% are taxes;
- 8% is due to the green certificates.

3.4 Financial

WACC
For the financial analysis and the calculation of the LCOH a Weighted Average Cost of Capital (WACC) of 6% is used.

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Technical lifetime

The lifetime of the all equipment is assumed to be 10 years. No residual value or reinvestments are considered. The lifetime of 10 years is within the range of the stack lifetime published by the IEA. In this study we assume a lifetime of approximately 80.000 hours.

	Alkaline electrolyser			PEM electrolyser			SOEC electrolyser		
	Today	2030	Long term	Today	2030	Long-term	Today	2030	Long term
Stack lifetime (operating hours)	60 000 – 90 000	90 000 – 100 000	100 000 – 150 000	30 000 – 90 000	60 000 – 90 000	100 000 – 150 000	10 000 – 30 000	40 000 – 60 000	75 000 – 100 00

Figure 3 IEA Future of hydrogen, stack lifetime

Levelized cost of hydrogen

In this study, levelized costs of hydrogen (LCOH) were calculated using the levelized cost of energy methodology:

$$\mathrm{LCOE} = \frac{\text{sum of costs over lifetime}}{\text{sum of electrical energy produced over lifetime}} = \frac{\sum_{t=1}^{n} \frac{I_t+M_t+F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}}$$

I_t: investment expenditures in the year t
M_t: operations and maintenance expenditures in the year t
F_t: fuel expenditures in the year t
E_t: hydrogen produced in the year t
r: discount rate
n: expected lifetime of system or power station

This methodology leads to an average price at which hydrogen should be sold to reach a business case of zero NPV over the lifetime.

4 Scenarios

In this chapter scenarios for hydrogen production, transport, storage and consumption as a fuel for buses are presented. Based on interviews with market parties, modulations and calculations, specifications of source of hydrogen and electrolysis are determined as well as specifications of required storage, compression and speed of transfer of hydrogen. Subsequently, total costs of ownership and levelized costs of hydrogen are calculated. Four scenarios are distinguished:

1. **Local solar,** Production of hydrogen by a combination of (locally produced) solar energy and electricity obtained from the existing grid;
2. **Local solar and wind,** Production of hydrogen by a combination of (locally produced) solar energy, wind energy and electricity obtained from the existing grid;
3. **Only green electricity,** Production of hydrogen by a combination of solar energy and wind energy, including large storage capacities;
4. **High full load hours,** Production of hydrogen by a combination of (locally produced) solar energy, wind energy and electricity obtained from the existing grid, reaching full load electrolysis.

4.1 Scenario 1: local solar

In this scenario we assume a local solar PV park producing electricity to cover demand of the electrolyser on a yearly basis. The electrolyser will run as much as possible on this green energy source. When the hydrogen buffer is too low, grey electricity from the grid is used to produce hydrogen. In general, the system will run on solar energy in summer periods and will use grid power in wintertime.

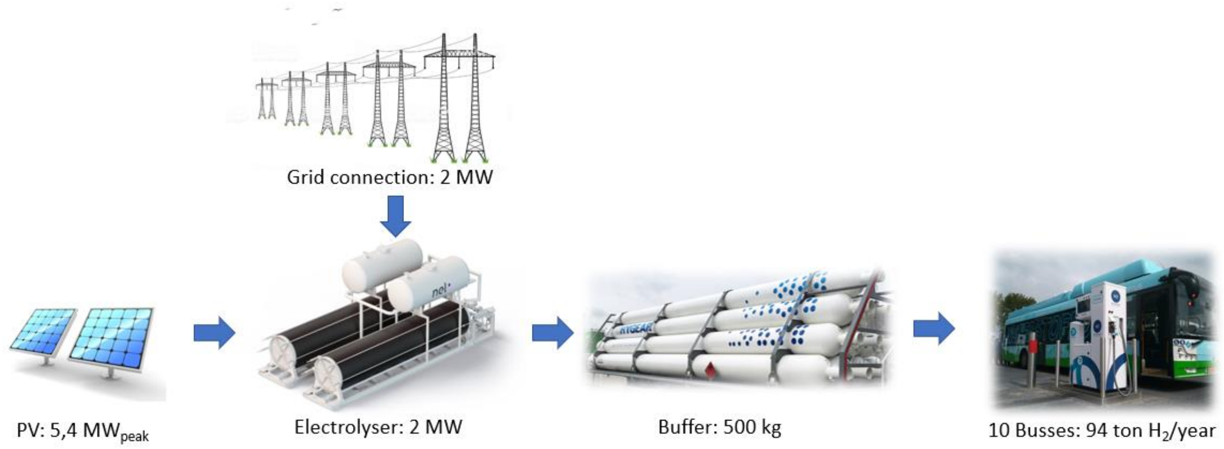

Figure 4 Overview of components in scenario 1

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4.1.1 System overview and assumptions

Scenario one was based on the following assumptions:

- Merely local solar power as a renewable source;
  - The total amount of solar energy covers the total amount of electricity required. And thus, the same amount of MWh/yr. However, as there is a mismatch between solar power and hydrogen production, grey electricity is required;
- Grid electricity for the remaining requirement;
- Buffer size and control to make sure that there is never a shortage of hydrogen to fuel buses;
  - To optimize the usage of green electricity the model was made such that grey electricity would only be used when the buffer reaches below the minimum amount for one consecutive use-cycle (when the buses must be fueled in the 3-hour morning period);
  - Initial buffer level is equal to the minimum amount: 216kg.

Table 5 provides an overview of the main system component sizing for scenario 1. It also shows some key parameters of the functioning of the production plant and fueling station. These parameters include:

- The absolute and relative usage of green electricity;
- The absolute and relative usage of grey electricity;
- The surplus of green electricity that could not be used due to electrolyzer and buffer size limitations;
- The Levelized Cost of Hydrogen (LCOH);
- The total initial CAPEX;
- And a breakdown of the LCOH per main component (subsidies, electrolyzer, and fuel station).
-

Table 5: Overview of system components and key parameters – scenario 1

Component overview Scenario 1			
Component	**Value**	**Unit**	
Electrolyzer	**2.0**	**MW**	
Sun	5.4	MWp	
Wind	0	MW	
Buffer	500	kg	
Hydrogen produced from local green energy	**58,018**	**kg/yr**	**62%**
Hydrogen produced from grid	35,969	kg/yr	38%
Full load hours production	2,796	hr.	
Surplus green electricity	18,293	kg/yr	
LCOH	**€ 16.70**	**/kg H2**	
CAPEX	€ 6,809,445		
LCOH Subsidies	-€ 1.98	/kg H2	
LCOH Subtotal Electrolyzer	€ 13.40	/kg H2	
LCOH Subtotal Fuel station	€ 5.29	/kg H2	

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4.1.2 Cost overview and sensitivity

In Table 6 an investment cost overview of the entire electrolyser and fuel station is provided.

Table 6: Cost overview scenario 1

Costs overview scenario 1							
	Assumption	Unit	Used Capacity		CAPEX	OPEX	
Electrical connection	€ 27,795	€/#	1	Conn.	€ 27,795		€ 59,680
Electrolyser Fixed	€ 500,000	€/#					
Electrolyser Variable	€ 1,000,000	€/MW	2	MW	€ 2,500,000	5%	€ 125,000
Installation engineering and control	40%				€ 1,011,118		
Contingency	10%				€ 353,891		
Subtotal Electrolyser					**€ 3,892,804**		**€ 184,680**
Compressor	€ 500,000	€/#*	30	kg/hr,	€ 600,000	4%	€ 24,000
Redundant compressor	€ 500,000	€/#*	30	kg/hr,	€ 600,000	4%	€ 24,000
Buffer 20 Bar	€ 50,000	€/#	1	#	€ 50,000	3%	€ 1,500
Buffer 50 Bar	€ 500	€/kg	284	kg	€ 142,000	3%	€ 4,260
Buffer 550 Bar	€ 30,000	€/#	9	#	€ 276,923	3%	€ 8,308
Dispenser	€ 75,000	€/#	2	#	€ 150,000	3%	€ 4,500
Piping and valves	€ 75,000				€ 75,000	3%	€ 2,250
Installation engineering and control	40%				€ 757,569		
Contingency	10%				€ 265,149		
Subtotal fuel station					**€ 2,916,642**		**€ 68,818**
Total CAPEX					**€ 6,809,445**		

* A compressor unit is 25 kg/unit

Sensitivity analysis

The main component sizes for green power production and electrolyzer size are fixed in scenario 1, except for the buffer size. A sensitivity analysis was performed to discover the 'behavior' of the system and the LCOH with a varying buffer size. Figure 5 shows this sensitivity analysis.

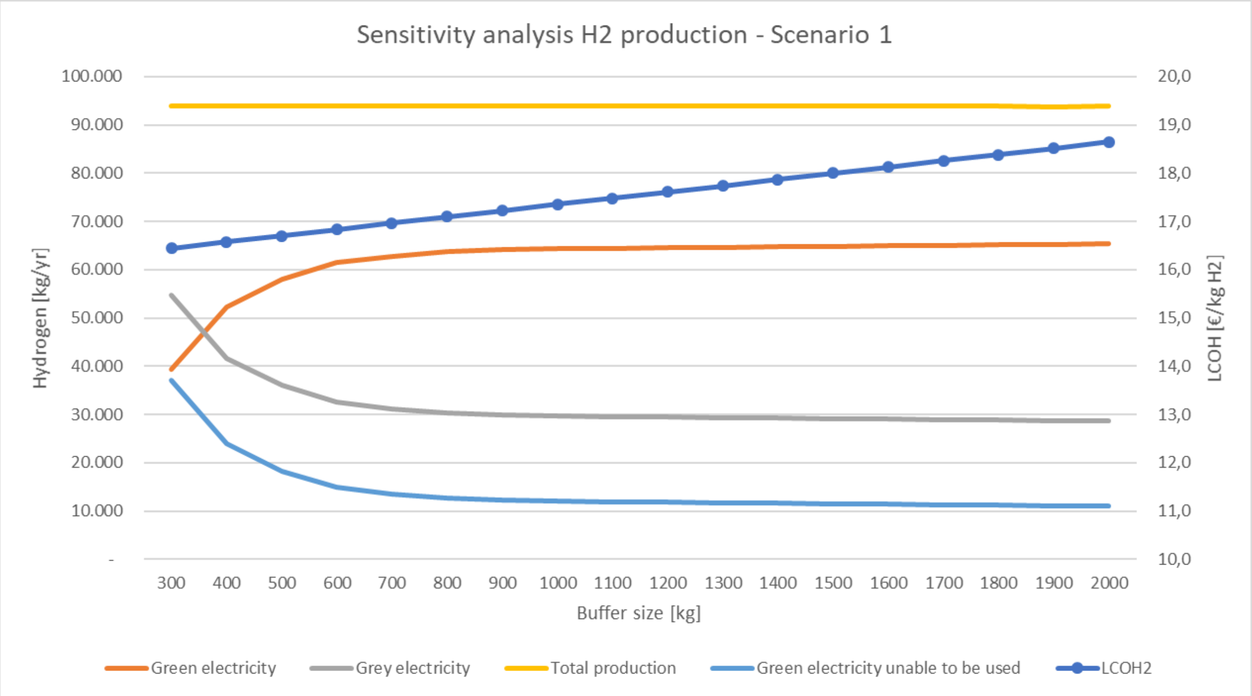

Figure 5: sensitivity analysis - scenario 1

It was found that for a buffer of approximately 500kg an 'optimal' balance was reached for the system. At this point the LCOH was still relatively low, there was no shortage from the buffer, a significant portion of green electricity was used, and overall solar power production covers the electricity requirement for the entire year. Further increase of the buffer size would only marginally increase the amount of green electricity usage, whilst at the same time increasing the LCOH.

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4.1.3 Electrolyser control

As the system was modelled with hourly data, there is the possibility of observing the system ´behavior´ during different seasons or days. Figure 6 shows the system ´behavior´ for scenario 1 for 3 summer days.

