A real-time energy management system for a grid-connected solar park using an electrolyser in the Netherlands

Optimizing to maximize the revenue

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TU Delft

Preface

This report concludes my master's degree in Mechanical Engineering at Delft University of Technology. Working on this thesis has increased my interest in the energy transition even more. During the process of writing this thesis, I received support from a number of people. I would like to thank my supervisors Henk Polinder and Michiel Wildschut for their expertise and guidance. The different perspectives have helped me a lot through this process. I would also like to thank my colleagues at Emmett Green for their support and the introduction to their EMS, in particular, I would like to thank Gjalt Annega.

S.J. Middelkoop
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Summary

The transition to renewable energy sources requires a different approach throughout the whole energy sector. The main renewable energy sources in the Netherlands, solar power and wind energy, have a highly intermittent nature. This can cause a high strain on the grid but it also compromises the reliability of the energy supply, dependent on the weather conditions. Furthermore, the energy is generated in the form of electricity. In the industry, electrified alternatives are not yet available for high-temperature processes. To be able to solve these problems electrical energy can be stored, to relieve the strain on the grid, and by releasing the electricity when the generation is low, the reliability can be increased. Power-to-gas uses electrical energy for the production of hydrogen or methane. Hydrogen can replace natural gas in industrial processes.

To optimize the use of different assets at a renewable energy site an energy management system (EMS) can be used. Making optimal use of the assets decreases the strain on the grid and increases the reliability of the grid and the competitiveness of using green hydrogen. Research into EMS shows that hardly any research has been done for real-time EMS with an electrolyser, focusing on the supply of energy instead of the demand and taking into account the different electricity markets.

An EMS has been developed for a solar park in the Netherlands using an alkaline electrolyser. The EMS is developed with a two-step optimization, to be able to take into account the time scales of the electricity markets and the specifications of the electrolyser. The first step optimizes once a day and determines the state of the electrolyser based on the day-ahead market one day in advance. The second step determines the electrolyser power and is optimized every minute for the next fifteen minutes. In this optimization, the state of the electrolyser is used as an input. This allows for the electrolyser to respond to sudden changes in the imbalance market, and thus increase the reliability of the grid.

Simulations have been done based on the data from 2020, 2021 and 2022. The use of the electrolyser is limited to some days in the year with a lot of solar generation. Throughout the simulated years, the energy prices have exploded. However, the effect on the use of the electrolyser is limited. During a day that the electrolyser is used, the electrolyser is put on standby during imbalance peaks.

Different scenarios have been tested to get insight into how the use of the electrolyser is influenced by these changes. The alkaline electrolyser has been compared to the polymer electrolyte membrane (PEM) electrolyser, leading to lower revenue generated by the PEM electrolyser. The more flexible behaviour of the PEM electrolyser could not compensate for the lower lifetime and the lower efficiency, using this EMS. The EMS with an electrolyser that can go to standby is compared to an electrolyser without standby, which is the option to temporarily not generate hydrogen while staying on. The standby state leads to higher revenue, without standby the revenue was sometimes even negative caused by the two-step optimization. The EMS allows the electrolyser only to use electricity from the solar park to ensure the use of solar energy under normal conditions, this is compared to an EMS that allows the use of the grid for the electrolyser. However, the use of the electrolyser was hardly increased by this relief of constraints. At last, different hydrogen prices are compared. The higher hydrogen prices lead to more use of the electrolyser. This effect is much higher for 2021 than for 2022, caused by the high natural gas and electricity prices in 2022.

A real-time EMS for this system can be developed using a two-step optimization taking into account two different electricity markets using mixed-integer linear programming. The use of the electrolyser under current conditions is low. Forecasts show that the spread in electricity prices will increase in the coming years, using this EMS could increase the use of electrolysers in that case. The effect of changing the electrolyser specifications was limited.

This real-time EMS contributes to the ability of an alkaline electrolyser to respond to the sudden changes in the grid and by doing this making it possible to use alkaline electrolysers for balancing the grid and contributes to the use of green hydrogen in the industry for a competitive price. Next to this, the research into the influence of different specifications of the electrolyser and the hydrogen market created focal points for further research into the alkaline electrolyser at a solar energy site.

Samenvatting

De overgang naar duurzame energie vereist verandering in de hele energie sector. Hoeveel energie met zon en windenergie, de meest gebruikte duurzame energie in Nederland, wordt opgewekt is sterk wisselend. Dit zorgt voor een hoge belasting van het eletriciteitsnet wanneer er veel energie wordt opgewekt. Daarnaast beperkt het ook de betrouwbaarheid van het net wanneer er weinig opwekking is. De energie is opgewekt in de vorm van elektriciteit. Echter, in de industrie zijn er nog weinig electrische alternatieven voor veel processen op hoge temperaturen. Voor het oplossen van de problemen met duurzame energie kan energie opgeslagen worden om de belasting op het net te verlagen en de betrouwbaarheid te verhogen. Power-to-gas zet electrische energie om naar waterstof of methaan. Dit kan vervolgens gebruikt worden om aardgas te vervangen in de industrie.

Een energie management systeem (EMS) kan gebruikt worden voor het optimaliseren van het gebruik van verschillende technieken. Het optimale gebruik hiervan leidt tot het verminderen van de belasting op het net, het verhogen van de betrouwbaarheid en verbetert het vermogen van een netwerk van duurzame energie met waterstof om te concurreren met fossiele brandstoffen. Literatuurstudie naar EMS'en met een electrolyser die zijn ontwikkeld, laat zien dat er bijna geen onderzoek is gedaan naar real-time EMS'en, waarbij de focus ligt op het aanbod van de energie in plaats van de vraag. Ook wordt er geen rekening gehouden met de verschillende electriciteitsmarkten in Nederland.

Een EMS is ontwikkeld voor een zonnepark in Nederland wat gebruik maakt van een alkaline electrolyser. Het EMS bestaat uit een twee-staps optimalisatie. Hiervoor is gekozen om rekening te kunnen houden met de verschillende tijdspannen van de elektriciteitsmarkten en de specificaties van de electrolyser. De eerste optimalisatie stap wordt een dag van tevoren gedaan en bepaalt de status van de electrolyser. De tweede stap wordt elke minuut uitgevoerd voor de volgende vijftien minuten en bepaalt de output van de electrolyser, waarbij de status van de electrolyser als input wordt gebruikt. Hierdoor kan de electrolyser reageren op veranderingen in de imbalans markt en daardoor de betrouwbaarheid van het electriciteitsnet verbeteren.

Er zijn simulaties gedaan met de data van 2020, 2021 en 2022. Het gebruik van de electrolyser is gelimiteerd tot de dagen met veel opwekking van zonne energie. De prijzen zijn geëxplodeerd in de gesimuleerde jaren, maar het effect op het gebruik van de electrolyser is beperkt. Op een dag dat de electrolyser wordt gebruikt, wordt de electrolyser in standby gezet tijdens de pieken van de onbalans markt.

Verschillende scenarios zijn getest om inzicht te krijgen het effect van deze veranderingen op het gebruik van de electrolyser. Een alkaline electrolyser is vergeleken met een PEM electrolyser. De PEM electrolyser is flexibeler in gebruik, maar dit kon niet opwegen tegen de kortere levensduur en de lagere efficiëntie bij het gebruik van dit EMS. Een electrolyser die in standby gezet kan worden is vergeleken met een electrolyser waarbij dat niet kan. De standby stand zorgt voor een hogere omzet en zonder standby kan het voorkomen dat het gebruik van de electrolyser een negatief effect heeft tijdens een piek in de onbalans prijs. Het gebruiken van de electrolyser met electriciteit uit het net wordt vergeleken met een EMS waarbij dit niet mag, waarbij het verschil in gebruik van de electrolyser hierin beperkt is. Er zijn ook verschillende waterstof prijzen vergeleken, waarbij hogere prijzen leiden tot meer gebruik van de electrolyser. Het verschil hierin is in 2021 veel hoger dan in 2022, door de hoge prijzen in 2022.

Een real-time EMS voor dit systeem kan worden ontwikkeld door het gebruik van een twee-staps optimalisatie die rekening houdt met de verschillende electriciteitsmarkten en gebruik maakt van mixed-integer linear programming. Het effect van de verschillende scenarios was beperkt, waarbij alleen het aanpassen van de waterstof prijzen een groter verschil liet zien.

Dit real-time EMS draagt bij aan de mogelijkheid van het gebruiken van een alkaline electrolyser voor het reageren op de veranderingen op het electriciteitsnet, waardoor het mogelijk wordt om een alkaline electrolyser te gebruiken voor het in evenwicht houden van het net. Het draagt ook bij aan gebruik van groene waterstof voor een concurrerende prijs in de industrie.

Nomenclature

Abbreviations

DA	Day ahead market
EMS	Energy management system
FCR	Frequency containment reserve
H_2	Hydrogen
HHV	Higher heating value
LHV	Lower heating value
MILP	Mixed Integer Linear Programming
NG	Natural gas
O_2	Oxygen
P2G	Power to gas
PEM	Polymer electrolyte membrane
RES	Renewable energy source

Parameters

η	Efficiency of the electrolyser
B_t^{first}	First phase start up state electrolyser at minute t
B_t^{start}	Start up state electrolyser at minute t
$c_{i,t}$	Cost of component i in minute t
D^{begin}	First phase of start up time of the electrolyser
D^{switch}	Total start up or shut down time of the electrolyser
E_t^{gen}	Solar energy generation in minute t
E^{loss}	Energy losses during start of the electrolyser
E^{site}	Energy demand at the site
n^{cells}	Number of cells of the electrolyser
P^{cap}	Maximum operating power of the electrolyser
$P^{el,start}$	Last value of p^{el} from previous optimization interval
P^{min}	Minimum operating power of the electrolyser
$P^{opt,start}$	Last value of p^{opt} from previous optimization interval
P^{ramp}	Maximum ramp rate per minute of the electrolyser
$P^{standby}$	Power used in standby
R	Thermal resistance
S_t^{el}	Given state electrolyser at minute t
$T^{outside}$	Outside temperature
$T^{standby}$	Temperature of the electrolyser during standby

Variables

p_t^{el}	Electrolyser power at minute t [kW]
p_t^{opt}	Temporary decision variable electrolyser power at minute t [kW]
U_t^{st}	Binary variable, 1 if electrolyser is on standby at minute t, 0 otherwise
U_t	Binary variable for the state of the electrolyser, 1 if electrolyser is on, 0 if electrolyser is off
$Y_t^{firststart}$	Binary variable, 1 if electrolyser is in the first phase of starting up (without hydrogen generation) at minute t, 0 otherwise
Y_t^{start}	Binary variable, 1 if electrolyser is starting up at minute t, 0 otherwise

$y_{i,t}$	The amount of energy from component i at minute t
Y_t	Binary variable, 1 if electrolyser is turned on at minute t, 0 otherwise
Z_t^{stop}	Binary variable, 1 if electrolyser is shutting off at minute t, 0 otherwise
Z_t	Binary variable, 1 if electrolyser is turned off at minute t, 0 otherwise

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Introduction

1.1. Background and motivation

The European Union proposed the European Green Deal in 2019, which aimed to reach climate neutrality of the EU economy by 2050 [1]. This requires the change to renewable energy sources. Renewable energy sources have different characteristics compared to energy from fossil fuels, on which the energy sector is based nowadays. This has consequences for the whole process. Two different characteristics with their complications to the current process are mentioned below:

- The main renewable energy sources (RES) that are used in the Netherlands, solar power and wind energy, have a highly intermittent nature. The increasing share of renewable energy causes a high strain on the national grid, which can lead to congestion. In multiple regions in the Netherlands, the grid is congested. This prevents new renewable energy parks from being built because new feed-in connections are restricted [2]. A high share of renewable energy can also compromise the reliable energy supply.
- These renewable energy sources provide energy in the form of electricity. Some applications, previously relying on fossil fuels, can be electrified and therefore can use green energy. However, for industry electrification is still limited. This is often caused by the need for high temperature processes, for which electrified alternatives are not yet available [3].

To be able to reach climate neutrality, both of these problems must be solved. Two solutions are presented here:

Storage
Storage of electrical energy can relieve the strain on the grid and improve reliability by storing energy when the generation is high and releasing this energy when the generation is low. Electrical energy can be stored in different ways. The storage techniques can be divided into five classes: mechanical, electrochemical, chemical, electromagnetic and thermal [4]. In each classification, multiple technologies exist. Each technology has its strengths and weaknesses and some technologies are further in development than others. The choice for one of the technologies can be made based on the needed capacity, the duration of storage, the needed flexibility, the location and the readiness of the technology. The technologies also have different efficiencies, lifetimes and costs. It is also possible to combine multiple technologies to combine the strengths of the different technologies [5]. However, storage only solves the first of the above-mentioned problems.

Power-to-gas
The electrical energy generated by renewable energy sources can be used for the production of gases. Power-to-gas (P2G) can be a solution for the second-mentioned problem. Electrical energy can be used for the production of methane or hydrogen. In both cases, hydrogen is produced with an electrolyser. For the production of methane, the hydrogen is further converted into methane. Hydrogen or methane can replace natural gas in the natural gas network. Furthermore, hydrogen can be used as a transport fuel or to replace fossil fuels in industrial processes that require high temperatures [6]. P2G can also be

used as a type of chemical storage, when the hydrogen is converted back to electricity when needed.

A renewable energy site can be connected to a larger energy system. Lithium-ion batteries are often used for storing solar energy, because of their high flexibility and high energy density and because they can easily be connected to the grid [5]. P2G and battery storage have different characteristics and have therefore complementary roles to accommodate intermittent generation [7]. This leads to renewable energy systems that can consist of different technologies and can be connected to different loads and/or the grid. To ensure that renewable energy systems are used in their most beneficial way, an energy management system (EMS) can be developed. This EMS optimizes the use of different components. The objective of the optimization is determined based on the goal of the system and determines the behaviour of the system.

Currently, the cost of production of green hydrogen is a large barrier, since this is not competitive with grey or blue hydrogen yet [8]. The production of grey or blue hydrogen results in CO_2 emission, which is then captured and stored for blue hydrogen. The production of green hydrogen does not result in CO_2 emissions because renewable energy is used. However, often green hydrogen replaces natural gas in an industrial process. Therefore, it is even more important that it can compete with the natural gas price, which is also not yet the case. The largest component of costs for the production of green hydrogen are the electricity costs, under continuous operation [8]. Using an EMS that optimizes the use of the electrolyser when the electricity costs are low will increase the competitiveness of green hydrogen. This also relieves the strain on the grid, since the electricity prices reflect the energy surplus or shortage at that time.

As explained, the generation of electricity is intermittent, but also the electricity demand is not constant. The national grid operators have to match the generation and demand at all times. This is done by using different electricity markets and balancing markets, all with different prices and timescales [9]. Dependent on the market on which the electricity is traded, the price predictions become available at different moments and often the realised energy prices are only available after selling. Therefore, it is not possible to use one price as the electricity price.

1.2. Knowledge gap

In the literature study, found in Appendix B, the different EMS that have been developed using an electrolyser and an economic objective are researched. The researched articles covered a broad range of applications, using different components in the system. This also gave results in terms of the feasibility of using hydrogen. Almost no literature was found that made an EMS with a supply perspective, based on the generated energy. Also, most EMS were developed for simulation, not for real-time application. The articles that did develop an EMS for real-time application, used one grid price, not taking into account the different markets. To my best knowledge, no EMS has been developed for the use of an electrolyser, using the different timescales of multiple energy markets, to determine the behaviour of the electrolyser in real-time with the available data. Developing an EMS with an electrolyser that takes into account the multiple energy markets in a real-time application with a supply perspective can help solve the problems with the increased share of renewable energy mentioned above. It can increase the competitiveness of green hydrogen on the market and contributes to relieving the strain on the grid at times with high renewable energy production and to keeping balance on the grid using the short-term electricity prices.

1.3. Research goal

The research goal is to develop an optimization model for the use of an electrolyser at a grid-connected solar park for simulation and real-time application, optimizing to an economic objective, taking into account the different timescales of the energy markets in the Netherlands. This model can be combined with an energy management system with battery storage and different electricity markets. The EMS that is developed will be used to simulate different scenarios of the electrolyser and hydrogen market to determine how the system is influenced by these changes.

1.4. Research question

In order to reach the above-mentioned research goal, the following research question is answered in this thesis:

How to develop a real-time energy management system for a grid-connected solar park with an electrolyser and how is the system influenced by different specifications of the electrolyser and the hydrogen market?