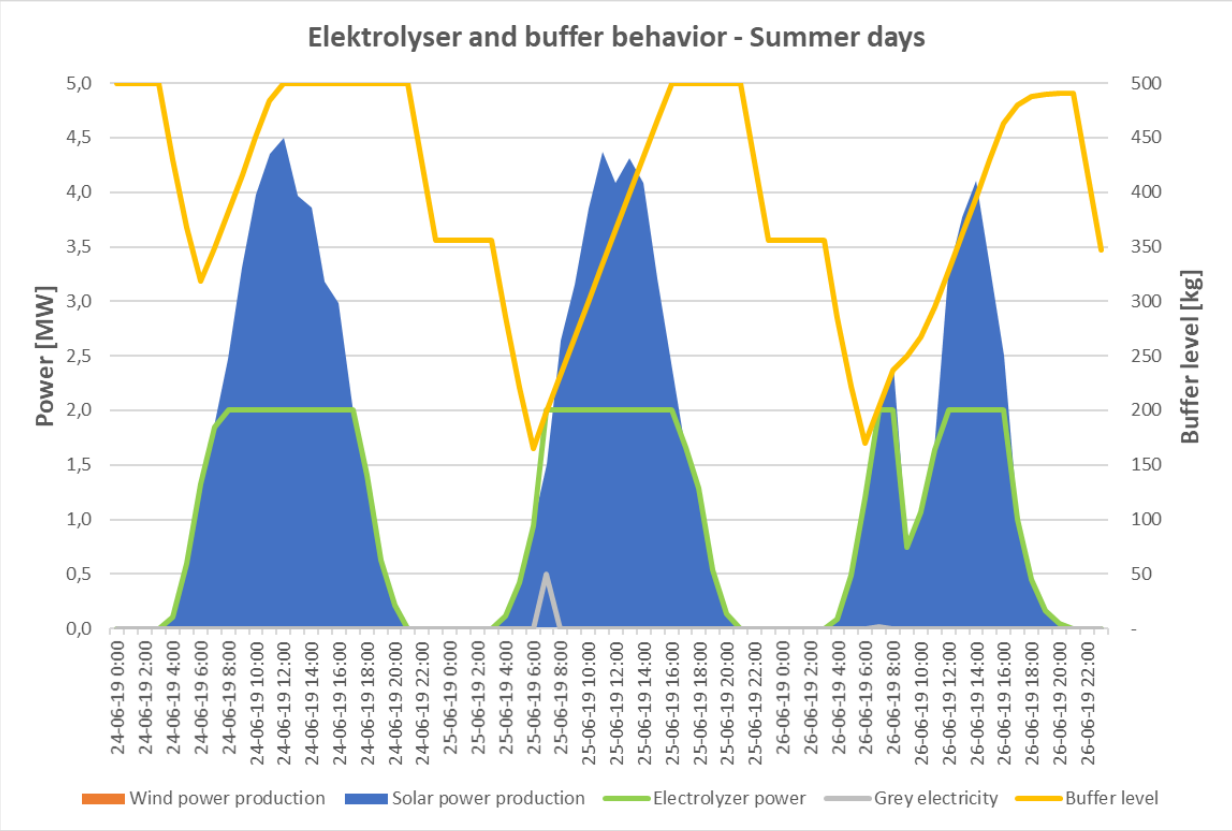


Figure 6: Electrolyzer system behavior - summer days - scenario 1

This figure shows where solar power production exceeds the maximum capacity of the electrolyzer. This surplus is seasonal and cannot be avoided, hence the requirement for grey electricity when solar power is not enough in winter. This figure shows that during these three particular days hardly any grey electricity is required. It is only required when the buffer level is below 216kg and there is not enough solar power. Last, the figure also shows that the buffer reaches maximum capacity on all these three days.

Figure 7 shows 3 winter days.

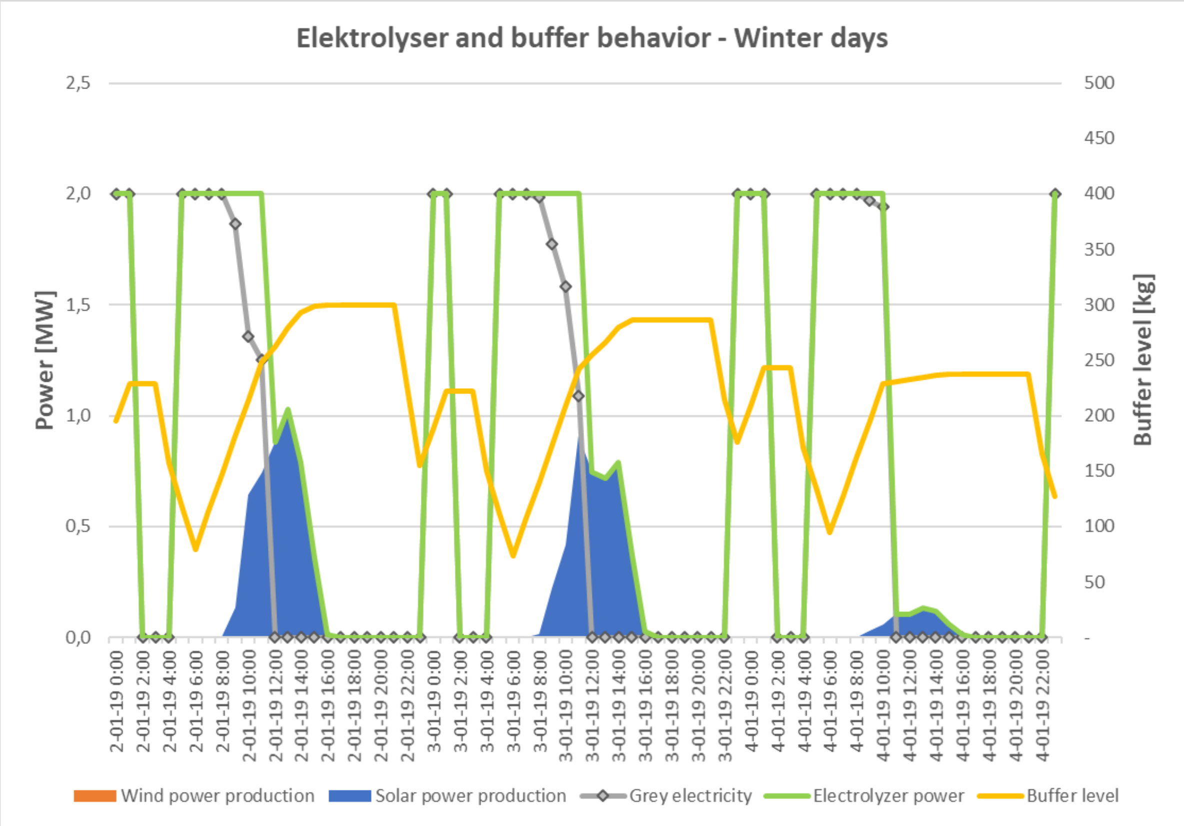


Figure 7:Electrolyzer system behavior - winter days - scenario 1

This figure clearly shows that the usage of grey electricity is necessary for proper functioning of the fuel station. The graph for grey electricity and the graph for the electrolysis power coincide on most parts of the graph. Solar power is not nearly sufficient for enough hydrogen production. Also, the buffer never reaches its maximum capacity. It only manages to maintain enough for the maximum usage of the fuel station.

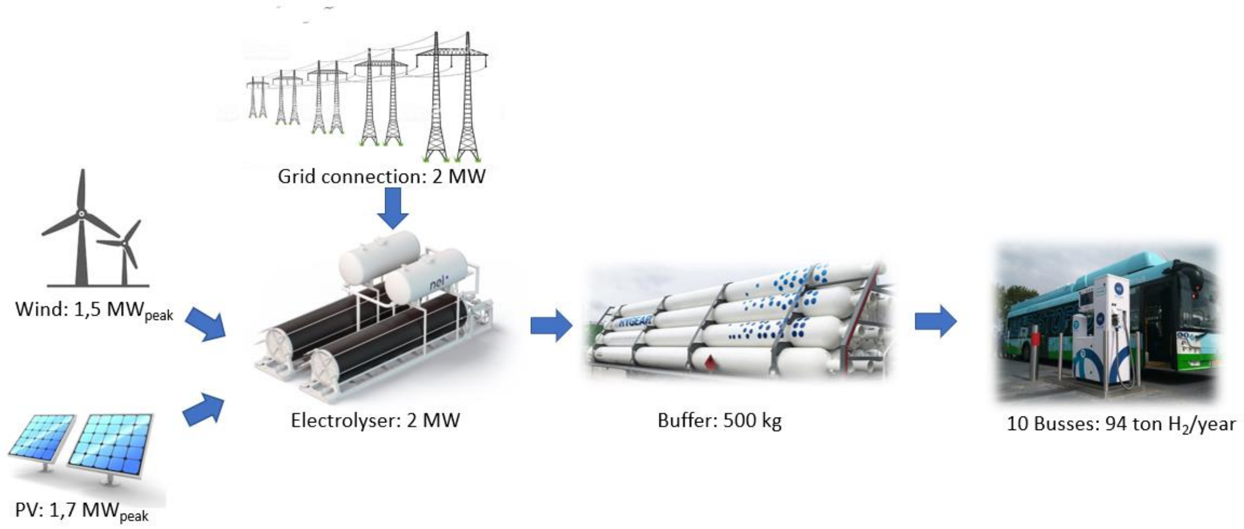
4.1.4 Conclusions

For scenario 1 the following overall conclusions can be made:

- An LCOH of 16€/kg H_2 using 62% direct solar energy.
- The fuel station can only operate properly with the addition of grey electricity. Using only solar power requires an unrealistically large buffer of 30,000kg and a larger electrolyser, resulting in an LCOH of: 65 €/kgH2.

4.2 Scenario 2: Local solar and wind

In this scenario we added local wind production to feed the electrolyzer. Combining wind and solar energy provides a more constant supply of renewable energy. When no renewable sources are available, the grid is used as power source.



4.2.1 System overview and assumptions

For scenario 2 the case was based on the following main assumptions:

- Solar and wind power as a renewable source:
  - The total amount of green energy should cover the total amount of electricity required and thus, the same amount of MWh/yr. However, as there is a mismatch between green power and hydrogen production, grey electricity is required;
  - For the installed capacity of PV and wind roughly a 50/50% division is used based on experience in earlier projects, no optimization has been performed;
- Grey electricity for the remaining requirement;
- Buffer size and handling such that there would never be a shortage of hydrogen when required:
  - To optimize the usage of green electricity the model was made such that grey electricity would only be used when the buffer reaches below the minimum amount for one consecutive use-cycle (when all the busses must be fueled in a 3-hour period, 216kg);
  - Initial buffer level is 216 kg.

Table 7 below provides an overview of the main system component sizing for scenario 2. It also shows some key parameters of the functioning of the production plant and fueling station. These parameters include:

- The absolute and relative usage of green electricity;
- The absolute and relative usage of grey electricity;
- The surplus of green electricity that could not be used due to electrolyzer and buffer size limitations;
- The Levelized Cost of Hydrogen (LCOH);
- The total initial CAPEX;
- And a breakdown of the LCOH per main component (subsidies, electrolyzer, and fuel station).

Table 7:Overview of system components and key parameters - scenario 2

Component overview Scenario 2			
Component	**Value**	**Unit**	
Electrolyzer	**2**	**MW**	
Sun	1.7	MWp	
Wind	1.5	MW	
Buffer	500	kg	
Green electricity used	**67,537**	**MWh**	**72%**
Grey electricity required	26,430	MWh	28%
Full load hours production	2,796	hr.	
Surplus green electricity	26,107	kg/yr	
LCOH	**€ 16.71**	**/kg H2**	
CAPEX	€ 6,809,445		
LCOH Subsidies	€ -1.98	/kg H2	
LCOH Subtotal Electrolyzer	€ 13.40	/kg H2	
LCOH Subtotal Fuel station	€ 5.29	/kg H2	

Because the main components that influence system costs are the same as in scenario 1 (electrolyzer 2MW, buffer 500kg), the LCOH and other financial parameters are the same. There is currently no financial effect of the sizing of solar and wind power.

4.2.2 Cost overview and sensitivity

In Table 8 a cost overview of the entire electrolyser and fuel station is provided.