To be able to answer the research question, multiple sub-questions have been set that have to be answered first:

1. What optimization methods should be used for the use of the electrolyser to meet the requirements?
2. What parameters have to be included in the model?
3. How can the mathematical model developed with the optimization method be implemented?
4. What is the effect of varying the specifications of the electrolyser and hydrogen market?

1.5. Report outline

The research is documented in a report with five chapters. The outline of the report is as follows:

- Chapter 1 consists of the introduction with the research questions,
- Chapter 2 contains the literature research,
- Chapter 3 provides the system description,
- Chapter 4 contains the model description,
- Chapter 5 presents the results and the discussion,
- Chapter 6 provides the conclusions and recommendations.

2 Literature research

The first chapter gave a brief introduction to the relevance of the development of an EMS. In this chapter more insight is given into the current state of research.

2.1. Electrolyser

Green hydrogen is generated using renewable energy. As mentioned in the introduction, this renewable energy is mostly generated in the form of electricity. Green hydrogen, therefore, has to be produced using electricity, using an electrolyser. A lot of research has been done into electrolysers in recent years. Resulting in multiple different electrolyser technologies being developed. Each type of electrolyser uses the same principle; electrolysis. Water is split up into hydrogen and oxygen using electricity. This allows the production of hydrogen without the generation of carbon dioxide, using electricity that is generated by renewable energy sources.

Newly developed technologies show promising results in terms of higher efficiency and possibilities for flexible use. However, they are still in the testing phase. Two different technologies, the alkaline electrolyser and the polymer electrolyte membrane (PEM) electrolyser, are already commercially available and could therefore be used in a renewable energy system. In this research, an alkaline electrolyser is used for the development of the model.

An alkaline electrolyser has some specifications that have to be taken into account when using this electrolyser in a renewable energy system and thus use the electrolyser intermittently. The electrolyser has a start-up time that needs to be taken into account. Next to this, changing the operating power has a ramp-up or ramp-down time. The electrolyser may not be used under the minimum operating power to prevent a higher risk of dangerous mixing of hydrogen and oxygen.

Next to this, in the literature, models can be found that used a more extensive representation of the electrolyser. In literature, some models have been developed using the possibility for the electrolyser to go to standby [10, 11]. This allows for more flexible use of the electrolyser and the possibility to respond to changes in the electricity prices, and thus the electricity imbalance. Therefore, implementing the standby mode in the model could improve the results.

Some models in the literature included a representation of the temperature of the electrolyser at every time [10, 12, 13]. This requires precise modelling of the electrolyser process, where the electrolyser balances around the desired temperature. The temperature gives insight into the power the electrolyser uses at each time, which influences the efficiency. This increases the accuracy of the modelling of the electrolyser. However, Zheng et al. found that the effect of adding the temperature was limited [10].

In other research, the stable operation of the electrolyser is taken into account during optimization, to limit the degradation of the electrolyser [14, 15, 16, 17]. However, research into the effect of the flexible operation on degradation is still limited. Therefore it is not certain how and if flexible operation influences degradation [8, 18, 19, 20]. The models that took stable operation into account had to determine a weight factor for the stable operation. The effect of stable operation on degradation is still uncertain and can not be quantified, therefore the effect of adding stable operation to the results is also uncertain.

Adding temperature and stable operation of the electrolyser increases the accuracy of the electrolyser modelling, however, the effect on the results is expected to be limited. The focus of this EMS is not on the most accurate modelling of the electrolyser and therefore the temperature and stable operation are not taken into account. The added value of this EMS is in the integration of the electricity markets into the model and their different time scales.

2.2. Electricity markets in the Netherlands

The electricity network of the Netherlands has to change from a demand-based system to a source-based system. With an increased share of renewable energy sources, the importance of balancing the power of the grid has become even more important. There are several systems in place to decrease the power imbalance. These systems are all based on the principle that for market parties it is uneconomical to increase the power imbalance and can be advantageous to reduce the power imbalance [21]. This ensures that the market itself manages the power balance. Different balancing markets are in place, with the same principle. Parties have to be able to decrease the imbalance when needed, for example, by using their assets for reserving power. They can store or release the power from the asset when needed to decrease the imbalance. Balancing is done in real-time when the frequency deviates from the 50 Hz that the grid operates on.

Next to the balancing markets, different electricity markets are used that have different time scales.
The forward and futures market is a contract market, where electricity is traded months and years ahead [22]. This market is not interesting for optimization.

The day-ahead market trades electricity one day in advance. Trading is done on an hourly basis. Parties can place a bid based on their predictions for generation or consumption [22, 23]. The day-ahead price is determined based on the highest accepted bid and is therefore only known afterwards. However, predictions of the price can be made by looking at forecasts and historical data.

The intraday market trades electricity throughout the day itself and can be used continuously on this day until an hour before delivery. This market is mainly used to adjust trades that are already made, causing lower liquidity [23, 24].

The imbalance market is a real-time market and the price only becomes available after the delivery. Predictions on the prices can however be made, fifteen minutes before delivery the first prediction becomes available and converges every minute to the actual price. This price is set for a window of fifteen minutes. The imbalance price is determined based on the imbalance between the demand and supply, to give the right incentive to the market [21]. This causes the market to be more fluctuating than the other markets. Therefore, this market is profitable for renewable energy systems with multiple assets.

The day-ahead and imbalance price had similar averages in 2020 and 2021 [24]. Therefore, the day-ahead price can be used as a prediction for the average imbalance price. The average natural gas price increased by 340% from 2020 to 2021, with a steep increase throughout 2021 [24]. This is mainly caused by the lower supply of Russian gas, but enhanced by the relatively low gas storage at the end of the winter of 2020 to 2021 and the recovered demand compared to 2020. The high natural gas prices still largely determined the height of the electricity prices, caused by the way the electricity markets are set up. In 2021, the average day-ahead price increased by 225% compared to 2020 [24]. In 2022, the natural gas price and thus the electricity prices increased even further.

In the coming years, the share of renewable energy will increase. This will change the electricity generation from demand-driven to supply-driven, increasing the imbalance between supply and demand. The effect of using renewable energy sources can already be seen. The difference between the imbalance price and the day-ahead price was in 2021 higher than in the previous years [24]. Since the

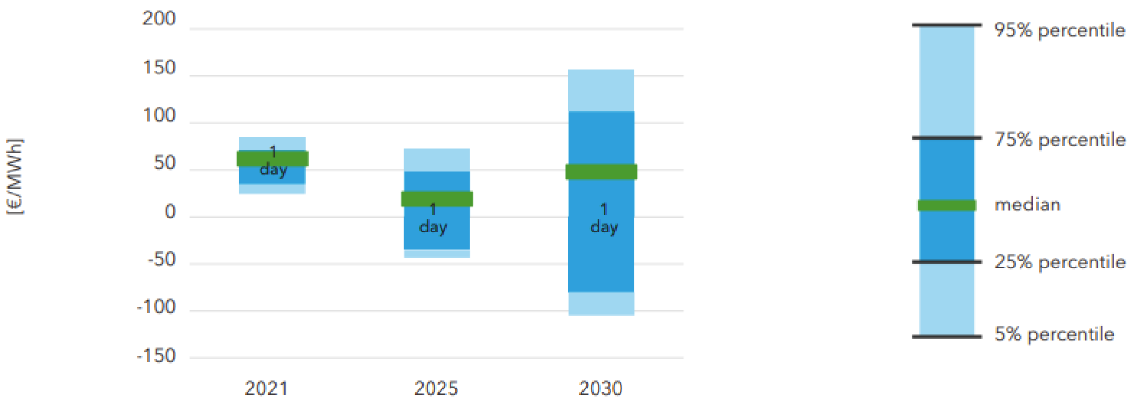


Figure 2.1: Maximum daily price variation of the year on the day-ahead market in the Netherlands as forecasted by DNV using her European Power Market Model [25].

height of the imbalance price is used to decrease the imbalance, the difference between the day-ahead price and the imbalance price can be used as a measure for the imbalance in the grid. DNVs power price forecast predicts that until 2030 electricity made with natural gas will dominate the price-setting [25]. From 2030 the impact of renewable energy sources gradually increases. This will cause seasonal changes to affect the day-ahead prices. Next to this, the daily price variation on the day-ahead market will increase. Figure 2.1 shows the daily price variation forecasted by DNV of the day with the most price variation of that year. This is caused by the increase in renewable energy and the decrease in controllable supply.

The more intermittent generation pattern will increase the need for the use of renewable energy systems that can locally control assets based on the different electricity markets, to help balance out the supply and demand. Since the height of the electricity price on the different electricity markets is used to decrease the imbalance, an energy management system that optimizes the maximum revenue will improve the stability of the grid.

The different electricity markets with different characteristics can influence the use of the electrolyser substantially. The forecasts for the future electricity markets show that the effect of the different electricity markets will increase even further. No literature on EMS models was found that took into account different electricity markets. The electricity market that was used is often not mentioned and the prices known ahead of time. In those cases, using the electrolyser will not help with balancing the grid. Developing an EMS taking the electricity markets into account will make it possible for the electrolyser to improve the grid stability by being able to respond to the price incentives set by the grid operator.

2.3. Renewable energy systems

The reviewed research in the literature study, focused on reaching the demand. The optimization was focused on optimizing the use of the different assets to reach the demand of this site. However, as discussed above, the electricity process requires a change from demand-driven to supply-driven. Therefore, it is important to also use the supply perspective when developing an EMS for a renewable energy system. The research into systems with this perspective is still limited. No literature was found that took into account different electricity markets with different time spans and times the prices become available.

2.4. Optimization methods

In literature a broad range of optimization methods has been used to model an EMS with an electrolyser. In the literature assignment in Appendix B, a flowchart was made that summarizes all the different optimization methods found. Figure 2.2 shows this flowchart. In this thesis the focus lies on the optimization of the revenue that is made, therefore the optimization will be single-objective. Adding a second objective, will decrease the results for the economic objective and is therefore not desirable.

For single-objective optimization, it is possible to have a rule-based algorithm, linear optimization, quadratic optimization or non-linear optimization. A rule-based algorithm relies on expert knowledge to determine an optimal solution and does not use an optimization model, therefore it is not optimization. This method is therefore not chosen for this thesis. The choice between linear, quadratic and non-linear is made based on two factors: how accurate the model the system represents and the solution time.

To represent the system with a linear model, some simplifications might have to be made on certain characteristics of the electrolyser that could be represented without simplifications with a quadratic or non-linear model. On the other hand, a linear model has a shorter computation time than the quadratic model and the computation time of a non-linear model is even longer. A trade-off between these factors has to be made. This model will be part of a real-time EMS, that needs to be easily scalable to large projects. The accuracy of the model does not seem to be limited a lot by linearizing the model, based on the literature that is reviewed. Therefore, the shorter computation time has a higher importance than a slightly more accurate model. This is also found the most in literature. To take into account the state of the electrolyser, binary variables need to be used. This leads to a model with both continuous and integer decision variables. Therefore, the optimization method that is used is mixed-integer linear programming (MILP).

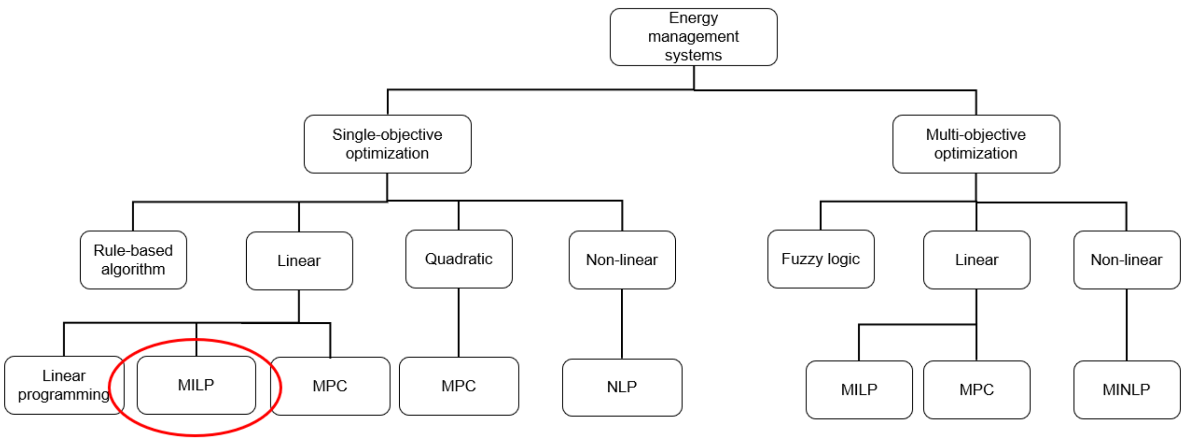


Figure 2.2: Flowchart optimization methods (Appendix B)

MILP problems have some specifications. The model of the renewable energy system has to be modelled according to those specifications, to be able to use this optimization method. A MILP problem has an objective function together with constraints, that determine the feasible region. Decision variables are the variables of which the height can be determined to reach the optimal solution. The decision variables can both be integers and continuous variables. MILP is a linear method, therefore both the objective function and all the constraints have to be linear. The renewable energy system needs to be represented by a linear model. In this system, two different solutions are used to linearise the system. The state of the electrolyser is a binary variable that can be used to linearise a non-linear constraint. The big-M method can also be used to linearise a constraint by rewriting it, without having to change the behaviour of the system [26].

The big-M method uses a large constant M combined with a binary value. This method can be used to make either-or and conditional constraints linear. The binary variable or (1 - the binary variable) can be multiplied with the constant M, which can be used in an inequality constraint to turn the constraint on or off. For example, when for a larger-than constraint the constant M is added, the constant M is large enough to make this constraint always met, independent of the value of the decision variables. This means that the constraint is then turned off.

3 System description

In this chapter, the system that is studied in this thesis is described. The parameters that are used to represent the system are listed. Next to this, different scenarios are explained that will be used for the simulations.

3.1. System description

A new solar park will be built in an area with industry that is interested in being more sustainable. To be able to store the energy that is generated temporarily, a battery is placed at the site. The industry in the area is planning on replacing the natural gas used in their processes with green hydrogen, produced with an electrolyser. This will be done gradually, starting with mixing hydrogen into the natural gas. To be able to provide this green hydrogen, an electrolyser will be placed at the site of the solar park.

An EMS has been developed by Emmett Green for a solar park with battery storage in the Netherlands. The battery can store energy from the solar park, buys and sells energy from the grid at different markets and can be used in the reserve markets that maintain the frequency in the grid. Combining both the battery storage and the electrolyser results in an energy site as shown in Figure 3.1

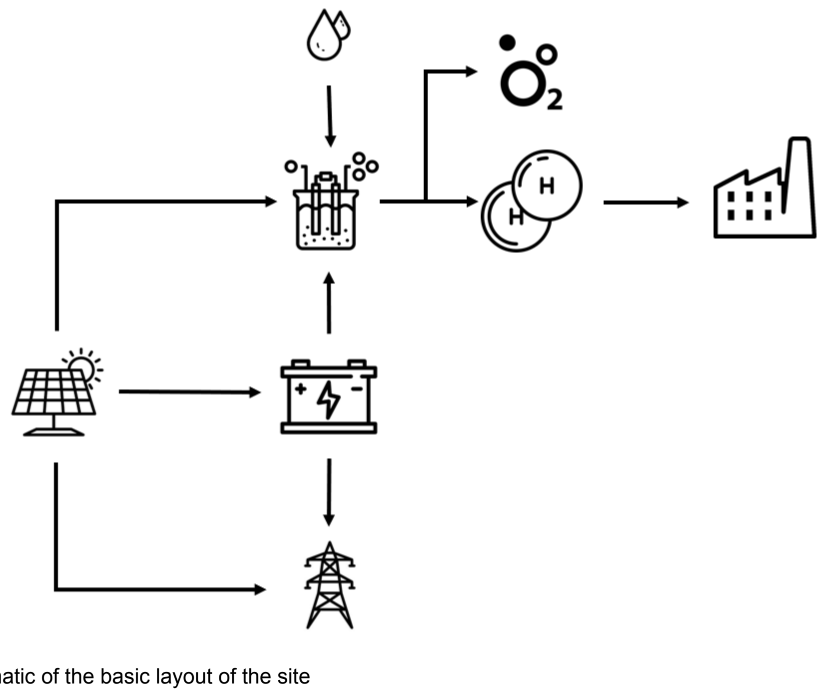


Figure 3.1: Schematic of the basic layout of the site

The energy site described needs to be managed to determine how to use the different assets. To be able to provide the industry with green hydrogen at times that this is most profitable, the EMS must also be able to optimize the use of the electrolyser. The battery storage will be out of scope, to be able to focus on the modelling of the electrolyser. Later, the model that has been developed in this thesis can then be combined with the current EMS developed by Emmett Green to optimize the use of both the electrolyser and the battery storage, using the multiple energy markets. The EMS developed will optimize the use of the electrolyser compared to the grid. The demand for gas from the industry is much higher than can be delivered by the solar park and the hydrogen percentage in the gas mixture is flexible, therefore the hydrogen demand will not constrain the use of the electrolyser. In this research, hydrogen will only be used for the industry. The EMS needs to be able to manage the use of the assets when electricity is generated, therefore the EMS is a real-time application. Therefore, it is important to take into account which data is available at which moment. Next to this, the EMS also needs to be able to be used as a simulation to test the EMS and the effect of varying different technical input values.