Table 8: Cost overview scenario 2

Costs overview scenario 2							
	Assumption	Unit	Used Capacity		CAPEX		OPEX
Electrical connection	€ 27,795	€/#	1	Conn.	€ 27,795		€ 59,680
Electrolyzer Fixed	€ 500,000	€/#					
Electrolyzer Variable	€ 1,000,000	€/MW	2	MW	€ 2,500,000	5%	€ 125,000
Installation engineering and control	40%				€ 1,011,118		
Contingency	10%				€ 353,891		
Subtotal Electrolyzer					**€ 3,892,804**		**€ 184,680**
Compressor	€ 500,000	€/#*	30	kg/hr,	€ 600,000	4%	€ 24,000
Redundant compressor	€ 500,000	€/#*	30	kg/hr,	€ 600,000	4%	€ 24,000
Buffer 20 Bar	€ 50,000	€/#	1	#	€ 50,000	3%	€ 1,500
Buffer 50 Bar	€ 500	€/kg	284	kg	€ 142,000	3%	€ 4,260
Buffer 550 Bar	€ 30,000	€/#	9	#	€ 276,923	3%	€ 8,308
Dispenser	€ 75,000	€/#	2	#	€ 150,000	3%	€ 4,500
Piping and valves	€ 75,000				€ 75,000	3%	€ 2,250
Installation engineering and control	40%				€ 757,569		
Contingency	10%				€ 265,149		
Subtotal fuel station					**€ 2,916,642**		**€ 68,818**
Total CAPEX					**€ 6,809,445**		

* A compressor unit is 25 kg/unit

Sensitivity analysis

The main component sizes for green power production and electrolyser size are fixed in scenario 2, except for the buffer size. A sensitivity analysis was performed to discover the 'behavior' of the system and the LCOH with a varying buffer size. Figure 8 shows this sensitivity analysis.

With a buffer size of 500kg the system would perform properly. At this point the LCOH was still relatively low, there was no shortage from the buffer, a significant portion of green electricity was used, and overall solar power production covers the electricity requirement for the entire year. Further increase of the buffer size could further increase the amount of green electricity that could be used, whilst also increasing the LCOH.

The difference with scenario 1 is that in scenario 2 an increase of the buffer size would have a more significant impact on the amount of green electricity that could be utilized. For example, at a buffer size of 800kg, 83% of the hydrogen could be produced using green electricity, at an LCOH of €16,7/kg

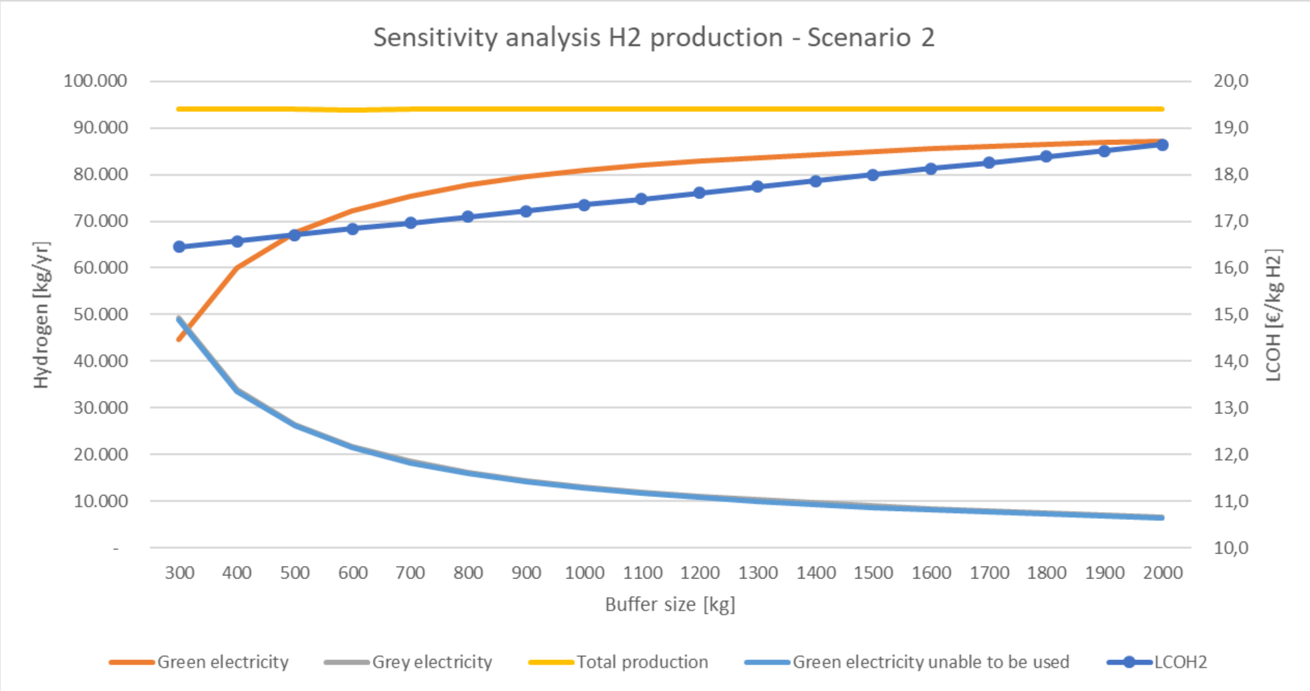


Figure 8: Sensitivity analysis - scenario 2

4.2.3 Electrolyser control

As the system was modelled with hourly data, there is a possibility to observe the system ´behavior´ during different seasons or days. Figure 9 shows the system ´behavior´ for scenario 2 for 3 summer days.

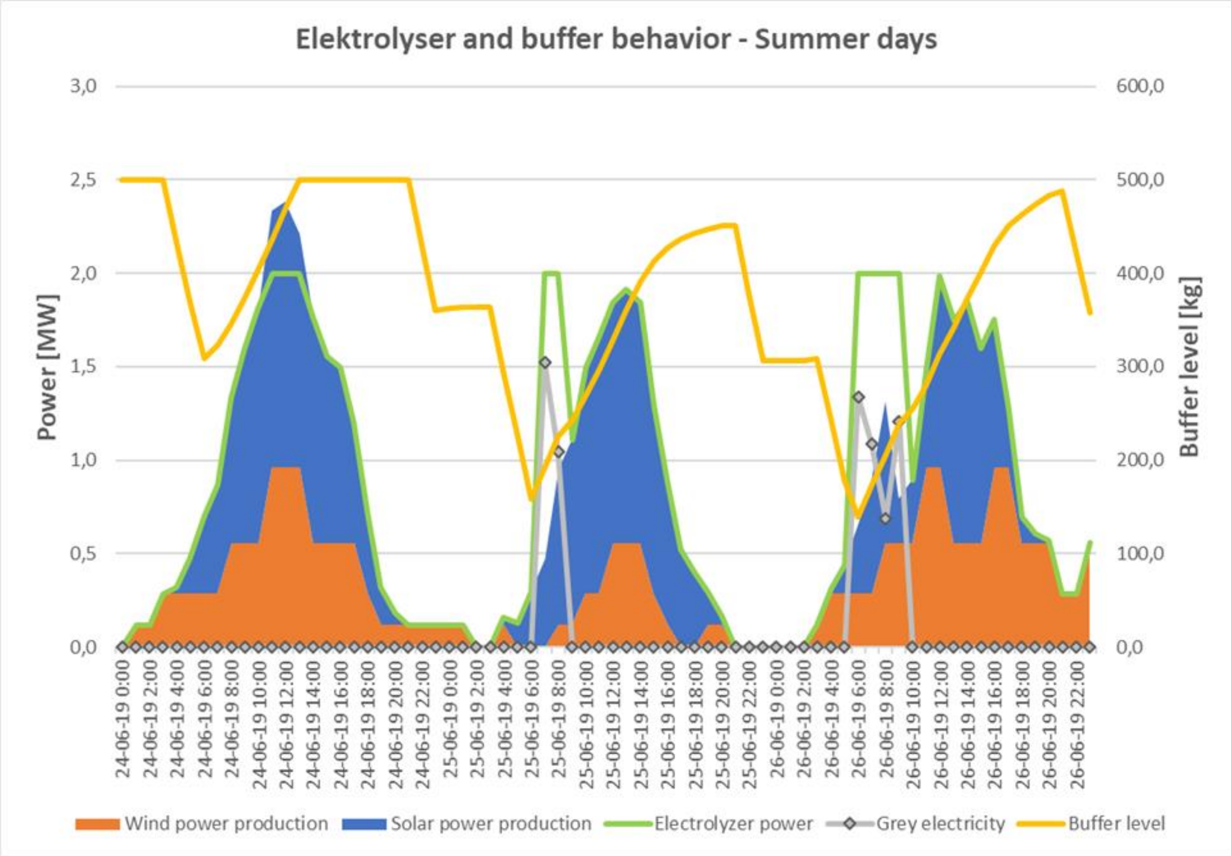


Figure 9: Electrolyzer system behavior - summer days - scenario 2

This figure shows where solar or wind power production exceeds the maximum capacity of the electrolyzer. This surplus is seasonal and cannot be avoided, hence the requirement for grey electricity when solar power is not enough in winter. However, because the solar system size is smaller, there is much less surplus, and thus a much more even balance of the electrolyzer power and the solar (and wind) power.

In comparison with scenario 1 there is a larger grey power demand during summer. However, when looking at the entire year overall the amount is less. As with scenario 1, grey power is only used when the buffer level is below 216 kg and there is not enough green power. Because of the smaller solar and wind power capacity the buffer level does not reach its maximum capacity on all days. However, this is not required.

Figure 10 shows 3 winter days in comparison.

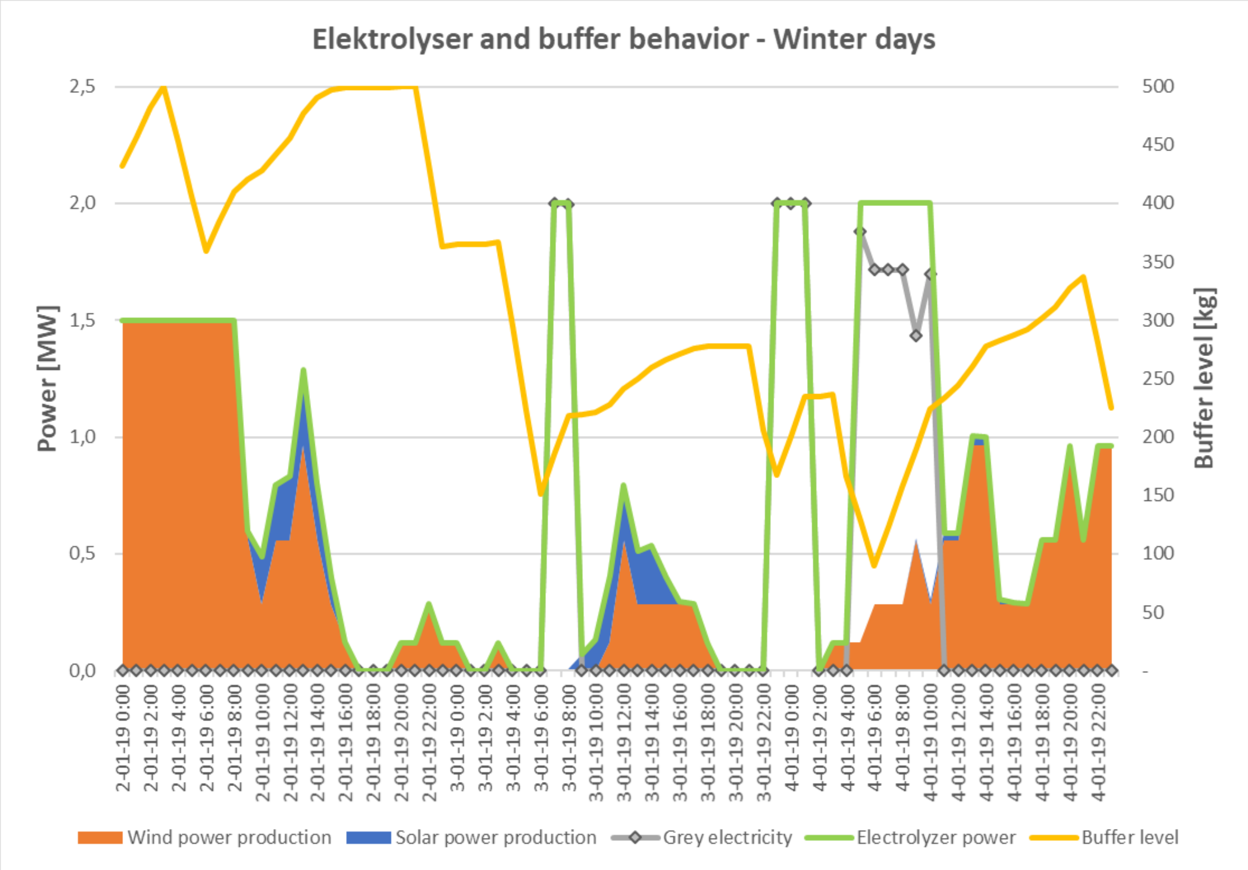


Figure 10:Electrolyzer system behavior - winter days - scenario 2

In scenario 2 there is less requirement for grey electricity than in scenario 1. Because now a combination of solar and wind power is used, there is more green electricity available to produce hydrogen. Solar power is not nearly sufficient for enough hydrogen production. The buffer has a higher average level than compared with scenario 1.

Overall conclusions

For scenario 2 the following overall conclusions can be made:

- The LCOH is 16 €/kg H_2 the same as scenario 1, but now using 72% of green electricity;
- It can only operate properly with the addition of grey electricity. Using only solar and wind power a very large buffer of 7,500 kg, resulting in an LCOH of: 26 €/kgH2.

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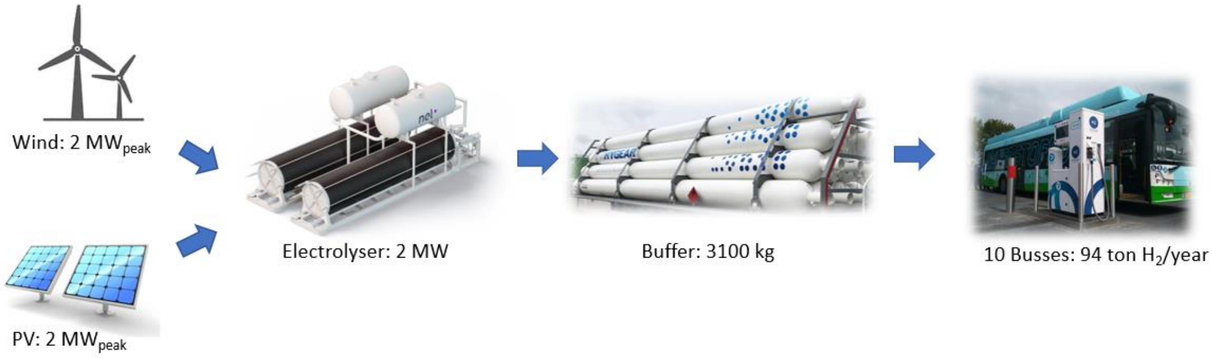
4.3 Scenario 3: Only green electricity

This scenario represents the off-grid situation. In this scenario, the electrolyser is directly powered by the installed solar and wind power. A large buffer ensures the availability of hydrogen for the busses.



4.3.1 System overview and assumptions

Scenario 3 was based on the following main assumptions:

- Solar and wind power as the only power source:
    - The installed renewable capacity is scaled to the electrolyser power;
- No use of grid electricity;
- Buffer size and handling such that there would never be a shortage of hydrogen when required:
    - Initial buffer level is 216 kg.

Table 9 provides an overview of the main system component sizing for scenario 3. It also shows some key parameters of the functioning of the production plant and fueling station. These parameters include:

- The absolute and relative usage of green electricity;
- The absolute and relative usage of grey electricity;
- The surplus of green electricity that could not be used due to electrolyzer and buffer size limitations;
- The Levelized Cost of Hydrogen (LCOH);
- The total initial CAPEX;
- And a breakdown of the LCOH per main component (subsidies, electrolyzer, and fuel station).

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Table 9: Overview of system components and key parameters - scenario 3

Component overview Scenario 3			
Component	**Value**	**Unit**	
Electrolyzer	**2**	**MW**	
Sun	2	MWp	
Wind	2	MW	
Buffer	3,100	kg	
Green electricity used	**95,720**	**MWh**	**100%**
Grey electricity required	-	MWh	0%
Full load hours production	2,796	hr	
Surplus green electricity	19,365	kg/yr	
LCOH	**€ 19.30**	**/kg H2**	
CAPEX	€ 8,768,643		
LCOH Subsidies	€ -1.98	/kg H2	
LCOH Subtotal Electrolyzer	€ 12.63	/kg H2	
LCOH Subtotal Fuel station	€ 8.65	/kg H2	

In scenario 3, the electrolyzer has the same size as in scenario 1 and 2 (2 MW). However, for there is no use of grey electricity the buffer capacity needs to be sufficient to provide the required amount of hydrogen when needed. In scenario 3 the buffer needs to be at least 3,100 kg to avoid any shortage of hydrogen, given the solar power and wind power sizes (2MW installed capacity for solar and wind power each). There is currently no financial effect of the sizing of solar and wind power.
Because of the larger buffer size, the LCOH and initial CAPEX for scenario 3 is higher.

4.3.2 Cost overview and sensitivity

In Table 10 a cost overview can be seen of the entire electrolyser and fuel station.

Table 10: Cost overview scenario 3

Costs overview scenario 1							
	Assumption	Unit	Used Capacity		CAPEX	OPEX	
Electrical connection	€ 27,795	€/#**	-	Conn.			
Electrolyzer Fixed	€ 500,000	€/#					
Electrolyzer Variable	€ 1,000,000	€/MW	2	MW	€ 2,500,000	5%	€ 125,000
Installation engineering and control	40%				€ 1,000,000		
Contingency	10%				€ 350,000		
Subtotal Electrolyzer					**€ 3,850,000**		**€ 125,000**
Compressor	€ 500,000	€/#	30	kg/hr,	€ 600,000	4%	€ 24,000
Redundant compressor	€ 500,000	€/#	30	kg/hr,	€ 600,000	4%	€ 24,000
Buffer 20 Bar	€ 50,000	€/#***	1	#	€ 50,000	3%	€ 1,500
Buffer 50 Bar	€ 500	€/kg	2,884	kg	€ 1,442,000	3%	€ 43,260
Buffer 550 Bar	€ 30,000	€/#	9	#	€ 276,923	3%	€ 8,308
Dispenser	€ 75,000	€/#	2	#	€ 150,000	3%	€ 4,500
Piping and valves	€ 75,000				€ 75,000	3%	€ 2,250
Installation engineering and control	40%				€1,277,569		
Contingency	10%				€ 447,149		
Subtotal fuel station					**€ 4,918,641**		**€ 107,817**
Total CAPEX					**€ 8,768,642**		

* A compressor unit is 25 kg/unit

Sensitivity analysis

The main component sizes for green power production and electrolyser size are fixed in scenario 3, except for the buffer size. A sensitivity analysis was performed to discover the 'behavior' of the system and the LCOH with a varying buffer size. Figure 11 shows this sensitivity analysis.

As the system is now solely reliant of the buffer for enough hydrogen, a large buffer of 3,100 kg is required to avoid any shortage. Any further increase of the buffer would have little effect on any of the other factors except for the increased LCOH.

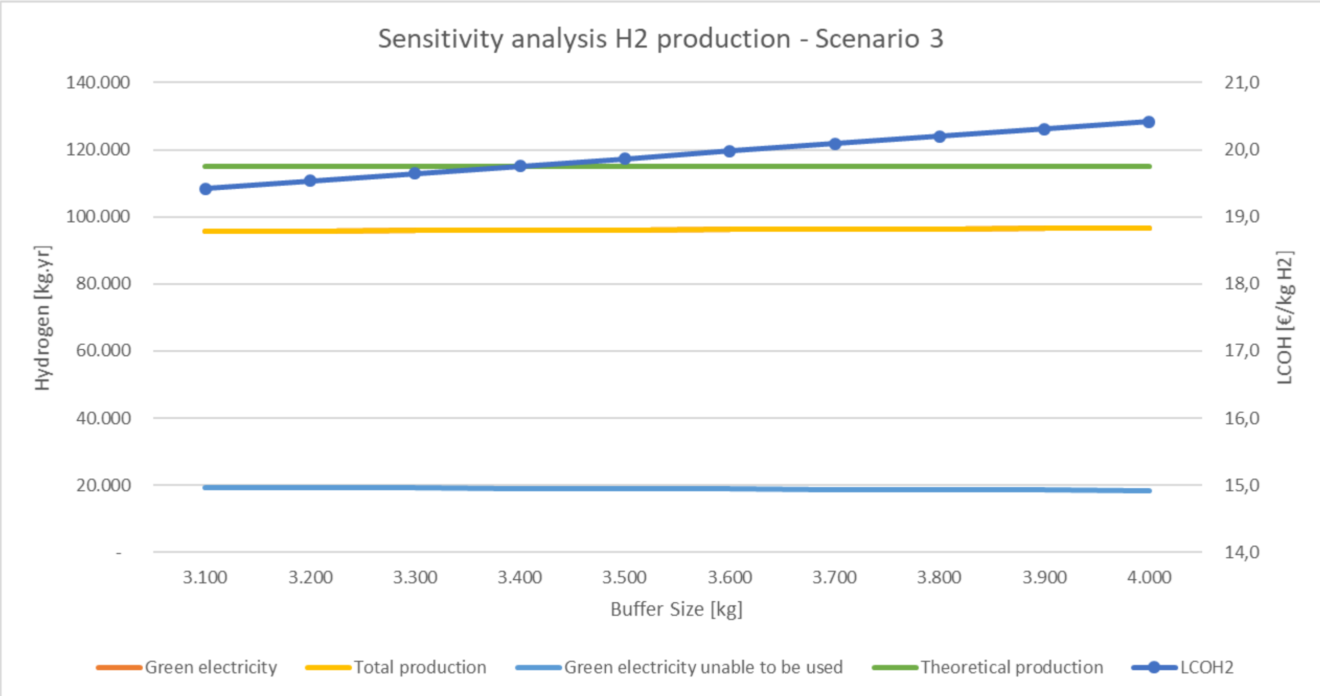


Figure 11: Sensitivity analysis - scenario 3

4.3.3 Electrolyser control

As the system was modelled with hourly data, there is the possibility of observing the system ´behavior´ during different seasons or days. Figure 12 shows the system ´behavior´ for scenario 3 for 3 summer days.