3.2. Parameters

The first step of the system description is to determine which parameters are relevant to represent the system. The parameters that are important to represent in this model can be split up into three categories: electrolyser parameters, system parameters and economic parameters. These are all further explained below.

3.2.1. Electrolyser parameters

An alkaline electrolyser is chosen for this project. Currently, only two different technologies for electrolysers are already commercially available in this size: the alkaline electrolyser and the PEM electrolyser. The alkaline electrolyser is the most mature technology and has been utilized throughout the world [27]. It has been shown that PEM electrolysers have some properties that are more suitable for dynamic operations. Currently, both types of electrolysers have different benefits, without a clear winner. However, the alkaline electrolyser was chosen for the benefits of a higher maturity, lower investment costs and longer lifetime [28]. Therefore, the electrolyser parameters, summarised in Table 3.1, are all based on an alkaline electrolyser. The choice for these values will be explained below.

Table 3.1: Parameters electrolyser

Parameter	Value
Capacity	20 MW
Minimum operating power	15% of capacity
Efficiency	65%
Ramp time	7.5% / min
Cold start	20 min
Shut down time	10 min
Lifecycle cost	1.11 €/ min
Losses start	300 kW
Standby power	6.6 kW

Capacity

The electrolyser that will most likely be used in the project has a peak capacity of the electrolyser that is used is 20 MW. A 20 MW electrolyser is one of the larger sizes that is used by the electrolyser suppliers. Therefore, this is also used in the model.

Minimum operating power electrolyser

The electrolyser can not operate in the whole range from zero to maximum capacity. At low operating power the risk of hydrogen and oxygen mixing during outflow increases, which can lead to a dangerous mix. At which operating point exactly this becomes dangerous depends on the electrolyser.

The minimum operating power of an electrolyser is the percentage of the maximum capacity before the chance on a dangerous mix becomes too high. For some electrolysers, this is already at 40% of the capacity. While some electrolysers have a minimum operating power of 10% of the capacity. Most electrolysers found on the market have a minimum operating power of around 15%. Therefore, the minimum operating power used for this model is 15% of the maximum capacity. [29, 30, 18, 31, 32]

Efficiency
The efficiency is not equal for all loads. It has a linear relation with slightly higher efficiency for a lower load. Since electrolysers are mostly tested at full load, this linear relationship is often not given. The efficiency at full load will be used to prevent an overestimation of generated hydrogen. The market survey of A. Buttler et al. found electrolyser efficiencies for alkaline electrolysers between 61% and 79% for full-load operation, using the lower heating value (LHV) of hydrogen [18]. DNV GL found an average efficiency of 81% in their market research, using the higher heating value (HHV) [29]. The HHV takes into account the energy put into the vaporisation of water and the LHV does not. Both values are used in industry and the literature [33, 34, 35]. An efficiency based on the HHV is 18% higher than an efficiency based on the LHV. In this case, it is chosen to use the LHV efficiency, because it is assumed that the energy used for the vaporisation of water is not reused. The efficiencies mentioned above are stack efficiencies, the stack contributes to about 80% of the efficiency loss [18, 36]. The efficiencies mentioned by A. Buttler et al. and DNV GL are based on electrolysers that were available on the market in 2018, because of the rapid development of the technologies the efficiencies of new electrolysers are already higher. Taking into account the extra development and the system efficiency, the constant efficiency that is used is 65%. This is the same estimation as is made in the IRENA report [8].

Ramp time
Within the operating range, the electrolyser can operate under different loads. However, changing between different loads takes time. The ramp-up/down time is for this model considered symmetric. The load can be ramped linearly by 15% every 2 minutes [29].

Start-up time
The electrolyser has a cold start when the electrolyser is turned on when it is off. The electrolyser has a hot start when it is turned on from a standby state. The time for a start-up is different for a cold or a hot start.

- The start-up time from the electrolyser from a cold start is determined by the time to build up the hydrogen and oxygen pressure and to heat the electrolyser, therefore the start-up time is influenced by the outside temperature. Cold start-up times until full load are in the range of twenty minutes until hours, depending on the electrolyser and the outside temperature [8, 18, 29, 37, 38]. The cold start-up time until the full load for this electrolyser is chosen at a half hour. Since the ramp-up time is also taken into account starting at the minimum load in this model, the start-up time until the minimum load is used. This takes twenty minutes because the ramp-up time from minimum load to full load is about ten minutes.
- The start-up time for a hot start is only determined by the ramp-up time because the pressure and temperature are still at operating conditions.

Shut down time
When the electrolyser is shutting down, the hydrogen and oxygen pressure is released. The shut down time is set at ten minutes. During this time, no power is used by the electrolyser.

Losses start
During the start-up time the hydrogen production already starts, however, this is not at the same efficiency as during normal operation of the electrolyser [8, 38]. How much hydrogen is generated during start-up is not clear. To be able to represent the hydrogen production during start-up, the start of the electrolyser is split into two parts. During the first half of starting up, no hydrogen is generated. During the second half of starting of the electrolyser, hydrogen is generated with extra losses. These extra losses are 300 kW, 10% of the minimum power of the electrolyser.

Lifecycle costs
The stack of the electrolyser has a lifetime of around 10 years, between 60,000-90,000 hours. The other components of the electrolyser system have a longer lifetime of about twenty years. The lifetime of the electrolyser is tested on continuous use at full load [8, 19, 39, 40]. However, in this application, the electrolyser will start or stop regularly and the load on the electrolyser will also be flexible. The effect of this on the degradation of the electrolyser is not clear. However, experts expect that the degradation is higher with flexible operation [18, 19, 20]. This is not added to the model, because it can not be quantified. This means that the lifetime of the electrolyser will probably be slightly overestimated. The cost of stack replacement that is used is 250 €/kW, with a stack of 20 MW, this leads to the cost of stack replacement of €5 million [39]. Using a lifetime of 75000 hours leads to the cost of using the electrolyser of 1.11 €/minute.

Standby power
The standby power is the amount of power the electrolyser uses to keep the electrolyser on standby. When the electrolyser is on standby, no hydrogen is generated, but the pressure and temperature of the electrolyser are kept at the operating level. This prevents the long start-up time when the electrolyser is turned on. The standby power ($P_{standby}$) is calculated by the following equation [41]:

$$P_{standby} = \frac{1}{R} * \frac{T_{standby} - T_{outside}}{n_{cells}} \tag{3.1}$$

The thermal resistance R of the electrolyser is $0.0314 K/kW$ [10]. The standby temperature $T_{standby}$ of the electrolyser is $80°C$ or $353K$. [8] The outside temperature $T_{outside}$ varies a lot and can be an input variable. For now, $10°C$ or $283K$ is used, because the effect of varying the temperature will be relatively small. The number of cells of this 20 MW stack is 336 cells [42].

3.2.2. System parameters

Together with the electrolyser parameters, the system parameters represent the system described in this chapter.

Solar energy
The energy that is generated by the solar park. Since the solar park is not built yet, there is no historical data available for the simulation. Simulated generation forecast data is used for one year. The solar energy is given hourly in kWh.

Site demand
The site demand is small compared to the electricity that is generated at the solar park. The site demand is all the energy that is needed to be able to run the site, except for the energy needed for the assets themselves. It is assumed that the site uses more energy than an average office. Therefore it is set to a constant value of 300 kW.

Maximum grid connection
The grid connection of the project has a maximum of 650 MVA. This is higher than what will be generated by solar energy and therefore the project will not be limited by the grid connection. The connection is chosen this large to be able to possibly expand the site later.

3.2.3. Economic parameters

The economic parameters determine the cost matrix of the optimization. This will be used to determine what is the most profitable use of the system.

Hydrogen price

The hydrogen is bought by industry in the region, that would otherwise use natural gas (NG). Therefore the willingness to pay is related to the price of NG. Next to this, the price is also determined by a CO_2 emission tax and a premium for renewable energy. Therefore the hydrogen price is determined by equation 3.2.

$$H_2\,price[€/kWh] = NG\,price[€/kWh] + CO_2\,tax[€/kWh\,NG] + green\,premium[€/kWh] \quad (3.2)$$

In Table 3.2 the different components are shown. The gas price is a set price every day. A data set with the daily historical TTF Dutch natural gas prices have been used for 2020, 2021 and the first semester of 2022. The gas prices are always influenced by the season, but the in second semester of 2021 and in 2022, the prices have gone up extremely [43]. The CO_2 emission tax is a yearly value and started in 2021. Therefore, the CO_2 emission tax in 2020 is zero. The CO_2 emission tax started in 2021 with 30 €/ t CO_2. One MWh NG emits 200 kg CO_2. Therefore, the CO_2 emission tax in 2021 is 6 €/ MWh. Each year the CO_2 emission tax increases by 10.56 €/ t CO_2, until a maximum of 125 €/ t CO_2, which is 25 €/ MWh. In 2022, the CO_2 emission tax is 8.11 €/ MWh [44]. The height of the green premium can depend largely on the company and might grow in the future. The simulations will be run with multiple values for the green premium. The baseline green premium value is set at 20 €/ MWh.

Table 3.2: Height of the different components of the hydrogen prices

Year	2020	2021	2022
Average gas price [€/ MWh]	9	46	124
CO_2 emission tax [€/ MWh]	0	6	8.11
Green premium [€/ MWh]	20	20	20

Oxygen price

Oxygen is produced together with hydrogen. To make the most use of the electrolyser, this oxygen can also be sold. However, the market for oxygen is relatively small. There is no oxygen demand in the region of the project and therefore it is chosen to set the hydrogen price to zero for this project. The oxygen that is produced is calculated in the model, to make it possible to add this when conditions change or for a different project.

Electricity markets

The EMS is based on two different electricity markets.

1. The first electricity market is the day-ahead market. On the day-ahead market electricity is traded in hourly blocks one day before, after which the hourly clearing price is determined [21]. Emmett Green makes predictions of the hourly clearing price. The price for buying and selling electricity is the same for every minute.

2. The second electricity market is the imbalance market. This market is a set price of which the first prediction is made public fifteen minutes before the start of the window of fifteen minutes. After this first prediction, every minute more accurate predictions become available. This imbalance data roughly follows the same pattern as the day-ahead market, however, the imbalance market has more extreme behaviour. The imbalance market has different prices for the grid feed-in and offtake price. The feed-in price is received for the energy that is sold to the grid and the offtake price has to be paid for the energy that is bought from the grid [21].

In the simulation, the forecasts for the day-ahead price and imbalance market prices from 2020, 2021 and the first semester of 2022 are used. The day-ahead forecasts made by Emmett Green are used. For the predictions of the imbalance market, a dataset from 2020, 2021 and the first semester of 2022 is available.

3.3. Scenarios

Different scenarios have been set up to determine if and how these factors influence the results. For all scenarios, one parameter or one set of parameters is changed, while the other parameters are according to the baseline. The different scenarios are run two times, once for the first semester of 2021 and once for the first semester of 2022. These two different periods are chosen to be able to see the behaviour of the system under two different situations. The prices in the first part of 2021 are still relatively low, and therefore this is seen as the baseline scenario for a non-crisis period. However, it is also possible that these prices will remain this high for a longer period of time. The data of the first semester of 2022 reflect the baseline for this crisis period.

In Table 3.3 the baseline is compared to the scenarios.

Table 3.3: The different scenarios that have been tested

	Baseline	Alternative scenarios		
1. Type of electrolyser	Alkaline	PEM		
2. Standby	Implemented	No standby		
3. Electricity from grid	Constrained	Not constrained		
4. Green premium	20 €/ MWh	0 €/ MWh	40 €/ MWh	60 €/ MWh

The scenarios that have been chosen all affect either the electrolyser or the hydrogen price. By analysing the different scenarios it is possible to see which factors influence the profitability of hydrogen in this system. The scenarios that have been compared are the following:

1. Type of electrolyser

The two different technologies for electrolysers that are already commercial are compared. The alkaline electrolyser is compared to a PEM electrolyser. These types of electrolysers have several different specifications, that, therefore, have to be changed in the simulation. The differences have been listed in Table 3.4. The shut down time and ramp time are both in a matter of seconds and are therefore in this model neglectable and have thus been set as respectively 0 minutes and 100 % / minute [8, 18, 29].

Table 3.4: Parameters that are different for a PEM electrolyser compared to an alkaline electrolyser

	Alkaline	PEM
Cold start time [min]	20	5
Shut down time [min]	10	0
Ramp time [% / min]	7.5	100
Efficiency [%]	65	60
Lifetime [1000 h]	75	50

2. Standby electrolyser

The long start-up time for a cold start limits the use of the electrolyser, which is the reason for the two-step optimization. However, the start-up time is mainly limited by the warming up of the electrolyser. By keeping the electrolyser on temperature and by not releasing the pressure, the start-up time can be reduced. The electrolyser will then stop producing hydrogen and use some power to stay on temperature. The startup time can then be reduced to the ramp-up time. This standby mode is implemented in the second optimization step, to be able to turn off based on the imbalance prices. The model with an electrolyser with this standby state is compared to a model without a standby state

3. Electricity from grid

The electricity from the grid can be used for the electrolyser, to be able to produce more hydrogen and oxygen. However, the intention of this project is to produce green hydrogen. Using the grid for the electrolyser results in hydrogen that is possibly produced with fossil fuels. When the use of the electricity from the grid is constrained to only the site demand, all the energy that is used for the electrolyser is green energy, directly from the solar park. In this scenario, constrained and unconstrained use from the grid are compared.

4. Green premium

As discussed in Section 3.2, the hydrogen price is based on the gas price and the CO_2 emission tax with a green premium, which represents the willingness of the industry to pay more for green energy. Over the years the CO_2 emission tax will increase and the green premium might depend on the company. Therefore, the hydrogen price is tested by different heights of the green premium. That can be caused by a higher willingness to pay by companies or because the CO_2 emission tax has increased. The CO_2 emission tax will keep increasing until 2030 at 25 €/MWh NG [44]. The different scenarios that are tested are a green premium of 0 €/MWh, 20 €/MWh, 40 €/MWh and 60 €/MWh. To put this in perspective, in 2020, the average gas price was 9 €/MWh, in 2021, the average gas price was 46 €/MWh and in the first semester of 2022, this was 124 €/MWh [43].

4

Model description

In this chapter, the model is described. The structure of the model is explained, after which the mathematical model is described. The implementation of the model and the possibility of the combination with other assets in the future are discussed.

4.1. Model set-up

With the available parameters and the choice of the optimization method, the model of the EMS is set up. The two markets that have been discussed before, the day-ahead market and the imbalance market, will both be used for the optimization. This is chosen because of their different specifications.

The fluctuating behaviour of the imbalance market with high peaks, makes this the most profitable market, especially when combined with assets that can be used during the valleys of the imbalance prices. Therefore, using the imbalance market as the reference market will give the most accurate representation of what electricity market will be used for selling the electricity. However, because of the short time in advance that the imbalance prices are known beforehand, it is not possible to determine the state of the electrolyser based on this market.

The day-ahead market is a more stable market, with prices that are usually around the average of the imbalance prices. The prediction of the day-ahead prices are known a day before, therefore this market is more suitable for determining the state of the electrolyser.

To make use of the benefits from both markets, the model has been divided into two different optimizations, as shown with a black box visualisation in Figure 4.1. Both optimizations use the same solar forecast and gas price predictions.

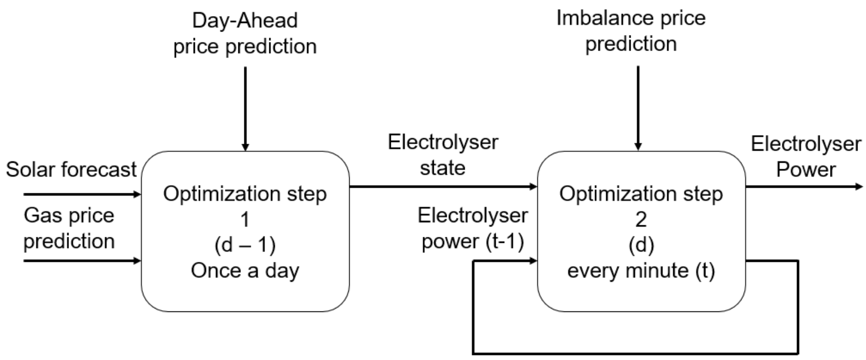


Figure 4.1: Black box visualisation of EMS

The two optimization steps are divided as follows:

1. Optimization step 1: one day in advance, a general planning for the electrolyser is made for the whole day. This is done based on the hourly grid price predictions for the day-ahead market. This optimization determines when the electrolyser will be on or off.