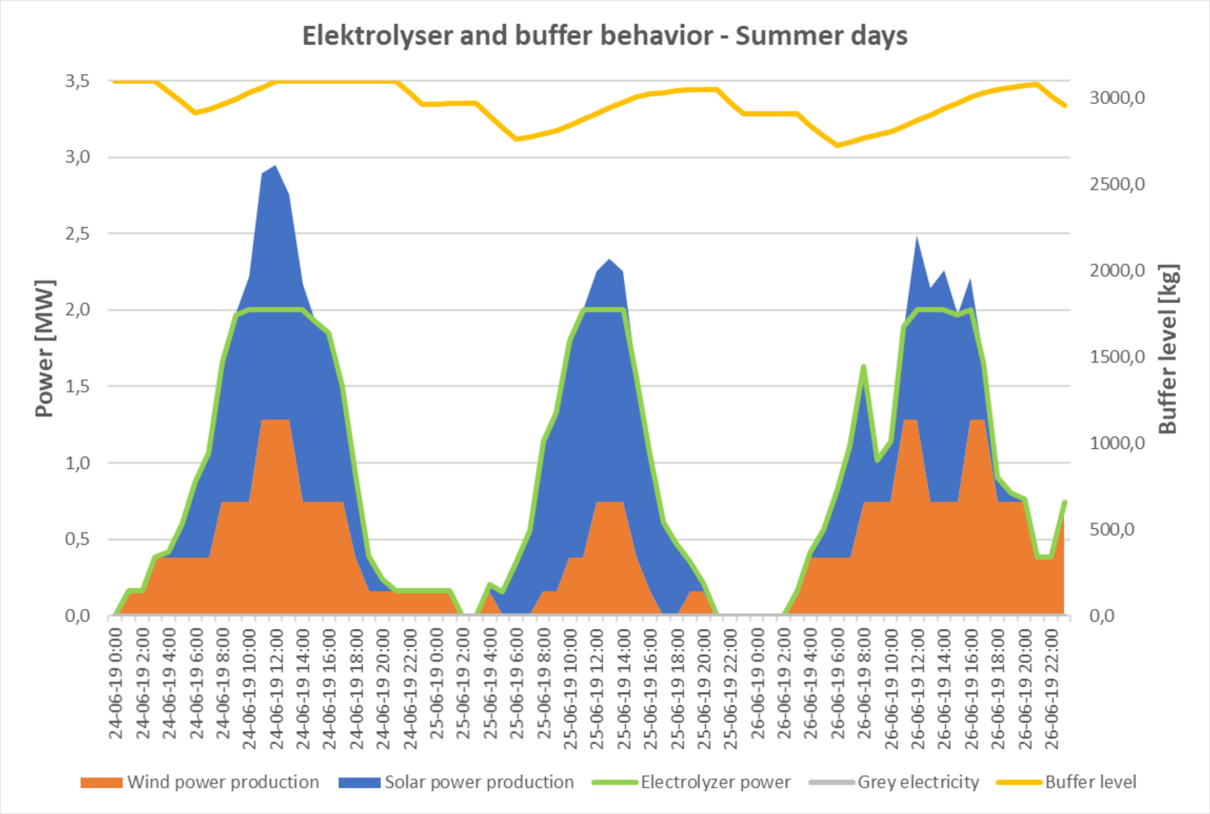


Figure 12: Electrolyzer system behavior - summer days - scenario 3

This figure shows where solar or wind power production exceeds the maximum capacity of the electrolyzer. This surplus is seasonal and cannot be avoided. At some points during the year, leading up to summer, the buffer reaches its limits. When this happens, both the electrolyzer and the buffer can act as limiting factors not allowing more hydrogen to be produced. Either because there is more renewable energy than the electrolyzer can handle, or the buffer is full. In summer the system could also function with a smaller buffer, as the mean buffer level is about 10x higher than the minimum requirement.

Figure 13 shows 3 winter days in comparison.

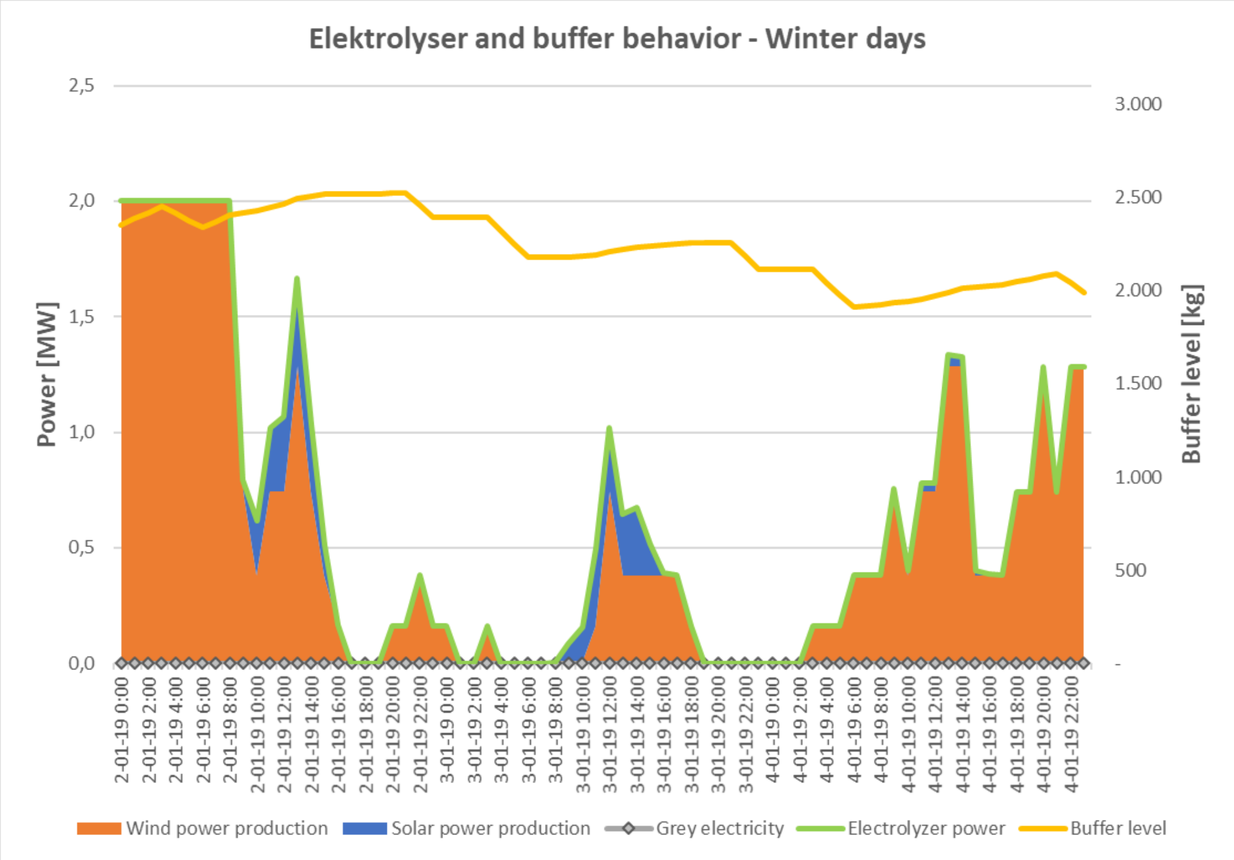


Figure 13: Electrolyzer system behavior - winter days - scenario 3

In winter the buffer level becomes a more critical factor. The buffer is this large because of consecutive days of low green power and constant demand. As Figure 13 shows, the buffer level drops below what was set as the minimum buffer level of 216 kg in scenario 1 and 2. Such a minimum cannot be set in scenario 3, for it is solely dependent on the buffer and green power for supply and hydrogen generation. Although the buffer level drops below the minimum, with this system sizing, there is never a shortage of hydrogen for the current use profile. In Figure 14, the buffer level during the year is provides, showing the need for such a large buffer only for a few moments a year when very little sun and wind is present.

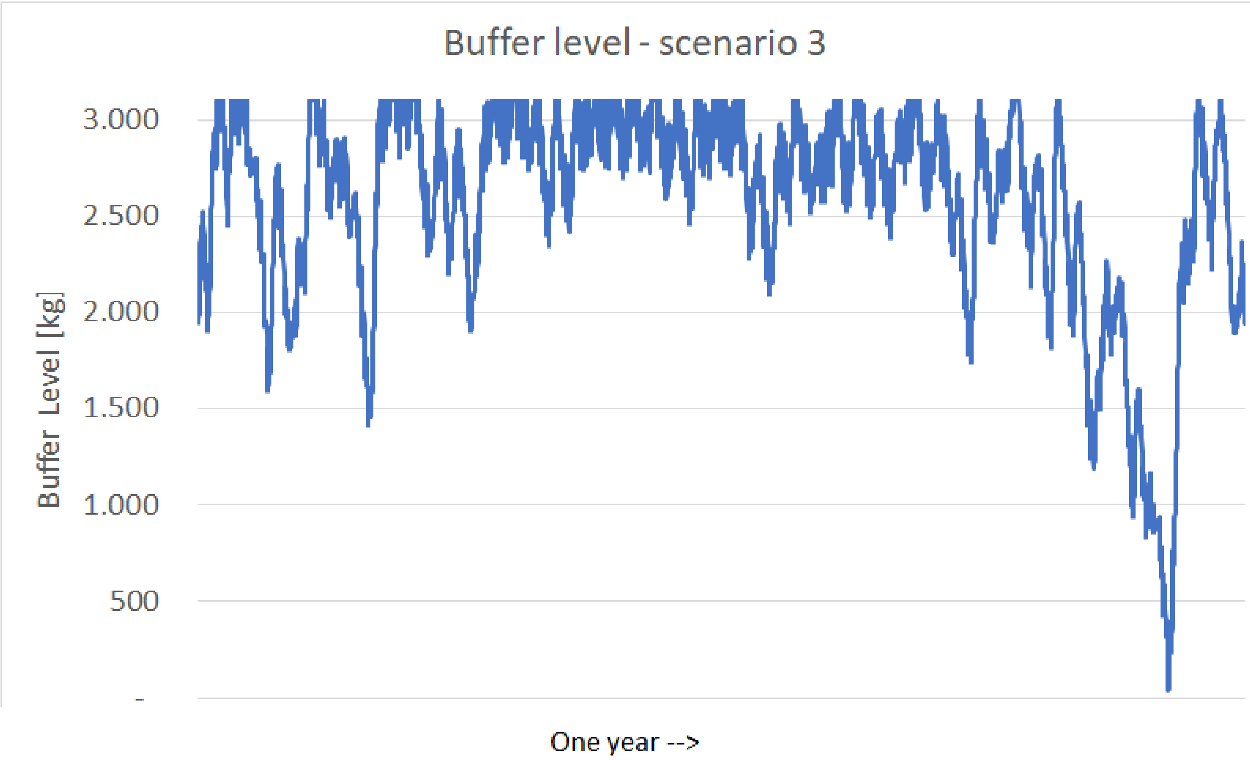


Figure 14 Yearly profile of the hydrogen buffer in scenario 3

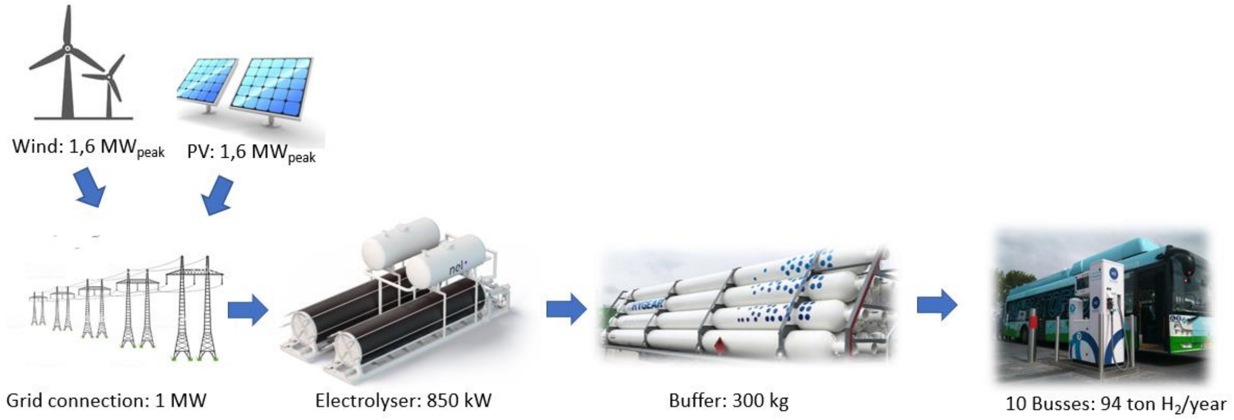
4.3.4 Conclusions

For scenario 3 the following overall conclusions can be made:

- The buffer size must be 3,100 kg to avoid any hydrogen shortage, this results in an LCOH of 19 €/kg H_2;
- Due to a large decrease in wind and solar production in autumn, the full buffer capacity is only used once a year.
- The system can function on merely solar and wind power, with the large buffer and the current component sizing (2 MW electrolyzer, 2 MWp solar power, 2 MW wind power);
- About 20% of the renewable energy cannot be used in this off-grid system;
- Further optimization of the various components could show a more optimal system sizing;
- In this off-grid situation no SDE subsidy will be granted and no energy tax will be collected. These effects are not considered in this analysis.

4.4 Scenario 4: High full load hours

To achieve the lowest costs for the hydrogen fuel station in this scenario, all components are considered as small as possible. The electrolyser runs in full load operation, therefore only a small buffer is necessary.



4.4.1 System overview and assumptions

For scenario 4 the case was based on the following main assumptions:

- Full load electrolyzer (0.85MW);
- Wind and solar as renewable sources;
  - Installed capacity identical for each source (1.6MW each);
  - Sized such that the combined power generation is enough to produce the entire required amount of hydrogen, in case all the green power could be used (without electrolyzer or buffer limitations);
- Grey electricity used;
  - Whenever the buffer is not full, and green electricity production is not sufficient to power the electrolyser. (<0.85MW);
- Buffer size and handling such that there would never be a shortage of hydrogen when required;

Table 11 provides an overview of the main system component sizing for scenario 4. It also shows some key parameters of the functioning of the production plant and fueling station. These parameters include:

- The absolute and relative usage of green electricity;
- The absolute and relative usage of grey electricity;
- The surplus of green electricity that could not be used due to electrolyzer and buffer size limitations;
- The Levelized Cost of Hydrogen (LCOH);
- The total initial CAPEX;
- And a breakdown of the LCOH per main component (subsidies, electrolyzer, and fuel station).

Table 11: Overview of system components and key parameters - scenario 4

Component overview Scenario 4			
Component	**Value**	**Unit**	
Electrolyzer	**0.85**	**MW**	
Sun	1.6	MWp	
Wind	1.6	MW	
Buffer	300	kg	
Green electricity used	50,754	**MWh**	**54%**
Grey electricity required	43,093	MWh	46%
Full load hours production	6,580	hr	
Surplus green electricity	15,736	kg/yr	
LCOH*	**€ 13.96**	**/kg H2**	
CAPEX	€ 4,884,445		
LCOH Subsidies	-€ 0.84	/kg H2	
LCOH Subtotal Electrolyzer	€ 9.77	/kg H2	
LCOH Subtotal Fuel station	€ 5.04	/kg H2	

*LCOH is calculated using a fixed electricity price, the business case of the renewable power is not included.

In scenario 4 the electrolyzer is sized such that it can run at almost full load the entire year. In this case about 54% of the hydrogen is produced using green electricity. Both the LCOH and the initial CAPEX are lower because the electrolyzer and the buffer size are smaller than in the previous 3 scenarios.

4.4.2 Cost overview and sensitivity

Table 12 provides a cost overview of the entire electrolyser and fuel station.

Table 12: Cost overview scenario 4

Costs overview scenario 4							
	Assumption	Unit	Used Capacity		CAPEX		OPEX
Electrical connection	€ 27,795	€/#**	1	Conn.	€ 27.795		€ 26.008
Electrolyzer Fixed	€ 500,000	€/#					
Electrolyzer Variable	€ 1,000,000	€/MW	2	MW	€ 1.350.000	5%	€ 67.500
Installation engineering and control	40%				€ 551.118		
Contingency	10%				€ 192.891		
Subtotal Electrolyzer					**€ 2.121.804**		€ 93.508
Compressor	€ 500,000	€/#	30	kg/hr,	€ 600.000	4%	€ 24.000
Redundant compressor	€ 500,000	€/#	30	kg/hr,	€ 600.000	4%	€ 24.000
Buffer 20 Bar	€ 50,000	€/#***	1	#	€ 50.000	3%	€ 1.500
Buffer 50 Bar	€ 500	€/kg	184	kg	€ 42.000	3%	€ 1.260
Buffer 550 Bar	€ 30,000	€/#	9	#	€ 276.923	3%	€ 8.308
Dispenser	€ 75,000	€/#	2	#	€ 150.000	3%	€ 4.500
Piping and valves	€ 75,000				€ 75.000	3%	€ 2.250
Installation engineering and control	40%				€ 717.569		
Contingency	10%				€ 251.149		
Subtotal fuel station					**€ 2.762.642**		€ 65.818
Total CAPEX					**€ 4.884.445**		

* A compressor unit is 25 kg/unit

Sensitivity analysis

The main component sizes for green power production and electrolyser size are fixed in scenario 4, except for the buffer size. A sensitivity analysis was performed to discover the 'behavior' of the system and the LCOH with a varying buffer size. Figure 15 shows this sensitivity analysis.

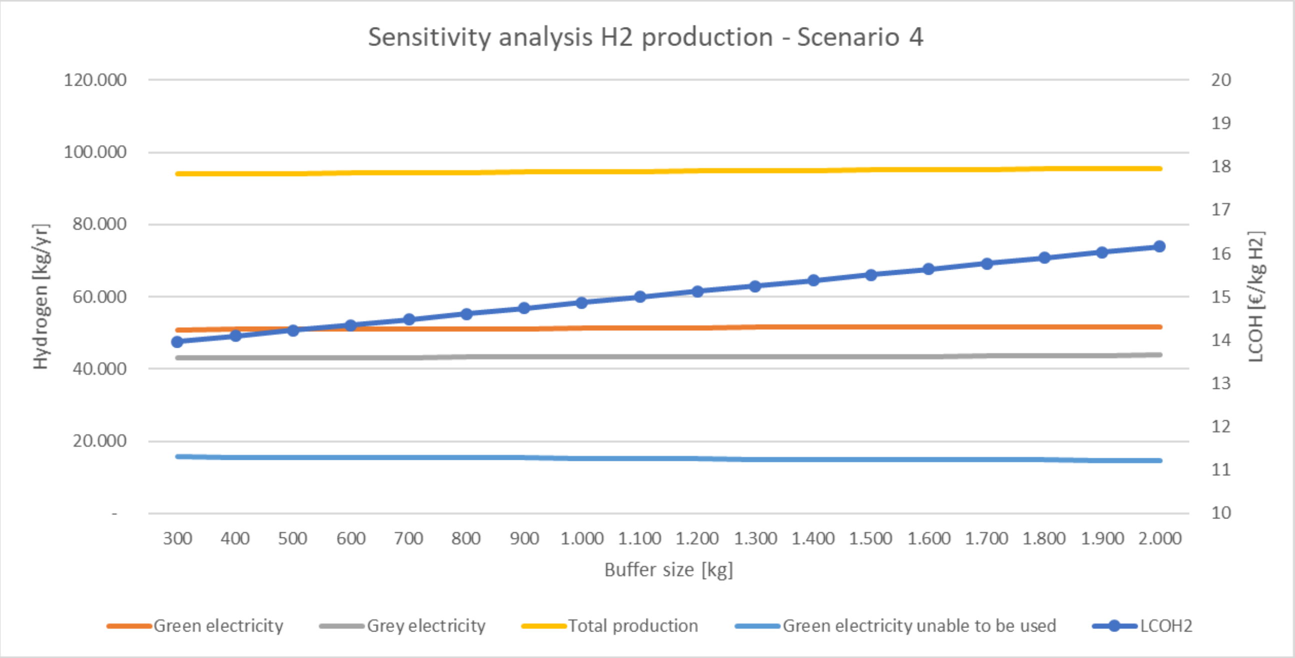


Figure 15: Sensitivity analysis - scenario 4

Figure 15 shows that in the case of a full load electrolyser there is a negligible effect of the buffer size on the amount of green hydrogen produced. With a buffer of 300 kg (all else being equal), there is never a shortage of hydrogen. Any further increase of the buffer size only increases the CAPEX and LCOH, without any benefits. This is because the electrolyser does not have any flexibility in capacity and should always run in order to produce enough hydrogen.

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4.4.3 Electrolyser control

As the system was modelled with hourly data, there is the possibility of observing the system ´behavior´ during different seasons or days. Figure 16 shows the system ´behavior´ for scenario 4 for 3 summer days.

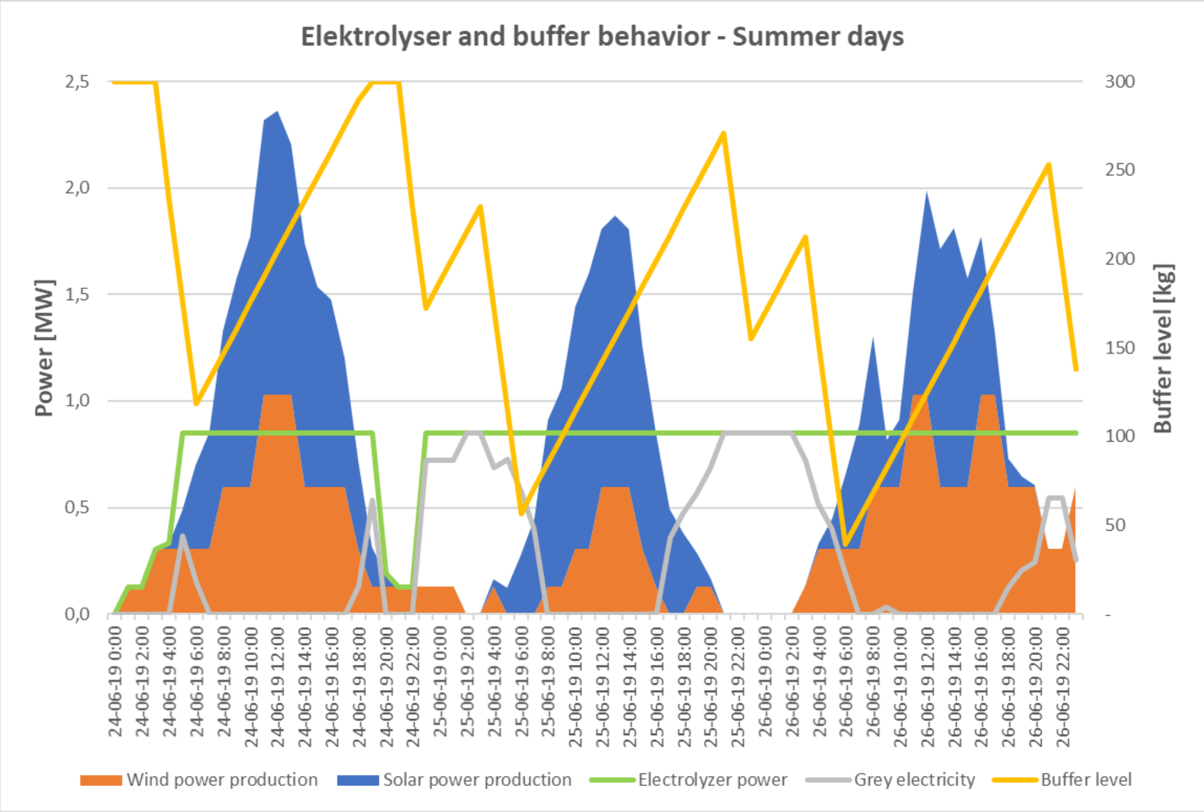

Figure 16: Electrolyzer system behavior - summer days - scenario 4

Figure 16 shows where solar or wind power production exceeds the maximum capacity of the electrolyzer. As both the installed capacity solar and wind are larger than the maximum capacity of the electrolyzer, there is often the case of a green power surplus. However, the surplus cannot always be utilized. Grey electricity is required to make this system work properly, considering the condition that there is never a shortage of hydrogen supply. This system does reach a full buffer on some of the summer days shown in Figure 16. Also, the electrolyzer can almost produce every hour, except for when the buffer is full. The system never reaches a no supply situation.

Figure 17 shows 3 winter days in comparison.