2. Optimization step 2: the second optimization is done when the imbalance price predictions are available. The imbalance price is a set price for a block of fifteen minutes, this price only becomes available at the end of this block. Every minute a prediction is made for the price of the current block and the next block. This prediction becomes more accurate when it is closer to the end of the current block. The optimization runs every minute with the predictions for the next fifteen minutes. Because the amount of minutes for which a price prediction is available is between fifteen and thirty minutes depending on where in a current block the time is, always the first fifteen minutes that are available are used. The state of the electrolyser, determined in the first optimization step, is used as an input.

The EMS does not trade energy on the day-ahead market but only on the imbalance market. This choice is made because the focus of this EMS is on determining the optimal use of the electrolyser. When the electrolyser is on, selling hydrogen is more profitable than the day-ahead market. Therefore, based on the second optimization step, electricity will only be sold to the grid when the imbalance prices are high. When the electrolyser is off, it could be more profitable at times to sell electricity using the day-ahead market than using the imbalance market. This is a different optimization that is not focused on in this thesis. However, this can be implemented when combining this model with the EMS of Emmett Green.

The two optimization steps are explained in more detail below. The complete mathematical models including the equations for both optimization steps are described in Appendix C.

4.2. Mathematical model global planning

Every day the use of the electrolyser is planned for the next day, using the gas price prediction for that day, the solar forecast and the hourly day-ahead price prediction. The system and electrolyser parameters are used in the optimization. Next to the parameters, decision variables are used to determine the behaviour of the assets. In the optimization, the values of the decision variables are determined to reach the maximum revenue. The decision variables are listed below:

- Energy for each asset for every minute ($y_{i,t}$), the amount of energy that is sold or bought by the different assets. This can be divided into: grid off-take, grid feed-in, hydrogen sold and oxygen sold. Both grid assets and hydrogen are all implemented in kWh. This is chosen to have a more visible comparison between the assets and to be able to compare this to natural gas.

- The power of the electrolyser for every minute (p_t^{el}). This decision variable is needed to determine how the energy from the solar park is divided and to determine how much hydrogen and oxygen is generated.

- To represent the minimum power and the ramp rate of the electrolyser, a second decision variable for the electrolyser power is needed. This is a temporary decision variable (P_t^{opt}) that is used to limit the electrolyser power to the ramp rate.

- The state of the electrolyser is represented by a binary decision variable (U_t).

- A change in the state of the electrolyser is represented by binary decision variables, when the electrolyser is starting (Y_t) or when the electrolyser is stopping (Z_t).

- To represent the behaviour of the electrolyser during the starting or stopping, binary decision variables are added that stay 1 during the whole starting (Y_t^{start}) and stopping (Z_t^{stop}) duration.

- The last decision variable is a binary decision variable that represents the first part of the starting of the electrolyser (Y_t^{first}) and is added to be able to make a distinction between the behaviour of the electrolyser during the first part and the second part of the start-up of the electrolyser.

The electrolyser power is also optimized in this optimization step, to be able to accurately determine what the state of the electrolyser should be. However, this power is not used for the planning of the use of the electrolyser. The output of this optimization is the electrolyser state and the start state of the electrolyser. This is used in the second optimization step.

The optimization problem is built up from an objective function with constraints. The objective function determines the behaviour of the system within the boundaries of the constraints. These will be discussed in the sections below.

4.2.1. Objective function

$$max \sum_{i \in I} \sum_{t \in T} c_{i,t} * y_{i,t} - c_t^{lifecycle} * U_t = min \sum_{i \in I} \sum_{t \in T} -c_{i,t} * y_{i,t} + c_t^{lifecycle} * U_t \tag{4.1}$$

The objective is to maximize the revenue that is generated in the system. The objective function 4.1 multiplies the costs of each component ($c_{i,t}$) with the decision variable for the amount of energy ($y_{i,t}$). However, when the electrolyser is used, the lifetime of the electrolyser decreases. Therefore, to accurately determine the price of using the electrolyser the loss in lifetime has to be taken into account. This is done in the second part of the equation, the life cycle costs ($c_t^{lifecycle}$) are subtracted when the electrolyser is on, causing the binary decision variable for the state of the electrolyser (U_t) to be one. Since the goal is to maximize the revenue, this is a maximization problem. However, optimization problems are always minimization problems. Therefore, the objective function is rewritten as the negative of the objective function and is then minimized.

4.2.2. Constraints

The constraints limit the decision variables based on the specifications of the electrolyser and the system. Each constraint has to be linear to be able to be used in a MILP problem. Therefore, the efficiency is simplified to a constant efficiency. A linear efficiency dependent on the electrolyser power would lead to a quadratic relation between the electrolyser power and the generated hydrogen. For some other constraints, the big-M method is used to be able to reach the goal of the constraint, without making this a non-linear constraint [26].

The constraints can be divided into groups that together represent one specification of the system. The constraints are explained together in these groups.

Energy balance
The amount of energy bought from or sold to the grid together with the energy consumed by the electrolyser must be equal to the energy generated at the solar park minus the energy demand from the site, at every minute of the simulation.

Grid constrained
The grid constraints can be split into two groups. The first constraints prevent the use of the grid connection for feed-in and off-take over its capacity. The second group of constraints limit the use of the grid to prevent the use of the grid to operate the electrolyser. Outside of the optimization is determined for each time step if the site demand is bigger than the generated energy, when this is the case, the grid feed-in, thus the energy bought from the grid is limited to this difference. For the other time steps, the grid feed-in is set to zero.

Relation between electrolyser power and hydrogen
The relation between the electrolyser power and the hydrogen produced is under normal operating conditions determined by the efficiency. The electrolyser power is converted to energy and the hydrogen that is calculated is based on the amount of energy the hydrogen contains. When the electrolyser is starting, the relation between power and hydrogen is different. As discussed in Section 3.2, the assumption is made that the start-up time can be split into two parts, to be able to take this behaviour into account with a linear optimization problem. During the second part of starting up, the hydrogen that is produced at a time is less than during normal operation. This is implemented in the model by generating hydrogen with more losses than under normal operating conditions. During the first part of

starting up, the electrolyser does not produce any hydrogen yet. The big-M method is used to turn this constraint on or off depending on the state.

Relation between hydrogen and oxygen
Since oxygen is produced in the same process as hydrogen, the amount of oxygen can be calculated by the relation with hydrogen. By the molar equation of the electrolyser, the amount of oxygen generated is half of that of hydrogen. The oxygen is converted to kg because if the oxygen would be sold, this would be per kg.

Electrolyser capacity
The electrolyser power is limited to the maximum capacity for every minute.

Electrolyser power
The temporary decision variable for the electrolyser is used to limit the ramp up and down from the electrolyser every minute. The decision variable is compared to the decision variable from the minute before and limits the difference to the maximum ramp rate. When the electrolyser is off, the temporary decision variable is set to zero. This is based on the model of Zhang et al. [41]. The electrolyser power is then determined by adding the temporary decision variable to the minimum operating power, to prevent operating under the minimum power. When the electrolyser is off, this is also set to zero.

Starts and stops of the electrolyser
The behaviour during the starts and stops of the electrolyser is represented by multiple decision variables. The first decision variables constrain when the electrolyser is being turned on or off. These variables are then used to set the other decision variables that represent the stops and starts to one for the duration that is necessary to represent the specifications of the electrolyser. These decision variables have been used in the previous constraints to limit the electrolyser power during the start-up. A constraint is added to prevent starting and stopping of the electrolyser at the same time.

4.3. Mathematical model electrolyser with given state

Every minute the power of the electrolyser is determined by the second optimization step for the following fifteen minutes. The electrolyser state, which has been determined by the optimization one day earlier, is used as an input. Therefore, this model has fewer decision variables and constraints. When the electrolyser is off for the whole duration of the optimization, this step only calculates the electricity that is bought from and sold to the grid. At the times the first optimization step has determined that the electrolyser is on, the electrolyser power is optimized using the inputs shown in Figure 4.1. The electrolyser state, the electrolyser power from the last minute before the optimization and the imbalance prices are new inputs for this model, next to this the solar forecast and gas price prediction are used, that were also used for the first optimization. The electrolyser can not be turned off based on this optimization. However, the standby state of the electrolyser is added for this optimization. When the electrolyser is on standby, the temperature and pressure are kept at the operational level. This makes it possible to switch within the fifteen minutes that is in the scope of this optimization step and to respond to the imbalance market.

The mathematical model for this optimization has some overlap with the first optimization step. The decision variables that are used for this optimization are:

- Energy for each asset for every minute ($y_{i,t}$), the amount of energy that is sold or bought by the different assets.
- The power of the electrolyser for every minute (p_t^{el}). This decision variable is needed to determine how the energy from the solar park is divided and to determine how much hydrogen and oxygen is generated.
- A second decision variable for the electrolyser power is needed. This is a temporary decision variable (P_t^{opt}) that is used to limit the electrolyser power to the ramp rate.
- The standby state of the electrolyser, represented by a binary decision variable (U_t^{st}).

The decision variables that are used, will be optimized independent of the first optimization. However, some constraints are changed to take into account the first optimization. In addition, because the state of the electrolyser is an input, some decision variables in the first optimization are now parameters.

4.3.1. Objective function

$$min \sum_{i \in I} \sum_{t \in T} -c_{i,t} * y_{i,t} \tag{4.2}$$

Again, the objective function as presented in equation 4.2 multiplies the negative costs of a component with the amount. However, because the state of the electrolyser has already been determined, the cost for the use of the electrolyser is a constant and is therefore not involved in the objective function.

4.3.2. Constraints

The constraints also have some similarities with the first optimization. However, because the state of the electrolyser has already been determined, fewer constraints are needed. Some constraints are the same as in the first optimization, with the state of the electrolyser as an input. However, there are also a few constraints that are different. First, the constraints that are the same as in the first optimization are listed:

- Energy balance
- Relation between hydrogen and oxygen
- Electrolyser capacity

The other constraints are explained below.

Grid constrained

The use of the grid is still limited by the size of the grid connection. Next to this, the use of the grid for the electrolyser is still prevented. However, the state of the electrolyser has already been determined. When the energy generation is not enough to reach the minimum power at that moment, because of the maximum ramp rate, the electrolyser can't be turned off as was possible in the first optimization. The electrolyser can be placed on standby if necessary. However, this also requires power. Therefore, the energy needed for standby is added to the energy demand for the site, to determine the maximum energy that can be used from the grid.

Relation between electrolyser power and hydrogen

The relation between the electrolyser power and hydrogen is the same as in the first optimization when the electrolyser is on or starting. However, when the electrolyser is on standby, the electrolyser does use power, without generating hydrogen. To accommodate this, the standby energy is subtracted from the energy that is used by the electrolyser, resulting in zero hydrogen production.

Electrolyser power

The electrolyser power constraints are adjusted to be able to exceed the ramp down rate when the electrolyser is going to standby. The temporary electrolyser power is set to zero when the electrolyser is on standby. Next to this, the standby power is added to the electrolyser power, when the electrolyser is on standby.

Standby

The electrolyser can only be put on standby when the electrolyser is on, determined by the first optimization.

4.4. Implementation

The optimization of the electrolyser model is done in Python using the pulp package. This package is a linear programming modeller that can solve MILP problems [45]. Sections from the model with a specific goal are developed in a function or class, to prevent errors. The data is imported using import functions. When changing between simulation and application only those import functions need to be adjusted and the main code can stay the same. This can prevent errors in switching between application and simulation. An electrolyser class is made with the electrolyser specifications, this prevents calling the same variables to different functions in the electrolyser class. Two different functions are made for both steps of the optimization. The global optimization is run once a day, while the optimization with a given state is run every minute. The data that is imported can consist of data points that are not existing. These points are 'NaN' (not a number) values in the imported data lists. These values need to be removed before the optimization. When a 'NaN' value is found, the whole day is removed from the simulation to prevent a wrong result for that day.

During the writing of the code, good programming practices are implemented. This can prevent errors and simplifies the verification at the end [46]. The good programming practices that are implemented are listed below:

- Modular design: As discussed, the EMS is developed using functions and classes. This results in a modular design, which makes tracing errors more easy. Next to this, the optimization is developed in multiple steps. First, a basic version of the optimization is developed, after which more details are added to make the model more accurate. Using those steps during development also makes tracing errors easier by testing after each step.

- Error-free implementation: This can be reached in multiple ways, which are always focused on limiting the possibilities for mistakes. One of those methods is by minimizing the amount of code that is repeated. This can be prevented for example, by creating a function for a section of the code that has to be used in multiple parts of the code. Another way in which error-free implementation is implemented is by writing the code using a style guide, in this case, PEP8 [47].

4.5. Combining EMS with other assets

The EMS can also be combined with another EMS to be able to optimize the use of other assets. Currently, the electrolyser and grid, using the imbalance market, are optimized. The EMS developed by Emmett Green can steer multiple assets and trades in more markets. Using the developed EMS for the electrolyser in this EMS will optimize the use of all those assets together. The EMS from Emmett Green has a modular approach where all assets are separately optimized before combining all assets. This modular approach makes it possible for the electrolyser EMS to be added to this. After the optimization of the use of the electrolyser a new optimization is done in the main part of the Emmett Green EMS, where the other assets also send their request to receive or to deliver electricity. In this optimization, the real allocation of the energy is done.

For each asset, a separate module is created that optimizes the use of that asset and determines the request. The choice for this modular approach is made based on a few specifications of the system.

First of all, the modular approach makes it possible to change the assets that are involved in a specific project, without having to change a lot in the code. With this modular approach, one of the modules is simply not added to the main optimization, while otherwise the whole optimization would have been changed.

The different assets all have different time scales on which they need to act, dependent on the specifications of the markets and components. Because of the modular approach, the different modules can run at times when this is required based on the specifications, while the optimization with all assets can run every minute using the input from those modules. For example, the day-ahead market requires the module to place a bid the day before the actual time period. Therefore, the module runs on the day before and on the day itself, the accepted bids are used as an input for the EMS that runs every minute. Because of the modular approach, the EMS is not influenced by the different time scale of the day-ahead module.

The EMS is developed keeping the EMS of Emmett Green in mind. Therefore, it is possible to combine the code with the EMS of Emmett Green to expand the number of assets. The code is written in classes that can easily be combined.

5

Results & Discussion

In this chapter, the verification and validation are discussed. The results from the simulation and the simulations with different scenarios are shown and discussed. The chapter ends with some general remarks on the results.

5.1. Verification and validation

Verification and validation of the model are done to ensure that the model is developed correctly and that the model represents the system. The electrolyser model is divided into multiple functions and classes, next to an overall verification and validation, each class and function is verified and validated separately. Verification of optimization can be done using the same verification tests as is done for simulation. Verification and validation tests of the whole model are chosen that are most suitable for this application [46, 48].

5.1.1. Verification

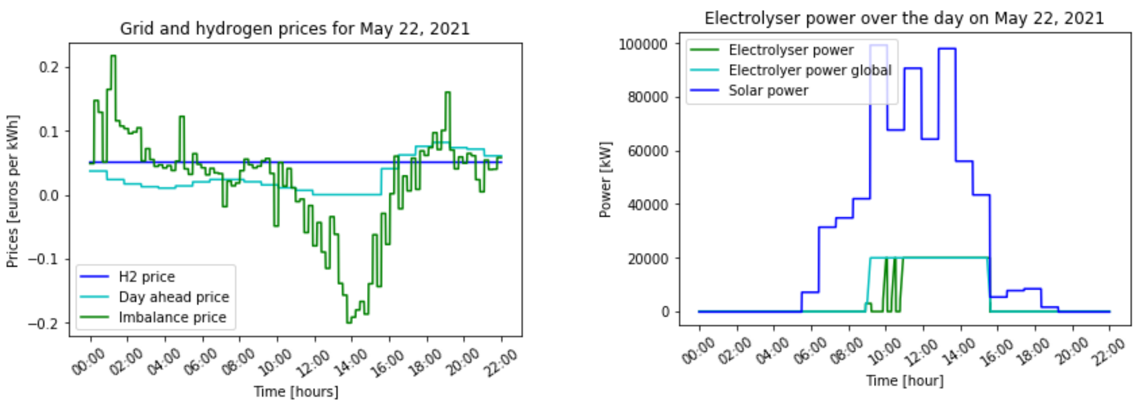
The verification tests are done after the implementation of the model, to ensure that the model is developed correctly. The verification tests are done at the end of implementation. They were chosen based on the verification tests that were suitable for this application, discussed by Roungas et al. and Kleijnen [46, 48]. The tests can be divided into the following types:

- Product testing: Testing to confirm if all requirements are met. The requirements of the EMS that are caused by the specifications of the electrolyser are mostly implemented by constraints. The requirements for the real-time application are implemented by the two-step optimization and the import functions.
- Continuity tests: Compare results from comparable days. The behaviour of the EMS should also be comparable.
- Special input testing: Changing input values to special inputs, for which the results can be predicted. The predicted results are then compared to the results of the simulation.
- Hand calculations: For some simple special input tests, it is possible to calculate the results with hand calculations to compare to the results of the simulation.
- Visualization: Figures or specific results can be used to verify certain aspects of the behaviour of the EMS. This can be combined with the different other verification tests to be able to see the results from the tests.