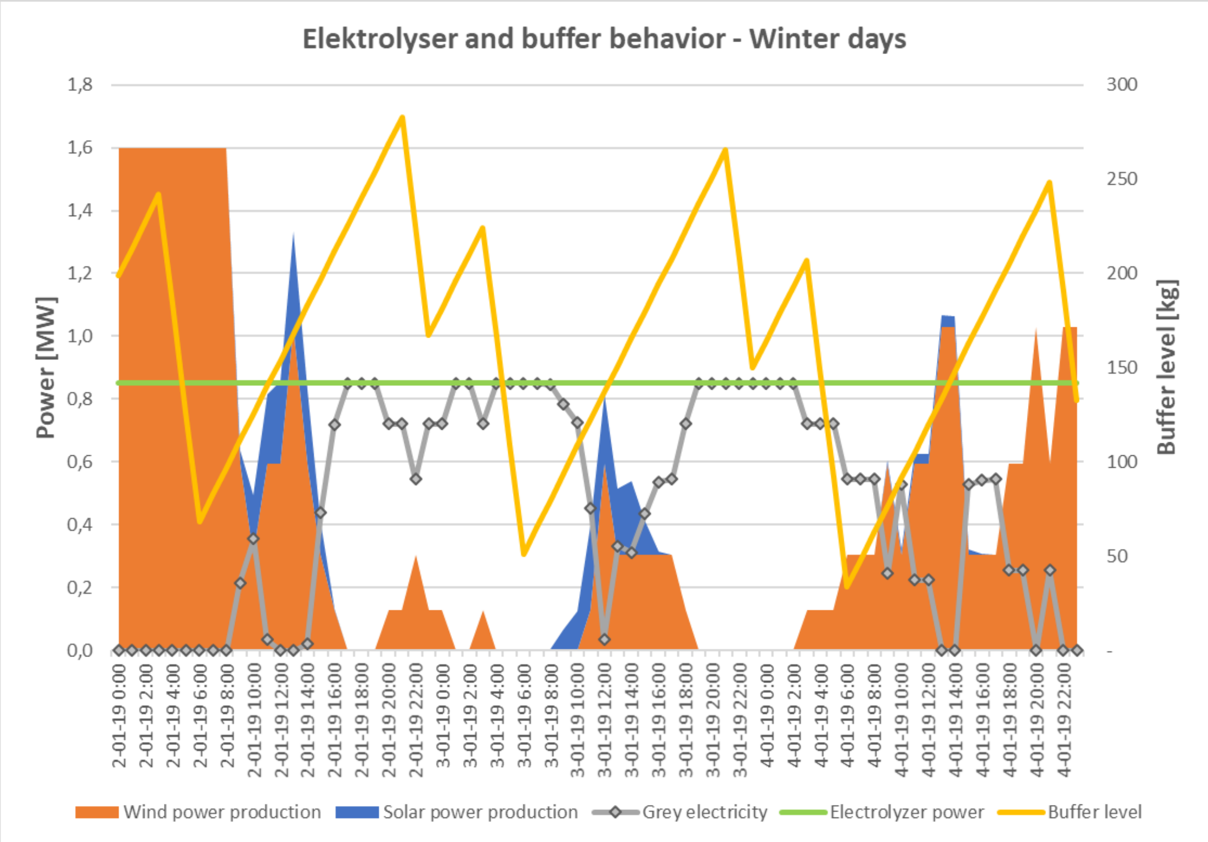

Figure 17: Electrolyzer system behavior - winter days - scenario 4

In winter a similar mean buffer level can be observed. This makes sense, as the system is less reliant on renewable energy, and grey electricity is used sooner than in scenario 1 and 2, thus contributing to a larger portion of the hydrogen produced.

4.4.4 Conclusions

For scenario 4 the following overall conclusions can be made:

- A LCOH of 14 €/kg H_2 using 54% of green electricity;
- A smaller buffer can be used compared to other scenarios. Because the production is a baseload enough hydrogen can be produced;
- The relative use of green electricity is lower, due to the condition of a (almost) full load electrolyser. This means grey electricity is used more often.

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5 A regional and national perspective on hydrogen

5.1 Synergies with electricity or gas grid

In the scenarios described, differences in flexibility result from the electrolyser and buffer size. In scenario 4 a small electrolyser and buffer should always run to produce enough hydrogen. Therefore, the grid synergies are limited to a base load consumer. This can only be beneficial in local grid areas with a large surplus of renewable electricity. Scenario 1 and 2 have limited flexibility to respond on local or national surpluses and shortages. It is possible to perform peak shaving of solar energy and to avoid production in in peak hours. During the morning and the evening peak grid loads are normally high. In Scenario 3 the system is off-grid, resulting in zero impact, but also no positive impact on the grid.

5.2 Oxygen users

During production of hydrogen, oxygen is produced at the same time. In the presented scenarios approximately 700 ton of oxygen a year is produced. Industrial users of oxygen in the vicinity of Emmen are not identified. It is therefore more likely the oxygen will be vented.

5.3 Adapt for car use (700 Bar)

To allow for cars at the fuel station must be adapted in a technical and organizational way. The technical adjustments are an extra high pressure buffer, a high pressure dispenser and another compressor which can compress up to 900 Bar. The CAPEX implications assuming 4 cars an hour and the possibility to fuel the 4 cars in a row are shown in Table 13.

Table 13 additional costs of car fuel system

Component		Extra costs (scenario 4)	Source
Extra compressor costs	25% higher Capex	€ 300,000	Based on price ratios in compressor costs from NREL "Hydrogen Station Compression, Storage, and Dispensing Technical Status and Costs" 2014
900 Bar buffer	20 kg extra high pressure buffer (2,5 m^3) 20% more expensive compared to 550 Bar	€ 70.000	Based on price ratio between 350 Bar and 700 Bar storage from SA "Hydrogen Storage Cost Analysis"
Car dispenser	Single 700 Bar dispenser	€ 100.000	NREL "Hydrogen Station Compression, Storage, and Dispensing Technical Status and Costs" 2014
Cooling system	For fast charging (2 kg/min) cooling to -40°C is required.	€ 200.000	NREL "Hydrogen Station Compression, Storage, and Dispensing Technical Status and Costs" 2014
Total		€ 670,000	

These investments will add ~1€ to the LCOH of the bus fuel station. When cars will use the fuel station this will result in a higher electrolyser capacity but also implies a higher hydrogen sales, we assume this is in balance.

The organizational adjustments have to do with the location of the fuel station, for busses the depot would be the most logical spot because of synergies between cleaning and fueling of the busses. This bus depot is a private and closed location this makes is difficult to use as public fuel station. For this reason the bus fuel station in Groningen is not open for public cars.

5.4 Customers and potential expansion of fleet

On several locations in Europe hydrogen fuel stations have been realized, out of which two have been realized in the northern part of The Netherlands to allow several special vehicles and two buses to fuel. Most likely, more vehicles are to come. Subsequently new fuel stations should be realized, eventually providing a network of hydrogen fuel stations.

The public transport office (OV-Bureau) of Groningen and Drenthe have recently announced to deploy a total 20 hydrogen buses in the Dutch provinces of Groningen and Drenthe. 10 hydrogen buses will potentially be operated from Emmen (south-eastern part of the province of Drenthe). Availability of a hydrogen fuel station in the province of Drenthe is thus requisite.

5.5 Experience with hydrogen

5.5.1 Legal and management experience

This paragraph provides a quick scan of required permits as well as points of attention regarding permitting procedures. Information is obtained from interviews with authorized supervision institutions and from Royal HaskoningDHV's legal experience from realization of existing hydrogen fuel stations in the northern region of The Netherlands.

The type of permits that should be requested and safety measures that should be considered, depend on several factors, such as:

- Required volumes of hydrogen;
- Types and measurements of installations;
- Pressure in installations;
- Type of compressor.

The following safety measures/ standards should at least be adopted:

- Construction requirements regarding PGS35 norms;
- Emergency procedures and measures.

Currently, the 'Omgevingsdienst Groningen' is involved in the legal and safety process for realization of a third hydrogen fuel station in the city of Groningen. From the implemented legal procedures, several lessons were learned:

- In order to request a permit, details of installations and pressure should be as specific as possible. Maps/floor plans should be included;
- Very often, a revision of the local spatial zoning plan is necessary to legally include safety contours related to hydrogen and thus to be granted a permit for the construction of the fuel station.

Above this, the following permits and studies should be requested/ carried out:

- Environmental permit (Wabo): Qualitative Risk Analysis (QRA) - Besluit externe veiligheid (Bevi);
- Construction permit (Wabo): substantiation of the electrolyzer and fuel station within the context of the environment and the applicable zoning plan;

- Besluit risico's zware ongevallen 2015 (Brzo, 2015). Concerns technical requirements for the operator of the intended facility. This is only required if 5 tons of hydrogen or more are present at location;
- In agreement with authorities, additional studies could be requested to be performed:
    - Research of soil and water at the specific location in order to determine soil conditions;
    - Calculation of possible discharge to surface water;
- Acoustic research and calculations in order to determine chance of occurrence of noise disturbance;
- Research on emissions to air: transport movements should be considered;
- Ecological research in order to determine if protected species which could potentially be harmed are present at the specific location.

The following intuitions should be informed and/or are responsible for processing of permits:

- Municipality where the hydrogen fuel station is intended; responsible for licensing and granting permits;
- Omgevingsdienst Drenthe; consulting institutions for licensing and granting permits and are responsible for supervision and enforcement regarding the environment;
- Waterboard Vechtstromen; responsible for licensing and granting permits related to aspects regarding water;
- Veiligheidsregio Drenthe: consulting institution on safety aspects and measures. The Veiligheidsregio should agree on the proposed safety measures;
- Province of Drenthe: are only responsible for licensing in several occasions.

Procedures:

- Revision of the local zoning plan by the relevant municipality in cooperation with operator/client: 6 – 9 months. In some cases, this procedure can be combined with the permitting procedure below;
- Preparation of construction and environmental (Wabo) permits in cooperation with authorized supervision institutions and operator/client: 3 – 6 months;
- Permitting process by authorities: 26 weeks. Permits can be submitted and processed simultaneously;
- All permits requests should be handed in through an online platform, referred to as OLO.

Due to changes in the Dutch legal framework (implementation Omgevingswet) these planning and permitting procedures will change significantly starting from the year 2021[1]. Although this is not intended to adversely affect the mentioned processing time, it is a point of attention. The consequences of this new law can be included in further elaboration of the project.
Legal and safety experience is easily transferrable between regions, provinces and institutions. Realization of a hydrogen fuel station will most likely not be subjected to any constraints regarding permitting, due to high political ambitions on hydrogen.

5.6 Financial benefits and incentives

The Dutch government supports the realization of innovative hydrogen projects to increase market share and to ultimately contribute to decrease CO_2-emissions. The Dutch government grants subsidies for a variety of types of projects, including small-scale initiatives and pilots, fiscal instruments and integral projects related to offshore wind energy. Also, the national government grants subsidies to sustainable transport solutions, such as hydrogen. This subsidy is referred to as 'DKTI Transport' and will open for application in the course of 2020.

SDE ++

[1] *The specific implementation date of the Omgevingswet still has to be defined and is experiencing delay as a result of the COVID-19*

To produce green hydrogen, SDE++ will be available from next October. The final details are not fully available yet. In the business case in this study, the subsidy amount based on a published letter from the minister of economics and climate.
The subsidy will be granted based on the lowest cost for the reduction of a ton of CO_2. Because hydrogen production is still very expensive compared to other techniques, hydrogen production projects will only be granted the subsidy if the budget is no emptied by techniques with higher CO_2 reduction for every euro.
The subsidy amount for hydrogen is 2.77 €/kg in October. This is a production-based subsidy over 15 years, only for 2000 full-load hours. It is assumed that an electrolyser which runs on the 2000 cheapest hours only runs on renewable energy. This energy does not emit any CO_2 therefore the CO_2 reduction is 8.58 kg CO_2/kg H_2.
In the SDE subsidy round the projects which need a low amount of subsidy for a reduction of CO_2 emissions are preferred over higher cost per reduced CO_2. On this scale, hydrogen production needs a subsidy intensity of 300 €/ton CO_2. In comparison wind needs 0-100 €/ton CO_2 and solar PV around 100 €/kg CO_2.

MIA/Vamil
Using the MIA regulation, 36% of the investment in both the fuel station (code: F3710) and the electrolyser (code: F4111) can be deducted from company tax. This results in a net benefit of 8% on the full investment. The Vamil regulation is also applicable and allows for flexible deprecation, 75% of the investment can be depreciated at self-chosen moment in time. This provides a liquidity and interest advantage. The MIA and Vamil can also be combined with SDE++.

EIA
The energy investment deduction is a tax incentive for energy transition related investments. When the electrolyser is used to convert excess renewable energy the EIA is applicable (code: 260201). A part, 45% of the investment in the electrolyser can be deducted from company tax and results in a ~10% benefit on the electrolyser, compressor and buffer. This regulation cannot be used in combination with MIA or SDE++ subsidy.