These tests are chosen because these tests are all focused on different aspects of the model. Together, the whole model is tested. The product tests are implemented to test the requirements, special input tests and hand calculations are carried out to be able to check the results of specific scenarios and the visualisation and continuity tests can be used to verify the results under normal operation. Each test can reveal errors that have been made during the development. If an error is found, all tests have to be done again, to ensure no new errors are implemented when solving the error. After carrying out all the tests, all aspects of the model have been tested and after passing the model is verified.

For each type of test, multiple tests can be carried out. These are discussed in Appendix D. As an example, Figure 5.1a shows the prices of May 22, 2021, and Figure 5.1b shows the behaviour of the electrolyser compared to the solar generation for the same day. This is a visualization test, that can be combined with some product tests. Figure 5.1b shows that the solar generation starts around 06:00 and stops around 16:00, the electrolyser is turned off at the same time, however, it is turned on later, around 08:00. Next to this, it shows that the electrolyser is put on standby a few times in the first few hours. Comparing this to Figure 5.1b, the day-ahead price is below the hydrogen price for most of the day. However, the efficiency and lifetime losses also have to be taken into account. Around 08:00 the day-ahead prices are decreasing compared to 06:00. This is when the electrolyser is turned on, showing that the efficiency and lifetime losses have been compensated by the price difference. After this, the day-ahead prices stay low until 16:00, when the solar generation also stops and the electrolyser is turned off. Between 08:00 and 11:00, the imbalance price is sometimes higher than the day-ahead price, resulting in the electrolyser going to standby. After this, the imbalance price is below the day-ahead price, resulting in the electrolyser being on. This shows that the behaviour of the model corresponds to the prices at the same time.

Figure 5.1 can be used for multiple product tests as well. The first test that can be done is the check that the electrolyser never uses power from the grid. Figure 5.1b shows that the electrolyser is only on when there is enough solar generation. It also shows that the electrolyser does not exceed its capacity of 20,000 kW. The last product test that can be seen here is that the electrolyser with a given state only optimizes the electrolyser use within the region where the global optimization determined that the electrolyser is on. Next to verifying these tests by visualisation, all product tests are done by adding checks to the code that prints an error when one of the tests is not passed. This ensures that the product tests are passed for every simulated day. The full test report can be found in Appendix D.



(a) Grid and hydrogen prices

(b) Electrolyser power, the global electrolyser power is the power determined by the first optimization step

Figure 5.1: Prices and electrolyser power for May 22, 2021

5.1.2. Validation

Validation is done to confirm if the model is reaching its intended purpose and represents the system. The validation tests that are done can be divided into the following tests:

- Compare the results of the EMS to the results when only the imbalance market could be used, not the electrolyser. To pass the validation test, the EMS should improve the results by generating higher revenues.

For this test, for different days the revenue generated by the EMS is compared to the revenue generated by only trading on the imbalance market. The revenues are compared in Table 5.1. On January 10, 2021 and January 20, 2022 the revenue is equal for both cases, this can be explained by the fact that

Table 5.1: Validation test comparing revenues per day

Day	Revenue with electrolyser [€]	Revenue without electrolyser [€]
January 10, 2021	5437	5437
March 15, 2021	16202	15902
May 22, 2021	- 10561	- 24704
January 20, 2022	11276	11276
May 26, 2022	57441	55300
May 28, 2022	208498	208598

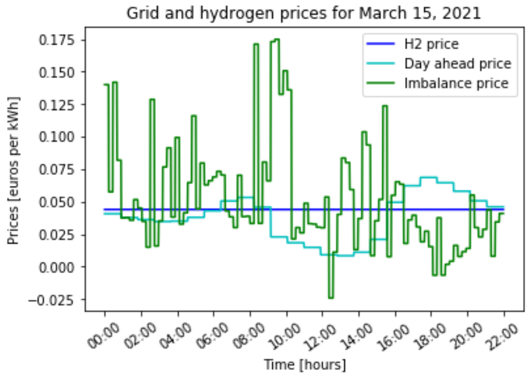
the electrolyser is not used on those days. On the other days, the revenue for the EMS is higher than the revenue from the imbalance market. On May 22, 2021 the revenues are negative in both cases. This is caused by a large period where the imbalance price is negative and a high solar generation, which is higher than the maximum capacity of the electrolyser, therefore the electricity is sold to the grid for a negative price. In reality, the solar power will then be curtailed. However, this was not included in the requirements of the model and does not affect the use of the electrolyser. Therefore, this day still passes the validation test. In Figure 5.1a can be seen that the imbalance prices are negative for a large share of the day and Figure 5.1b shows that the solar production is larger than the capacity. Therefore, electricity has to be sold using the imbalance market. On May 28, 2022 the revenue is much higher than on May 26, 2022. On both days, the electrolyser is turned on. However, for May 26 the imbalance price has some peaks and valleys, with the average around the day-ahead price. For May 28, the imbalance price is almost all day higher than the day-ahead price. Therefore, the electrolyser is on standby for most of the time and the revenue is much higher than on May 26. This validation test is passed because the revenue with the electrolyser is never lower than the revenue without the electrolyser.

- By visualization, compare the hydrogen price to the day-ahead price, to validate the state of the electrolyser.
- By visualization, compare the hydrogen price to the imbalance price, to validate the use of the electrolyser.

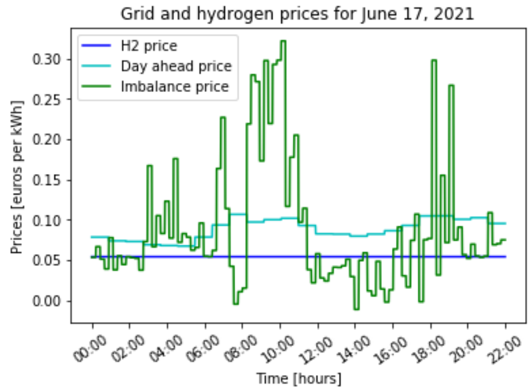
When comparing the hydrogen price to the electricity price, it is important to take into account the efficiency and lifecycle losses that occur when generating hydrogen. Therefore, the hydrogen price needs to be higher than the electricity price. The visualization test is done for 14 different days. The results of the validation are shown for two different days. In Figures 5.2a and 5.2b the day-ahead price, imbalance price and the hydrogen price are shown for March 15 and June 1, 2021. Comparing this to the electrolyser power shows that when the electrolyser is on, the hydrogen price is clearly above the day-ahead price for a few hours with solar generation on March 15. The state of the electrolyser is zero when the hydrogen price is around or below the day-ahead price, the state of the electrolyser is also zero when the solar generation is low. This can be seen when comparing the electrolyser power in Figure 5.2c and 5.2d, the electrolyser is on when the electrolyser power is not zero for the global optimization. The other days on which the validation is done, show similar behaviour. Therefore, this validation test is passed.

In the same way, validation can be done for the comparison with the imbalance prices. Comparing the electrolyser power in Figure 5.2c and 5.2d to the imbalance prices in Figure 5.2a and 5.2b shows that regardless of the imbalance price, the electrolyser power is zero, when the electrolyser state is zero. The electrolyser state, determined by the first optimization, is presented by the global line in the figure. When the electrolyser is on, the electrolyser is put on standby during peaks of the imbalance price and the electrolyser power is high in a valley. This is similar to the other days of the validation. Therefore, also this validation test is passed.

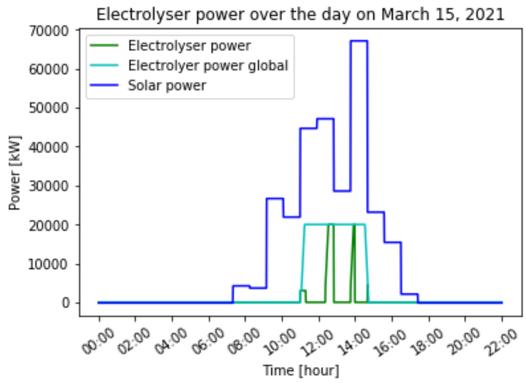
The EMS passed all verification and validation tests and can therefore be used to analyse the results.



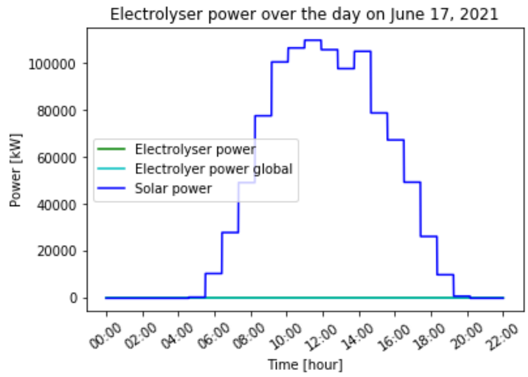
(a) Grid and hydrogen prices March 15, 2021



(b) Grid and hydrogen prices June 17, 2021



(c) Electrolyser power March 15, 2021, the global electrolyser power is the power determined by the first optimization step



(d) Electrolyser power June 17, 2021, the global electrolyser power is the power determined by the first optimization step

Figure 5.2: Prices and electrolyser power for two different days

5.2. Results & discussion simulation

The baseline simulation has been simulated for multiple years to generate results. In Table 5.2 the results of the full years of 2020 and 2021 are shown. From Table 5.2 and the heatmaps in Figure 5.3 can be seen that the use of the electrolyser is limited. The revenue shown in the heatmap is the total revenue of the week during the different hours. The different days of the week are added for each hour. The electrolyser is started 13 times in 2020 and 19 times in 2021, since the electrolyser never has two cold starts on the same day, the number of starts is equal to the number of days that the electrolyser is used. Some days have been removed from the simulation because of missing data, therefore the number of simulated days in the year is slightly lower. However, this still means that only 4% of the days in 2020 and 5.6% of the days in 2021 the electrolyser is used.

This also results in a small fraction of the total revenue, the added value of the electrolyser is for both years 0.4%. The added value is calculated as the percentage of the compensated electrolyser revenue of the total revenue. The compensated electrolyser revenue that is calculated is the electrolyser revenue minus the imbalance revenue, which would otherwise have been earned. Since the imbalance price is sometimes negative, this can also increase the revenue. However, when looking at the added value it is important to take into account that the peak solar generation can be more than 100 MW, while the electrolyser capacity is 20 MW. The revenue that can be made using the grid is therefore also larger. The percentage of the time the electrolyser is using its full capacity reflects this, when the electrolyser is on and not on standby, the electrolyser is in 77% of the time for 2020 and 75% of the time for 2021 at full capacity. Taking into account the ramp times, this means that the electrolyser is most of the time at full power, caused by solar energy production that is even higher than the maximum capacity of the electrolyser. The electrolyser is also relatively often on standby. This can be explained by the fact that the electrolyser state is determined based on the day-ahead price and the standby state on the imbalance price. The imbalance price fluctuates significantly more over the day than the day-ahead

Table 5.2: Results for simulations for a whole year

Simulation year	2020	2021
Time electrolyser is used [hours]	47	68
Number of cold starts	13	19
Days that the electrolyser is used [%]	4.0	5.6
Total revenue [1000 €]	3970	10295
Revenue only imbalance [1000 €]	3955	10252
Compensated electrolyser revenue [1000 €]	16	44
Electrolyser added value [%]	0.4	0.4
Standby time [hours]	14	26
Standby time [%]	31	39
Time at full power electrolyser [%]	77	75
Hydrogen produced [kg]	10986	13442

price, however, the average imbalance price is usually close to the day-ahead price. The average of the imbalance price must therefore be lower than what can be earned with hydrogen, therefore the time the electrolyser is on standby should be below 50% for the whole simulation. The hydrogen price is a set price every day and the day-ahead price is much less fluctuating than the imbalance market and therefore that the peaks of the imbalance price are often more profitable than using the electrolyser. This results in the electrolyser going to standby during the peaks. On days with high imbalance prices, the electrolyser can be in standby for most of the time.

Analysing the use of the electrolyser on some specific days can put these results in perspective. The electrolyser power of May 22, 2021 in Figure 5.1 and the electrolyser power of March 15, 2021 in Figure 5.2 show two different types of use of the electrolyser. On both days can be seen that when the electrolyser is on and not on standby the electrolyser immediately goes to full power. Next to this, it shows that the use of the standby state can be different per day, depending on the imbalance prices. On March 15 the electrolyser is on standby for a large portion of the time because of high imbalance prices, while on May 22 the electrolyser is on for most of the time since the imbalance price is at that time much lower. The different behaviour of the electrolyser per day shows the ability of the EMS to respond to the imbalance on the grid, driven by the imbalance prices. In Figure 5.2 can also be seen that on June 17, 2021 the electrolyser is off for the whole day because the day-ahead price is higher than the hydrogen price for the whole day.

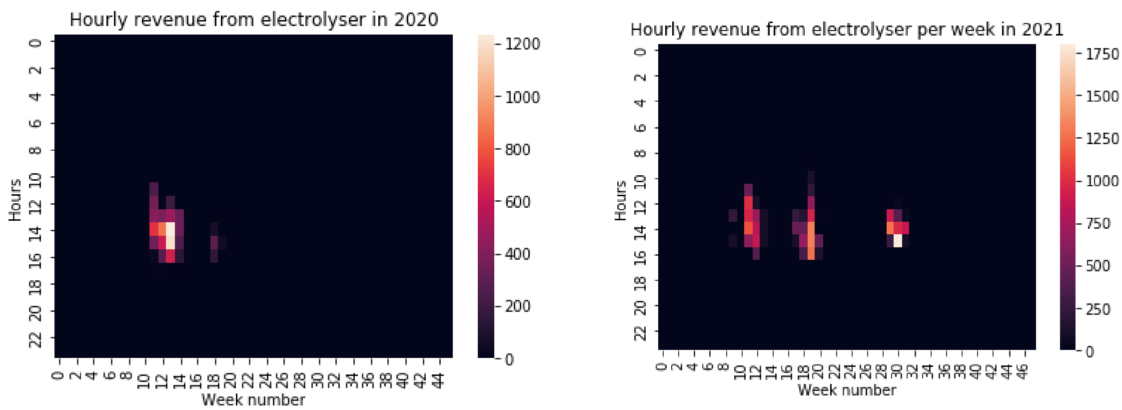
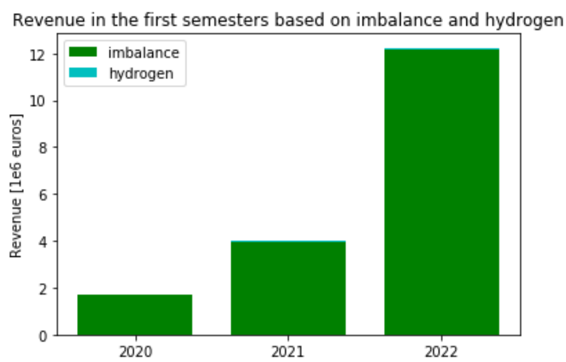


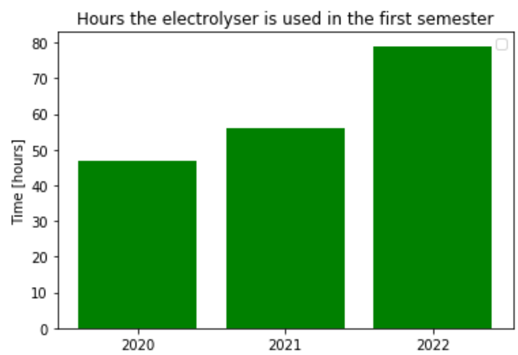
Figure 5.3: Heatmap with revenue from the electrolyser per hour and week in 2020 and 2021, the total revenues of the week per hour are displayed.