6 Conclusions

The results of the LCOH and green electricity percentage are summarised in Table 14. The LCOH ranges from 14 to 19 €/kg H_2, using respectively 54% to 100% of renewable energy.

Table 14 Summary of scenarios

Scenarios	LCOH*	Green electricity
1: Local solar	16 €/kg H_2	62%
2: Local solar and wind	16 €/kg H_2	72%
3: Only green electricity	19 €/kg H_2	100%
4: High full load hours	14 €/kg H_2	54%

*LCOH is calculated using a fixed electricity price, the business case of the renewable power is not included.

This study also includes a qualitative analysis, focusing on legal aspects. Several permits will have to be requested to obtain permission for realization of a hydrogen fuel station. The duration of the permitting process normally varies between 9 months to over a year, depending on the necessary procedures to follow. The northern region of The Netherlands already acquainted knowledge on legal procedures regarding the realization of hydrogen fuel stations.

Legal and safety experience is easily transferrable between regions, provinces and institutions. Realization of a hydrogen fuel station will most likely not be subjected to any constraints regarding permitting, due to high political ambitions on hydrogen.

A1 Business case

A1.1 Cashflow sheet

Below the business case calculation, scenario 4 is used as example

Jaar		0	1	2	3	4	5	6	7	8	9	10
		2020	*2021*	*2022*	*2023*	*2024*	*2025*	*2026*	*2027*	*2028*	*2029*	*2030*
Operational		0%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
Volumes												
Hydrogen	kg/jaar	-	93.847	93.847	93.847	93.847	93.847	93.847	93.847	93.847	93.847	93.847
Electricity electrolyser	MWh/jaar	-	5.586	5.586	5.586	5.586	5.586	5.586	5.586	5.586	5.586	5.586
Electricity compressor	MWh/jaar	-	263	263	263	263	263	263	263	263	263	263
Total electricity	MWh/jaar	-	5.849	5.849	5.849	5.849	5.849	5.849	5.849	5.849	5.849	5.849
Investment costs												
Investment Electrolyser	EUR	€ 2.121.804										
Investment Fuelstation	EUR	€ 2.762.642	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -
Totaal capex	*EUR*	*€ 4.884.445*	*€ -*	*€ -*	*€ -*	*€ -*	*€ -*	*€ -*	*€ -*	*€ -*	*€ -*	*€ -*
Operational costs												
General indexation		1,00	1,02	1,04	1,06	1,08	1,10	1,13	1,15	1,17	1,20	1,22
Indexation electricity		1,00	1,03	1,06	1,09	1,12	1,15	1,18	1,22	1,25	1,29	1,33
Electricity price	EUR/MWh	43,00	44,23	45,49	46,79	48,13	49,51	50,92	52,38	53,88	55,42	57,00
Green electricity certificates price	EUR/MWh	7,00	7,14	7,28	7,43	7,58	7,73	7,88	8,04	8,20	8,37	8,53
Electricity costs	EUR	€ -	€ 258.691	€ 266.086	€ 273.693	€ 281.517	€ 289.564	€ 297.841	€ 306.356	€ 315.113	€ 324.121	€ 333.386
Green electricity certificates	EUR	€ -	€ 41.761	€ 42.596	€ 43.448	€ 44.317	€ 45.203	€ 46.108	€ 47.030	€ 47.970	€ 48.930	€ 49.908
Energy tax (EB)	EUR	€ -	€ 79.472	€ 81.062	€ 82.683	€ 84.336	€ 86.023	€ 87.744	€ 89.498	€ 91.288	€ 93.114	€ 94.977
Energy tax (ODE)	EUR	€ -	€ 117.569	€ 119.920	€ 122.318	€ 124.765	€ 127.260	€ 129.805	€ 132.401	€ 135.049	€ 137.750	€ 140.505
O&M fuel station	EUR	€ -	€ 67.134	€ 68.477	€ 69.846	€ 71.243	€ 72.668	€ 74.121	€ 75.604	€ 77.116	€ 78.658	€ 80.231
O&M electrolyser	EUR	€ -	€ 95.378	€ 97.286	€ 99.231	€ 101.216	€ 103.240	€ 105.305	€ 107.411	€ 109.560	€ 111.751	€ 113.986
Total energy costs	*EUR*	€ -	*€ 300.452*	*€ 308.683*	*€ 317.141*	*€ 325.834*	*€ 334.767*	*€ 343.949*	*€ 353.385*	*€ 363.083*	*€ 373.051*	*€ 383.295*
Total energy tax	*EUR*	€ -	*€ 197.041*	*€ 200.981*	*€ 205.001*	*€ 209.101*	*€ 213.283*	*€ 217.549*	*€ 221.900*	*€ 226.338*	*€ 230.865*	*€ 235.482*
Total O&M	*EUR*	€ -	*€ 162.512*	*€ 165.762*	*€ 169.078*	*€ 172.459*	*€ 175.908*	*€ 179.427*	*€ 183.015*	*€ 186.675*	*€ 190.409*	*€ 194.217*
Total Opex	*EUR*	€ -	*€ 660.005*	*€ 675.427*	*€ 691.220*	*€ 707.394*	*€ 723.959*	*€ 740.924*	*€ 758.300*	*€ 776.097*	*€ 794.324*	*€ 812.994*
Subsidy												
Subsidy Revenue [€/kg H2]	*EUR*	€ -	*€ -79.168,32*	*€ -79.168,32*	*€ -79.168,32*	*€ -79.168,32*	*€ -79.168,32*	*€ -79.168,32*	*€ -79.168,32*	*€ -79.168,32*	*€ -79.168,32*	*€ -79.168,32*
Cashflow		***€ 4.884.445***	***€ 580.837***	***€ 596.258***	***€ 612.051***	***€ 628.226***	***€ 644.791***	***€ 661.756***	***€ 679.132***	***€ 696.928***	***€ 715.156***	***€ 733.825***

Figure 18 Cashflow sheet

A1.2 LCOH breakdown

Investment fuelstation	€	4,22
O&M fuel station	€	0,81
Electricity costs	€	0,16
Energy tax	€	0,10
subtotal fuel station	***€***	***5,29***
Investment electrolyser	€	5,63
Electricity costs (incl cert)	€	3,42
Energy tax	€	2,17
O&M electrolyser	€	2,17
subtotal electrolyser	***€***	***13,40***
Subsidie	***€***	***-1,98***
Totaal LCOH	***€***	***16,70***

Figure 19 LCOH breakdown scenario 1

Investment fuelstation	€	4,22
O&M fuel station	€	0,81
Electricity costs	€	0,16
Energy tax	€	0,10
subtotal fuel station	***€***	***5,29***
Investment electrolyser	€	5,63
Electricity costs (incl cert)	€	3,42
Energy tax	€	2,17
O&M electrolyser	€	2,17
subtotal electrolyser	***€***	***13,40***
Subsidie	***€***	***-1,98***
Totaal LCOH	***€***	***16,70***

Figure 20 LCOH breakdown scenario 2

Investment fuelstation	€	7,11
O&M fuel station	€	1,27
Electricity costs	€	0,16
Energy tax	€	0,10
subtotal fuel station	***€***	***8,65***
Investment electrolyser	€	5,57
Electricity costs (incl cert)	€	3,42
Energy tax	€	2,17
O&M electrolyser	€	1,47
subtotal electrolyser	***€***	***12,63***
Subsidie	***€***	***-1,98***
Totaal LCOH	***€***	***19,30***

Figure 21 LCOH breakdown scenario 3

Investment fuelstation	€	4,00
O&M fuel station	€	0,78
Electricity costs	€	0,16
Energy tax	€	0,10
subtotal fuel station	***€***	***5,04***
Investment electrolyser	€	3,07
Electricity costs (incl cert)	€	3,42
Energy tax	€	2,17
O&M electrolyser	€	1,10
subtotal electrolyser	***€***	***9,77***
Subsidie	***€***	***-0,84***
Totaal LCOH	***€***	***13,96***

Figure 22 LCOH breakdown scenario 4

A2 Sensitivity of scenario's in tables

Table 15 Scenario 1

Buffer size (kg)	LCOH (€)	From green electricity (kg)	From grid electricity (kg)	Total production (kg)	Green energy potential unable to be used (kg)
300	16.4	39,259	54,727	93,986	37,051
400	16.6	52,315	41,642	93,956	23,996
500	16.7	58,018	35,969	93,987	18,293
600	16.8	61,398	32,558	93,956	14,913
700	17.0	62,819	31,137	93,956	13,492
800	17.1	63,701	30,255	93,956	12,609
900	17.2	64,094	29,892	93,986	12,216
1000	17.4	64,305	29,651	93,956	12,005
1100	17.5	64,425	29,531	93,956	11,886
1200	17.6	64,525	29,431	93,956	11,786
1300	17.7	64,625	29,362	93,986	11,686
1400	17.9	64,725	29,232	93,956	11,586
1500	18.0	64,825	29,131	93,956	11,486
1600	18.1	64,925	29,031	93,956	11,386
1700	18.3	65,025	28,932	93,956	11,286
1800	18.4	65,125	28,864	93,988	11,186
1900	18.5	65,225	28,731	93,955	11,086
2000	18.6	65,325	28,631	93,956	10,986

Table 16 Scenario 2

Buffer size (kg)	LCOH (€)	From green electricity (kg)	From grid electricity (kg)	Total production (kg)	Green energy potential unable to be used(kg)
300	16.4	44,685	49,275	93,960	48,959
400	16.6	60,018	33,947	93,965	33,626
500	16.7	67,537	26,430	93,967	26,107

600	16.8	72,224	21,732	93,956	21,420
700	17.0	75,383	18,578	93,962	18,261
800	17.1	77,758	16,203	93,961	15,886
900	17.2	79,561	14,408	93,969	14,083
1000	17.4	80,875	13,083	93,958	12,769
1100	17.5	81,984	11,989	93,973	11,660
1200	17.6	82,844	11,127	93,971	10,800
1300	17.7	83,639	10,322	93,962	10,005
1400	17.9	84,311	9,656	93,967	9,333
1500	18.0	84,947	9,020	93,967	8,697
1600	18.1	85,481	8,488	93,969	8,163
1700	18.3	85,991	7,981	93,972	7,653
1800	18.4	86,445	7,540	93,985	7,199
1900	18.5	86,826	7,136	93,962	6,818
2000	18.6	87,233	6,728	93,961	6,411

Table 17 Scenario 3

Buffer size (kg)	LCOH (€)	From green electricity (kg)	From grid electricity (kg)	Total production (kg)	Green energy potential unable to be used(kg)
3,100	19.4	95,720	-	95,720	19,365
3,200	19.5	95,820	-	95,820	19,265
3,300	19.6	95,920	-	95,920	19,165
3,400	19.8	96,020	-	96,020	19,065
3,500	19.9	96,120	-	96,120	18,965
3,600	20.0	96,220	-	96,220	18,865
3,700	20.1	96,320	-	96,320	18,765
3,800	20.2	96,420	-	96,420	18,665
3,900	20.3	96,520	-	96,520	18,565
4,000	20.4	96,620	-	96,620	18,465

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Table 18 Scenario 4

Buffer size (kg)	LCOH (€)	From green electricity (kg)	From grid electricity (kg)	Total production (kg)	Green energy potential unable to be used(kg)
300	14	50,838	43,093	93,931	15,652
400	14	50,938	43,093	94,031	15,552
500	14	51,034	43,097	94,131	15,457
600	14	51,080	43,151	94,231	15,410
700	14	51,131	43,200	94,331	15,360
800	15	51,144	43,287	94,431	15,347
900	15	51,183	43,347	94,531	15,307
1,000	15	51,279	43,352	94,631	15,212
1,100	15	51,370	43,360	94,731	15,120
1,200	15	51,458	43,373	94,831	15,033
1,300	15	51,558	43,373	94,931	14,933
1,400	15	51,658	43,373	95,031	14,833
1,500	16	51,712	43,418	95,131	14,778
1,600	16	51,730	43,500	95,231	14,760
1,700	16	51,737	43,594	95,331	14,754
1,800	16	51,739	43,692	95,431	14,752
1,900	16	51,759	43,772	95,531	14,732
2,000	16	51,759	43,872	95,631	14,732