Figure 5.3 shows the revenue made by selling hydrogen generated by the electrolyser during the years 2020 and 2021. This gives insight into when in the year the electrolyser is used. These figures show that the use of the electrolyser is focused on specific areas of the year. The heatmaps also show that the electrolyser is mainly used between 10:00 and 16:00, with the highest production in the middle of these hours. This is to be expected because of the solar generation since the electrolyser can only be used with electricity from the solar parks. However it also shows that there is quite some variation in when the electrolyser starts, but hardly any variation in the time the electrolyser stops. During the winter the electrolyser is not used, this might be expected since the solar generation is also relatively low. Almost all revenue is created around March until May, in the spring. During these months the solar generation is also the highest. The rest of the days that the electrolyser is used are in the summer. However, not as often as in the months before. The electricity prices only low enough during days with the most solar generation, when the share of solar energy is higher in the future, the electricity prices could be low enough for the electrolyser during days with less solar generation.

Since the electrolyser is used mostly in the first six months of the year, the results from the first six months of 2020, 2021 and 2022 are analysed separately, shown in Table 5.3. By analysing three different years some differences or trends can be found. The first trend that can be noticed is the explosive growth of the total revenue over the three years, shown in Figure 5.4a. This also clearly shows that the revenue from the electrolyser is insignificant compared to the revenue generated with the imbalance market because the share from the electrolyser is almost not visible. When looking into the revenue that would be earned without the electrolyser and extra the revenue earned from the electrolyser specifically, it can be seen that the revenue from both has increased to more than six times the revenue from 2020. What also can be noticed is the increasing number of days and hours that the electrolyser is used, also shown in Figure 5.4b. The prices of both electricity and natural gas have exploded, however, the natural gas prices have increased even more than the day-ahead prices, resulting in more use of the electrolyser. Next to this, after 2020 the CO_2 emission tax has been added to the natural gas price and is increasing every year. Since it went from 0 to 6 €/ MWh in 2021 and to 8.11 €/ MWh in 2022, this leads to higher gas prices, which makes producing green hydrogen more attractive, also leading to more use of the electrolyser.



(a) Total revenue generated in with division in revenue from the imbalance market and the electrolyser



(b) Hours the electrolyser used

Figure 5.4: Electrolyser use in the first semesters of 2020, 2021 and 2022

Looking again at the revenue, the added value of the electrolyser is comparable. This can be explained by looking at the other results, the electrolyser has been used more, but it is also more in standby. This indicates that the behaviour of the imbalance market has become even more fluctuating to which the electrolyser responds by going to standby when the imbalance prices peak and by going to full power when the imbalance prices are low. When this is changed more often, the electrolyser is respectively less at full power because of the ramp times, which is the case over the years. The different years all have very different circumstances. However, the effect this has on the use of the electrolyser is limited because the height of the electricity prices was always coupled with the natural gas prices, which results in comparable results for every year.

Simulation year	2020	2021	2022
Time electrolyser is used [hours]	47	56	79
Number of cold starts	13	14	18
Days that the electrolyser is used [%]	8.1	8.4	12.1
Total revenue [1000 €]	1719	3989	12240
Revenue only imbalance [1000 €]	1703	3950	12148
Compensated electrolyser revenue [1000 €]	16	39	93
Electrolyser added value [%]	0.9	1.0	0.8
Standby time [hours]	15	24	42
Standby time [%]	31	42	54
Time at full power electrolyser [%]	77.6	75.9	67.2
Hydrogen produced [kg]	10985	10645	11551

Table 5.3: Results for simulations for the first semesters

5.3. Results & discussion scenarios

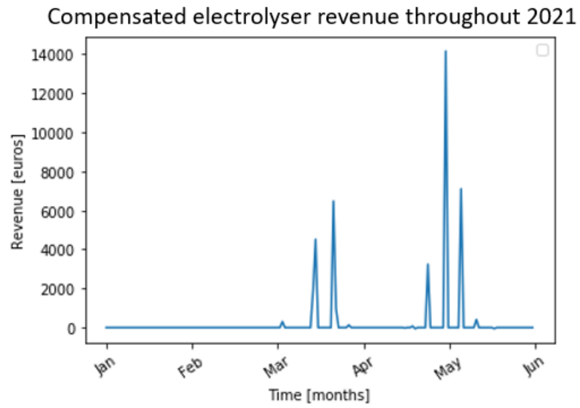
The first six months of 2021 and 2022 both have different circumstances. Therefore, these will both be used for the simulations. As discussed in Section 3.3 the circumstances of both years are two different possible future scenarios. Using these for the scenarios will result in a clear overview of the possible behaviour of the system. It is important to take into account that in 2020 and 2021 almost all revenue from the electrolyser has been generated in the first semester, therefore the results of the scenarios during the first semester might give a more optimistic image and can not be copied to the second semester.

5.3.1. Type of electrolyser

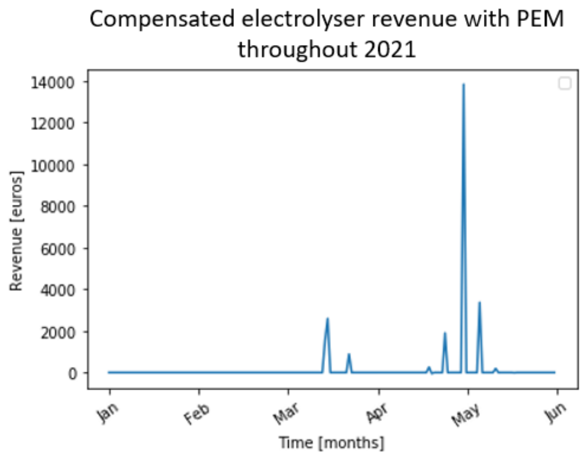
Figure 5.5 shows the difference in the compensated electrolyser revenue for the different types of electrolysers during the first semester of 2021 and 2022. This shows a lower revenue for a PEM electrolyser, both caused by lower peaks and fewer days the electrolyser is used. This can also be seen in Table 5.4. The time the electrolyser is used has increased more than the number of days the electrolyser is used, in 2022 the number of days the electrolyser is used is even equal for both types of electrolysers. The higher added value of the electrolyser is therefore mainly caused by the fact that the electrolyser is used for longer electrolyser use and the higher hydrogen production. This is caused by the higher efficiency and lower life cycle costs of the alkaline electrolyser. The results also show that the PEM electrolyser is almost always at full power, which can be explained by the more flexible behaviour of the PEM electrolyser. Using this EMS, the alkaline electrolyser gives better results, and the more flexible behaviour of the PEM electrolyser doesn't seem to outweigh the higher efficiency and longer lifetime of the electrolyser. However, this EMS is developed based on the behaviour of an alkaline electrolyser. Since the cold start of a PEM electrolyser is only five minutes, the two-step optimization might not be necessary. When the electrolyser behaviour can be fully based on the imbalance price, the PEM electrolyser might give better results because of the more fluctuating character of the imbalance market.

Table 5.4: Scenarios for alkaline and PEM electrolysers during the first semester of 2021 and 2022

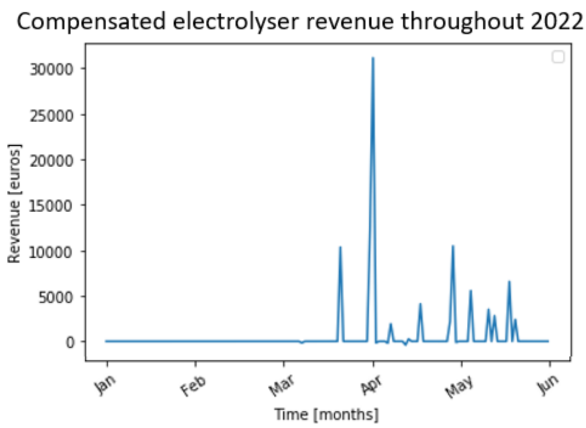
	2021		2022	
Type of electrolyser	Alkaline	PEM	Alkaline	PEM
Time electrolyser is used [hours]	56	30	79	61
Number of cold starts	14	11	18	18
Days that the electrolyser is used [%]	33.5	18.2	12.1	12.1
Total revenue [1000 €]	3989	3974	12241	12223
Compensated electrolyser revenue [1000 €]	39	25	93	75
Electrolyser added value [%]	1.0	0.6	0.8	0.6
Standby time [%]	41.9	37.4	53.5	55.1
Time at full power electrolyser [%]	75.9	96.4	67.2	89.1
Hydrogen produced [kg]	10644	6586	11551	9309



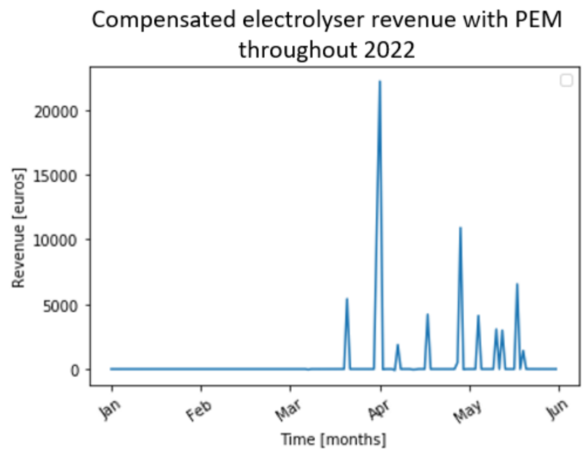
(a) Alkaline electrolyser for 2021



(b) PEM electrolyser for 2021



(c) Alkaline electrolyser for 2022



(d) PEM electrolyser for 2022

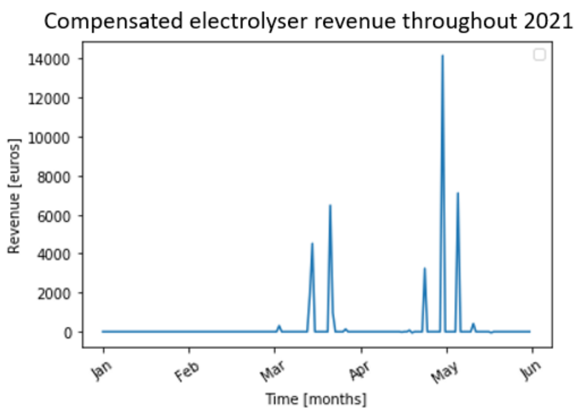
Figure 5.5: Hydrogen revenue, compensated with the imbalance price, for the different types of electrolyser in 2021 and 2022

5.3.2. Standby electrolyser

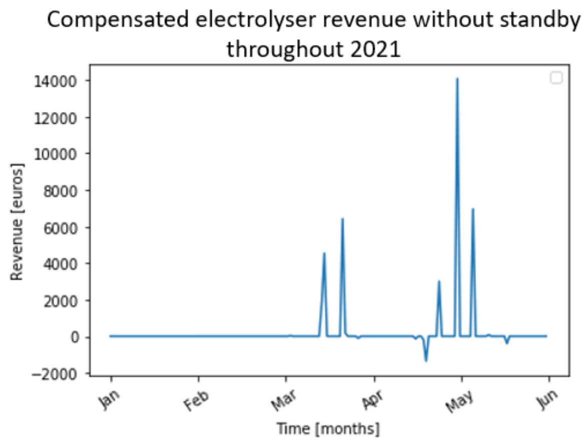
Table 5.5 shows the results of the scenarios with and without standby of the electrolyser. Since the first optimization step is for both scenarios the same, the number of cold starts and the time the electrolyser is on does not change. The total revenue is for both 2021 and 2022 higher when the electrolyser can go to standby. However, this effect is larger in 2022, which can be caused by the more fluctuating imbalance prices. Without standby, more hydrogen is produced, however, this extra hydrogen is generated when it would be more profitable to sell the energy to the grid, leading to the lower revenue. When the imbalance prices are higher, the electrolyser that can't go to standby will operate at the minimum operating point, leading to a lower full power percentage, while otherwise, the electrolyser will go to standby. Figure 5.6 shows that the compensated electrolyser revenue is sometimes negative, while that is not the case with standby.

Table 5.5: Scenarios with or without standby implemented during the first semester of 2021 and 2022

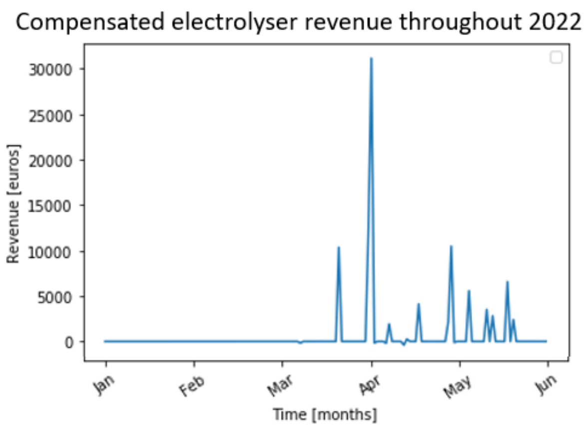
	2021		2022	
	Standby	No standby	Standby	No standby
Total revenue [1000 €]	3989	3985	12241	12221
Compensated electrolyser revenue [1000 €]	39	35	93	73
Electrolyser added value [%]	1.0	0.9	0.8	0.6
Time at full power electrolyser [%]	75.9	44.1	67.2	33.1
Hydrogen produced [kg]	10645	12540	11551	14845



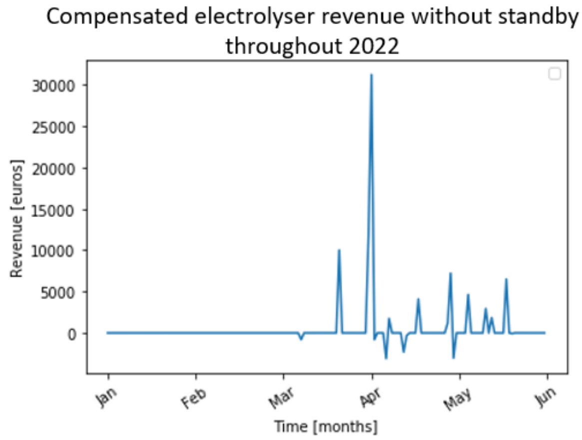
(a) With standby in 2021



(b) Without standby in 2021



(c) With standby in 2022



(d) Without standby in 2022

Figure 5.6: Hydrogen revenue, compensated with the imbalance price, with and without standby

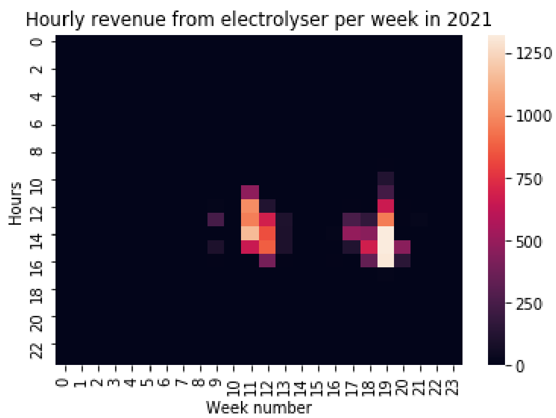
5.3.3. Electricity from the grid

Table 5.6 shows the results of the scenarios with and without constraint that prevents the use of the grid for the electrolyser. The electrolyser is used for only a few extra days without the constraint. The heatmaps in Figure 5.7 show the difference. The heatmaps are comparable for most of the year. Around weeks 11 and 12 in 2021, the revenue is higher without the constraint. This is caused by the higher revenue during the day because the electrolyser is used more days in those weeks. This is caused by low electricity prices during the day, on days with little solar generation. Next to this, the electrolyser is also used a few times outside of the solar generation hours. In 2021, the electrolyser is used once at night. In the first week of 2022, the electrolyser is turned on twice. This extra electrolyser use is caused by low electricity prices with low production of energy from the solar park. The weather is often the cause of low electricity prices. Since there is little solar generation, in this case, it can be caused by the wind. The production of wind energy in 2021 and 2022 is smaller than the production of solar energy [49], therefore a lot of wind energy production is needed to reach a low energy price, resulting in limited extra use of the electrolyser. The solar generation data are not specifically made for 2021 or 2022, therefore it is also possible that when the electrolyser is used extra during the day, this is caused by a different solar generation prediction than the actual solar generation, causing lower electricity prices. Currently, removing the constraint hardly affects the results, however, in the future this could be different. When the share of renewable energy is larger, the electricity prices could be low when there is a high wind energy generation. Since this electrolyser is connected to a solar park, the constraint then prevents the use of the electrolyser if the solar generation is too low. Removing the constraint could, in that case, increase the use of the electrolyser and the revenue.

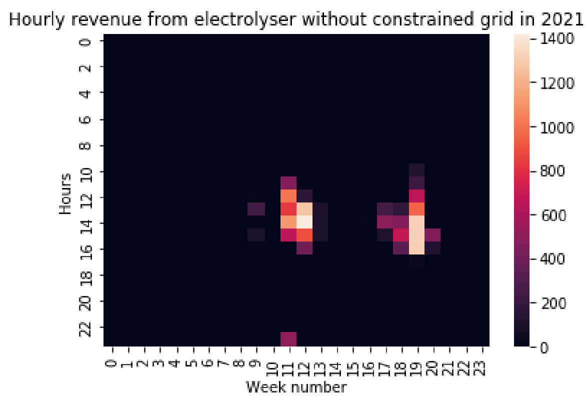
Table 5.6: Scenarios for constrained and not constrained grid use during the first semester of 2021 and 2022

	2021		2022	
	Constrained	Not constrained	Constrained	Not constrained
Time electrolyser is used [hours]	56	64	79	113
Number of cold starts	14	17	18	23
Days that the electrolyser is used [%]	8.4	10.2	12.1	15.4
Total revenue [1000 €]	3989	3993	12241	12283
Compensated electrolyser revenue [1000 €]	39	43	93	135
Electrolyser added value [%]	1.0	1.1	0.8	1.1
Standby time [%]	41.9	43.3	53.5	52.3
Time at full power electrolyser [%]	75.9	71.5	67.2	68.3
Hydrogen produced [kg]	10645	11704	11551	17426

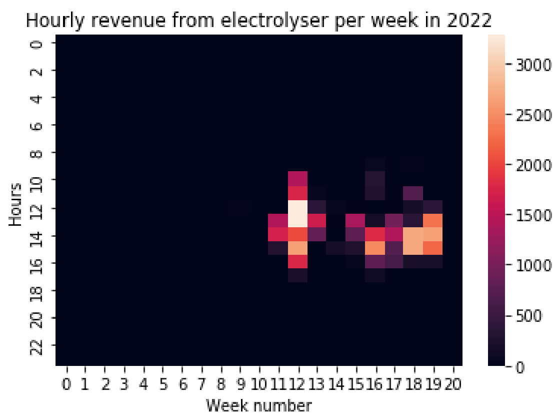
12.282.724



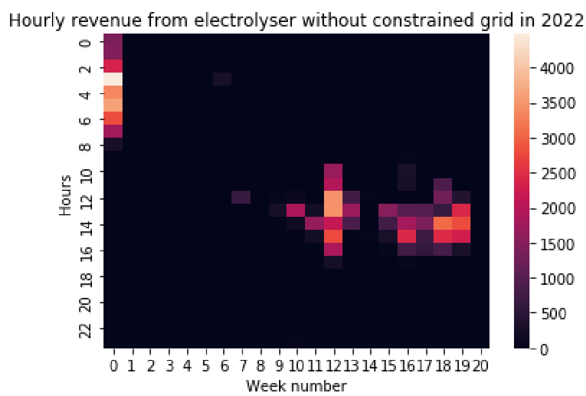
(a) With grid contraint in 2021



(b) Without grid constraint in 2021



(c) First semester of 2022



(d) First semester of 2022

Figure 5.7: Heatmaps with revenue from the electrolyser per hour and week without grid constraint

5.3.4. Green premium

The green premium is added to the hydrogen price to reflect either what industry is willing to pay extra or what could be added to the natural gas price to compensate for the CO_2 emission. In Tables 5.7 and 5.8 the results from the different green premiums are shown. Figure 5.8 shows the difference in hours the electrolyser is used for the different green premiums. This clearly shows that the green premium has a much larger effect in 2021. This is because the prices in 2022 are much higher and since the green premium is the same in both years, in percentages the green premium is lower. For 2021 and 2022 at the baseline of 20 €/ MWh, the electrolyser is used more often in 2022. For the higher green premiums, the use is much higher in 2021, the electrolyser is already used more with 40 €/ MWh in 2021 than with 60 €/ MWh in 2022. Also for the scenario without green premium, the difference with the baseline is larger in 2021 than in 2022.

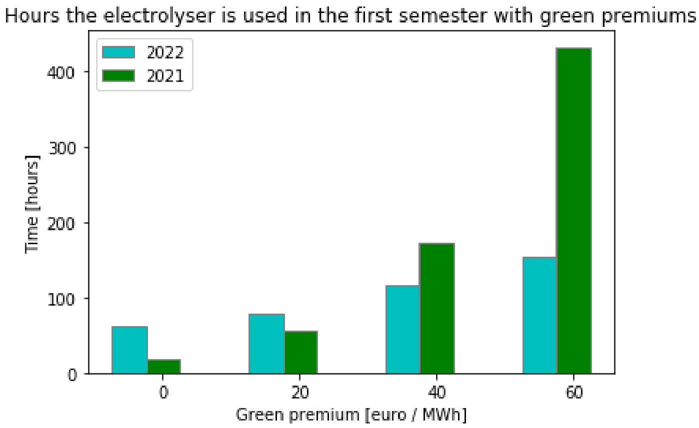


Figure 5.8: Hours the electrolyser is used for the different green premiums

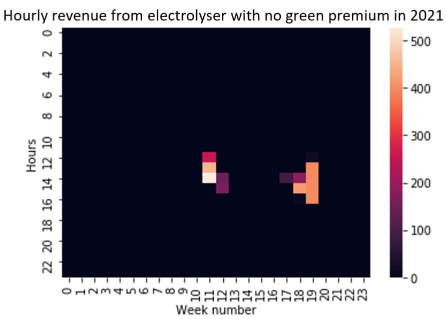
Looking at the added revenue of the electrolyser this is still a small percentage. One of the reasons this is only a small added value is because the added value is only the difference between the imbalance market and the hydrogen that is sold. Next to this, the electrolyser has a maximum capacity that is, for most days that the electrolyser is used, lower than the power that is generated by the solar panels. This means that even when the electrolyser is at its full capacity, electricity is still being sold to the grid. Also, the electrolyser has more constraints. The efficiency and the start-up time prevent that all electricity, used by the electrolyser, is used to generate revenue. However, at times the electrolyser is used, this is still more profitable than using the imbalance market. When interpreting these results it is important to take into account that the average natural gas price including the CO_2 emission tax in the first semester of 2021 was 27.64 €/ MWh, therefore adding a green premium of 60 €/ MWh would triple the average price of green hydrogen compared to the natural gas price. Comparing this to 2022 the natural gas price including CO_2 emission tax was 106.85 €/ MWh, for which the highest green premium is about 60% extra.

Table 5.7: Scenarios with varying green premium during the first semester of 2021

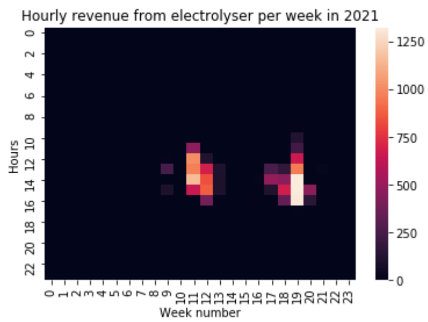
Height green premium [€/ MWh]	0	20	40	60
Time electrolyser is used [hours]	18	56	173	433
Number of cold starts	7	14	34	74
Days that the electrolyser is used	4.2	8.4	20.4	44.3
Total revenue [1000 €]	3966	3989	4085	4282
Compensated electrolyser revenue [1000 €]	16	39	135	331
Electrolyser added value [%]	0.4	0.98	3.3	7.5
Standby time [%]	28.5	41.9	29.9	23.8
Time at full power electrolyser [%]	76.0	75.9	78.4	79.1
Hydrogen produced [kg]	4144	10645	41558	115169

Table 5.8: Scenarios with varying green premium during the first semester of 2022

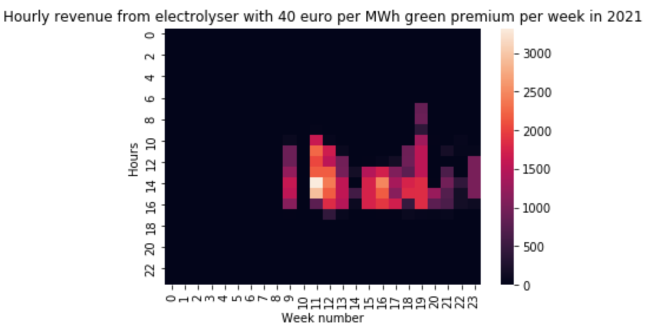
Height green premium [€/ MWh]	0	20	40	60
Time electrolyser is used [hours]	62	79	117	154
Number of cold starts	15	18	26	32
Days that the electrolyser is used [%]	10.1	12.1	17.4	21.5
Total revenue [1000 €]	12213	12241	12305	12383
Compensated electrolyser revenue [1000 €]	65	93	156	234
Electrolyser added value [%]	0.5	0.8	1.3	1.9
Standby time [%]	52.5	53.5	51.0	47.5
Time at full power electrolyser [%]	66.8	67.2	70.8	72.7
Hydrogen produced [kg]	9167	11551	18467	26525



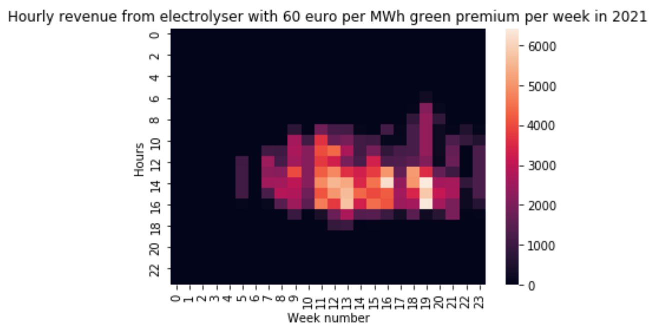
(a) No green premium



(b) 20 €/ MWh green premium

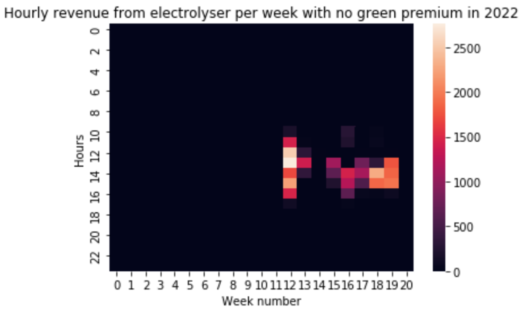


(c) 40 €/ MWh green premium

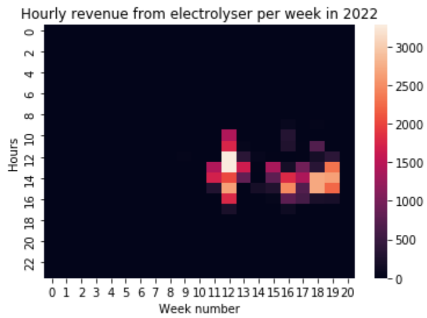


(d) 60 €/ MWh green premium

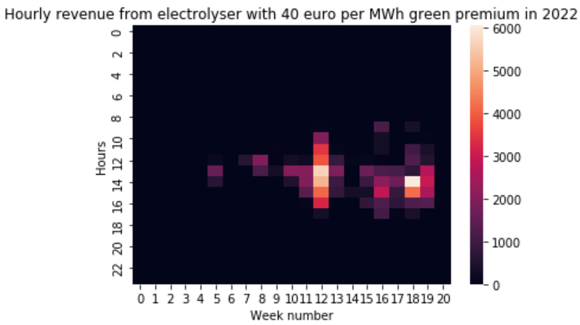
Figure 5.9: Heatmaps of the scenarios with different green premiums in 2021



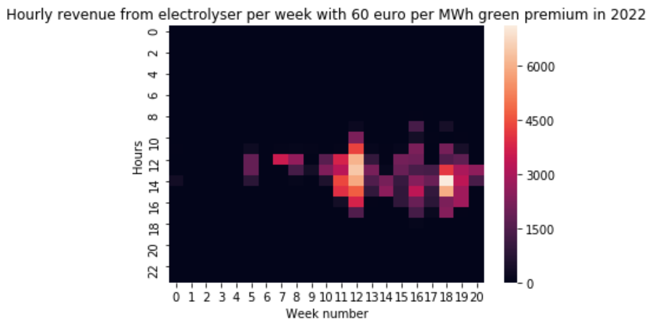
(a) No green premium



(b) 20 €/ MWh green premium



(c) 40 €/ MWh green premium



(d) 60 €/ MWh green premium

Figure 5.10: Heatmaps of the scenarios with different green premiums in 2022

5.4. Global discussion

Next to the discussed remarks in the previous sections, some global remarks can be made that need to be taken into account when interpreting the results that are found. The data that has been used has some limitations. The solar park still has to be built and therefore no historical solar generation data is available. The forecast of the generation data from the solar park is calculated based on predictions of the generations. Therefore this data is the same for every simulated year. On some days the solar data will not fit the day-ahead and imbalance data as well as on other days, which could influence the results. Next to this, in the second optimization step, the same solar forecast is used as in the first daily optimization step. Since the second optimization step is only just before the minute itself, the solar forecast could be much more accurate than for the daily optimization. Implementing this in the model could increase the accuracy of the planning. The grid prices for both the imbalance market and day-ahead market have relatively often missing data, which results in some days being removed from the simulation. Since the days that have been removed are distributed randomly over the year, this will not affect the results significantly. However, it is important that for the application, a good process is implemented to handle missing data and to still be able to continue the planning.

When the electricity prices are below zero, in reality, the electricity will not be sold to the grid, but the solar panels will be turned off. In this simulation the electricity is then still sold on the imbalance market, resulting in sometimes negative revenues. However, this does not affect the use of the electrolyser.

The CO_2 emission tax that is implemented is a part of the emissions trading schemes (ETS) permits that some companies need to have. Since this is a part of the ETS, the ETS is somewhat more than the CO_2 tax. Next to this, the ETS is also traded, therefore the price is fluctuating and resulting in sometimes high prices. However, the CO_2 emission tax is the minimum price. Implementing this into the EMS could result in higher use of the electrolyser, as could be seen in the increased use of the electrolyser for a higher green premium. However, the green premium that is used for the baseline scenario is already higher than the difference between the CO_2 emission tax and the average ETS in 2030.

When interpreting the results it is important to take into account that the results are generated based on the aspects of this specific system. Some specifications that might be different for a different system could influence the results. For example, the grid connection is in this case large enough to not limit the electricity flow to the grid. However, for other projects, it might be necessary to use a smaller grid connection, which could influence the use of the grid. Also, the results are based on a system with a solar park, the different behaviour of a wind park will also give different results. In the future, when a larger share of the electricity is generated with renewable power, the natural gas and electricity prices will not be coupled this strongly anymore which would also result in strongly different results.
At last, some simplifications have been made to the EMS. The electrolyser efficiency and temperature are kept constant and the degradation is only represented by the lifecycle costs. The electricity is only sold on the imbalance market and not on other electricity markets and the battery has not been implemented. The simplifications have all been made to fit the real behaviour as realistically as possible, however, they will have some effect on the results.

As discussed before, the added value of the electrolyser is limited. Of course, the number of days that the electrolyser is used is also very limited. However, even when the green premium is high in 2021 and the electrolyser is used on a larger number of days, the added value is not as high. This is because the grid is often even used when the electrolyser is on because the electrolyser can not use all the generated solar power. Next to this, during operating hours the grid is often used during the imbalance peaks.

6 Conclusion

6.1. Conclusions

This thesis aimed to answer the following research question:

How to develop a real-time energy management system for a grid-connected solar park with an electrolyser and how is the system influenced by different specifications of the electrolyser and the hydrogen market?

This is done by first answering the following sub-questions:

1. What optimization methods should be used for the use of the electrolyser to meet the requirements?

The optimization method that was chosen was MILP. The choice was made based on a trade-off between calculation time and the simplifications that had to be made. Based on the literature study, the effect of linearizing the system was expected to be limited. Mixed integer programming was chosen to be able to model the states of the electrolyser with binary variables.

2. What parameters have to be included in the model?

The relevant parameters for the electrolyser, electricity markets and system parameters have been chosen based on the literature and the available data. The electrolyser parameters that have to be included in the model have been determined based on the specifications of an alkaline electrolyser and the expected effect this will have on the EMS. Only electrolyser parameters are chosen that are expected to increase the accuracy of the planning of the results. For a real-time EMS and to contribute to the balancing of the grid, it is important to implement the different electricity markets in the model. Therefore, two different electricity markets with different behaviour are included into the model; the day-ahead market and the imbalance market. The relevant system parameters have been determined based on the specifications of the system.

3. How can the mathematical model developed with the optimization method be implemented?

The mathematical model developed with the optimization method has been split into a two-step optimization, to take into account the different electricity markets. The first optimization step is executed the day before, making a general planning for the use of the electrolyser for the next day. A mathematical model is developed for this first step, with an objective function to maximize the generated revenue and constraints using the parameters. The second optimization step is executed every minute, for the following fifteen minutes. This uses the output of the first optimization step for the state of the electrolyser. This allows for the short time frame of this optimization step. The electrolyser power is determined in this step. A mathematical model is developed, with some alterations compared to the mathematical model from the first step.

4. What is the effect of varying the specifications of the electrolyser and hydrogen market?

The results show that adding an electrolyser to a solar park with a grid connection can be a useful asset for when the electricity prices are low. However, the use of the electrolyser is limited to only specific days with the highest solar generation, which results in a compensated electrolyser revenue that is low compared to the revenue from the imbalance market at this site for the simulated years. Under these conditions, the use of the electrolyser does not increase the revenue significantly. For the different simulated years, the use of the electrolyser is comparable despite the exploding gas prices. This is because the increase in gas prices also results in an increase in electricity prices.

The different scenarios that have been simulated give insight into how these factors influence the use of the electrolyser. The impact of different values of the green premium is significantly different for the years 2021 and 2022. The results of 2021 show that increasing the CO_2 emission tax and having parties pay a higher green premium have effect and increase the use of the electrolyser. However, the hydrogen price has to increase significantly before this effect is reached. The height of the green premiums and CO_2 emission tax should reflect the height of the current gas prices to keep having the same effect for different years. Since the CO_2 emission tax has been determined before the energy crisis, this will not have the same effect as it would have had with prices comparable to the prices of 2021. Next to this, under the current conditions parties would still have to be prepared to pay well above the price they would have paid for natural gas.

The other scenarios did not show a large difference in the use of the electrolyser. Using a PEM electrolyser did not improve the results with this EMS, the use decreased because of the lower efficiency and shorter lifetime. Thus the choice between the existing types of electrolysers will not change the feasibility of the use of an electrolyser. The standby mode in the EMS did result in a slightly higher revenue, with comparable use of the electrolyser. Therefore, when this EMS is used for the planning of the use of the electrolyser an alkaline electrolyser should be used with a standby mode. Removing the constraint for the use of the grid for generating hydrogen did increase the use of the electrolyser and the revenue, however, this effect was only limited to very specific days and in most cases, it did not result in a different planning. Since for only using the electrolyser with purely green hydrogen from the connected solar park, a higher green premium could be expected, this will not increase the revenue.

Answering these sub-questions has led to answering the research question. A real-time EMS for this system can be developed using a two-step optimization taking into account two different electricity markets using MILP. The use of the electrolyser under current conditions is too low, and the effect of changing the electrolyser specifications was limited. The different green premiums to affect the hydrogen market, however, did influence the system and higher green premiums increased the use of the electrolyser.

This real-time EMS is a step towards a supply-based renewable energy system. It contributes to the transition to renewable energy in two ways:

- The ability of an alkaline electrolyser to respond to the sudden changes in the grid and by doing this making it possible to use alkaline electrolysers for balancing the grid.
- The use of green hydrogen in the industry for a competitive price.

Next to this, the research into the influence of different specifications of the electrolyser and the hydrogen market created focal points for further research into the alkaline electrolyser at a solar energy site.

6.2. Recommendations

Further research should focus on how the use of an electrolyser can be made feasible for a larger share of the time. As mentioned, under these conditions the use of the electrolyser is not feasible. However, some aspects can be indicated that could make the use feasible.

The use of an electrolyser, with these specifications, is limited as long as the gas prices determine the electricity prices. This could be uncoupled when the share of renewable energy is large enough or by storage of hydrogen. Storage of hydrogen makes it possible to generate hydrogen when there is a lot of solar power and sell the hydrogen when the gas prices are high, during the winter. However, research should be done into the feasibility of this.

This EMS focuses on the optimal use of the electrolyser itself. However, the revenue could be increased by connecting to other assets. Connecting to the already existing EMS at Emmett Green to make use of the battery and the implemented reserve and electricity markets will increase the total revenue. The battery could be used to generate hydrogen when there is no solar generation. Next to this, different electricity markets could be integrated into the electrolyser. With this model, only the imbalance market is integrated. The day-ahead market could be implemented by placing bids when the market is more profitable. Next to this, research could be done to determine if it is possible to use an electrolyser in balancing markets. Implementing this when the electrolyser is on and adjusting the hydrogen production when necessary can increase the reliability of the grid and possibly increase the revenue.

The use of the electrolyser is limited by the low efficiency of the electrolyser, therefore it is important that the research into electrolysers, both by improving the current types of electrolyser and research into new technologies, is continued to reach higher efficiencies to increase the competitiveness of hydrogen in the energy markets. Research into the degradation of electrolysers under flexible operation is important for the strategy of the use of the electrolyser.

This thesis found that a higher green premium does increase the use of the electrolyser, however, research has to be done into how much parties are willing to pay extra to use green hydrogen.

Next to research into the conditions around the electrolyser, more research into the specifications of the electrolyser for which simplifications have been made in this EMS could improve the accuracy of the planning. Implementing the temperature of the electrolyser could increase the accuracy of multiple specifications of the electrolyser, the power used on standby would be more accurate but also the time for a cold start is influenced by the electrolyser temperature. Also, the efficiency during start-up would be more accurate, because the efficiency is influenced by temperature. At last, adding the temperature could also have the benefit that it gives more insight into the residual heat to determine if it can be used for other purposes. Also, the efficiency could be added more accurately for the different electrolyser power levels and during startup. Currently, for both optimization steps, the same solar forecast is used.

For this EMS the day-ahead market has been used to determine when the electrolyser is on. This is done because the cold start from an alkaline electrolyser is not fast enough to respond to imbalance market. However, a PEM electrolyser has a faster response time and therefore comparing both electrolysers with this EMS is not a fair comparison, since this is the main benefit of a PEM electrolyser. Modelling a PEM electrolyser without the first optimization step will result in a better comparison.

Another way of operating an alkaline electrolyser is by having the electrolyser always on standby and optimizing the use of the electrolyser using only the imbalance market. Research should be done into comparing both methods to determine which method gives the best results for different projects. The electrolyser is now connected to a solar park, when the EMS is connected to wind energy or a combination of both the distribution of the electrolyser use over the year could be very different. More research should be done into the different use of the electrolyser, using different renewable energy sources and the effects of this. Next to the renewable energy source and the electrolyser type, more extensive research could be done into other specifications of the energy site to determine what would be the optimal set-up for an energy site.

This research focused on the price that is expected that parties are willing to pay for hydrogen and to compare this to the electricity prices, therefore the price paid for hydrogen is always higher than the current imbalance price. When an electrolyser is not directly coupled to a solar park, the electricity prices are the biggest cost contribution for the electrolyser. However, the investment costs and the operational costs are not included in this research. A full cost analysis should be done to determine for what price and number of operational hours the electrolyser can be used profitably.

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A

Scientific paper

A real-time energy management system for a grid-connected solar park using an electrolyser in the Netherlands: optimizing to maximize the revenue

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Abstract

This paper describes a real-time energy management system developed for a solar park in the Netherlands using an alkaline electrolyser. The optimization problem is split into a two-step optimization, taking into account the specifications of the electrolyser and allowing the electrolyser to respond to changes in the imbalance market. The first optimization step determines the state of the electrolyser one day in advance. The second optimization step determines the electrolyser power, using the state of the electrolyser as an input. Simulations using data from 2020, 2021 and 2022 show that the use of the electrolyser is limited to a number of days in the year with a lot of solar generation, causing the day-ahead prices to be low. Different scenarios have been tested to get insight into how the use of the electrolyser is influenced by these changes. The type of electrolyser, being able to put the electrolyser on standby and allowing the grid to be used for the electrolyser hardly affected the results. At last, different hydrogen prices are compared. The higher hydrogen prices lead to more use of the electrolyser. This real-time EMS contributes to the ability of an alkaline electrolyser to respond to the sudden changes in the grid and by doing this making it possible to use alkaline electrolysers for balancing the grid and contributes to the use of green hydrogen in the industry for a competitive price.

1 Introduction

The increasing share of renewable energy causes a high strain on the national grid because of its intermittent nature, which can lead to congestion and can compromise the reliable energy supply. In multiple regions in the Netherlands, the grid is congested [1]. Most renewable energy sources provide energy in the form of electricity. More and more applications can be electrified, however, for some industrial applications, this is not possible. Storage of the electrical energy can relieve the strain on the grid and improve the reliability by storing energy when the generation is high and releasing this energy when the generation is low [2]. However, this does not solve the problem for industrial applications that can not be electrified. Power-to-gas (P2G) can be a solution for those applications. The electrical energy is then used for the production of methane or hydrogen. The hydrogen, generated by an electrolyser, can be used as a transport fuel, to replace fossil fuels in industrial processes that require high temperatures, or can be added in small amounts to the natural gas network [3].

A renewable energy system can be created by connecting a renewable energy park with an electrolyser and the grid. To ensure that the grid and the electrolyser are used when this is suitable, an energy management system (EMS) can be developed. This EMS optimizes the use of different components to an objective, that determines the behaviour of the system. Currently, the cost of production of green hydrogen is a large barrier, since this is not competitive with the price of natural gas, which it often replaces [4]. Using an EMS that optimizes the use of the electrolyser to when the electricity costs are low will increase the competitiveness of green hydrogen. The prices of the electricity markets in the Netherlands are determined based on the imbalance in supply and demand, preventing an energy surplus or shortage. Optimizing the use of the electrolyser based on these prices will therefore also relieve the strain on the grid and improve reliability.

In the literature study, the different EMS that have been developed using an electrolyser and an economic objective are researched. The researched articles covered a broad range of applications, using different assets for their system. Almost no literature was found that made an EMS with a supply perspective, based on the generated energy. Also, most EMS were developed for simulation, not real-time application. The articles that did develop an EMS for real-time application, used one grid price, not taking into account the different markets and their different timescales. To my best knowledge, no EMS has been developed using the different timescales of multiple energy markets, to determine the behaviour of the electrolyser real-time with the available data. Developing an EMS with an electrolyser that takes into account the multiple energy markets in a real-time application with a supply perspective can increase the competitiveness of green hydrogen on the market and help solve the problems with renewable energy mentioned above.

The EMS is developed for a grid-connected solar park with an electrolyser in the Netherlands that is in close proximity of industry that is interested in hydrogen to make their process more sustainable. The research goal is to develop an optimization model for the use of an electrolyser at a grid-connected solar park using Python for simulation and real-time application, optimizing to an economic objective, taking into account the different time-scales of the energy markets in the Netherlands. The EMS will be developed in a way that it can be combined with a different energy management system with battery storage and different electricity markets in the future.

2 System description

An alkaline electrolyser is chosen for this project. Currently, only two different technologies for electrolysers are already commercial in this size: the alkaline electrolyser and the polymer electrolyte membrane (PEM) electrolyser. The alkaline electrolyser is the most mature technology and has been utilized throughout the world [5]. PEM electrolysers have shown to have some properties that are more suitable for dynamic operations. However, this does not yet outweigh the benefits of a higher maturity, lower investment costs and longer lifetime [6]. Therefore, the electrolyser parameters are all based on an alkaline electrolyser and are listed in Table 1. The hydrogen price is based on the daily gas prices, the CO_2 emission tax and a green premium. The green premium reflects how much a company is willing to pay extra for green energy.

Table 1: Parameters electrolyser

Parameter	Value
Capacity (P^{cap})	20 MW
Minimum operating power (P^{min}) [7, 8, 9, 10, 11]	3000 kW
Efficiency (η) [4, 7, 9, 12]	65%
Ramp time (P_{ramp}) [7]	7.5% / min
Cold start [4, 7, 9, 13, 14]	20 min
Shut down time	10 min
Lifecycle cost ($c^{lifecycle}$) [15]	1.11 €/ min
Losses start (E^{loss}) [4, 14]	300 kW
Standby power [16, 17]	6.6 kW

To be able to see how the specifications of the electrolyser and the hydrogen market influence the system, a few different scenarios will be tested. The alkaline electrolyser will be compared to a PEM electrolyser. To simulate a PEM electrolyser, the cold start and stop time decrease, the ramp rate is neglectable, the efficiency is slightly lowered and the life cycle costs are increased [4, 7, 9]. The model with standby mode is compared to a model without standby mode. The use of the grid is constrained to prevent that the electrolyser uses the grid and thus not only renewable energy to generate hydrogen, this is compared to when the grid is not constrained. At last scenarios with different heights of the green premium are compared.

3 Model description

The EMS is divided into two optimization steps to take into account the availability of the prices from the different electricity markets. Both steps use mixed-integer linear optimization. The state of the electrolyser, the standby state and the state of starts and stops are implemented as binary variables.

First, one day before a general planning for the electrolyser is made for the whole day. This is done based on the grid price predictions for the day ahead market. This optimization determines when the electrolyser will be on or off.

The second optimization is done when the imbalance price forecasts are available. The imbalance price is a set price for one time block of fifteen minutes, this price only becomes available at the end of this time block. Every minute a prediction is made for the price of the current time block and the next block. This prediction becomes more accurate when it is closer to the end of the current block. The optimization runs every minute with the new prediction of the price. Because the amount of minutes for which a price prediction is available is between fifteen and thirty minutes depending on where in a current block the time is, always the first fifteen minutes that are available are used. The state of the electrolyser, determined in the first optimization step is used as an input. This is done because the window of fifteen minutes is not enough to determine the optimal state of the electrolyser, caused by the long start-up time.

The two-step optimization is a unique way to make it possible to look ahead long enough to accurately determine the optimal state and to be able to respond to changes on the day itself, taking into account the electricity markets in the Netherlands.

For both optimization steps, a mathematical model has been set up. The objective function maximizes the revenue made by the different assets. The first optimization step compensates for the loss in lifetime of the electrolyser, when the electrolyser is used. Constraints are added to be able to take into account the electrolyser and system parameters.

4 Results & Discussion

The results are obtained by implementing the model into Python using the 'pulp'-package [18]. The baseline simulation has been simulated for multiple years to generate results, shown in Table 2. The electrolyser is started 13 times in 2020 and 19 times in 2021, since the electrolyser never has two cold starts on the same day the number of starts is equal to the number of days that the electrolyser is used. This means that only 4% of the days in 2020 and 5.6% of the days in 2021 the electrolyser is used.

This also results in a small fraction of the revenue, the added value of the electrolyser is for both years 0.4%. The added value is calculated as the percentage of the compensated electrolyser revenue of the total revenue. The compensated electrolyser revenue that is calculated is the electrolyser revenue minus the imbalance revenue, which would otherwise have been earned. Since the imbalance price is sometimes negative, this can also increase the revenue. However, when looking at the added value it is important to take into account that the peak solar generation can be more than 100 MW, while the electrolyser capacity is 20 MW. The revenue that can be made using the grid is therefore also larger.

The percentage of the time the electrolyser is using its full capacity reflects this, when the electrolyser is on and not on standby, the electrolyser is in 77% of the time for 2020 and 75% for 2021 at full capacity. Taking into account the ramp times, this means that the electrolyser is most of the time at full power, which indicates that the solar energy production might be even higher. The electrolyser is also relatively often on standby. This can be explained by the fact that the electrolyser state is determined based on the day-ahead price. The imbalance price fluctuates a lot more over the day than the day-ahead price, however, the average imbalance price is usually close to the day-ahead price. The average of the imbalance price must therefore be lower what can be earned with hydrogen, therefore the time the electrolyser is on standby should be below 50%. The different behaviour of the electrolyser shows the ability of the EMS to respond to the imbalance on the grid, driven by the imbalance prices.

Figure 1 shows the revenue made by selling hydrogen generated by the electrolyser during the years 2020 and 2021. The revenue shown is the total revenue of the week during the different hours. This shows when in the year the electrolyser is used. These figures show that the use of the electrolyser is focused on specific moments of the year. Almost all use of the electrolyser is in the first 6 months of the years. The first semesters therefore show somewhat higher use of the electrolyser in percentages. Over the years, the electrolyser is used more. This can be explained by the exploding gas prices, even though the electricity prices also increased and the implementation of the CO_2 emission tax in 2021. The added value of the electrolyser however did not increase, this can be explained by the higher standby times. The imbalance market on which the standby state of the electrolyser is based has become more fluctuating over the years, resulting in more valleys and peaks.

The simulations with the different scenarios have been done for the first semesters of 2021 and 2022, because they show two different future scenarios.

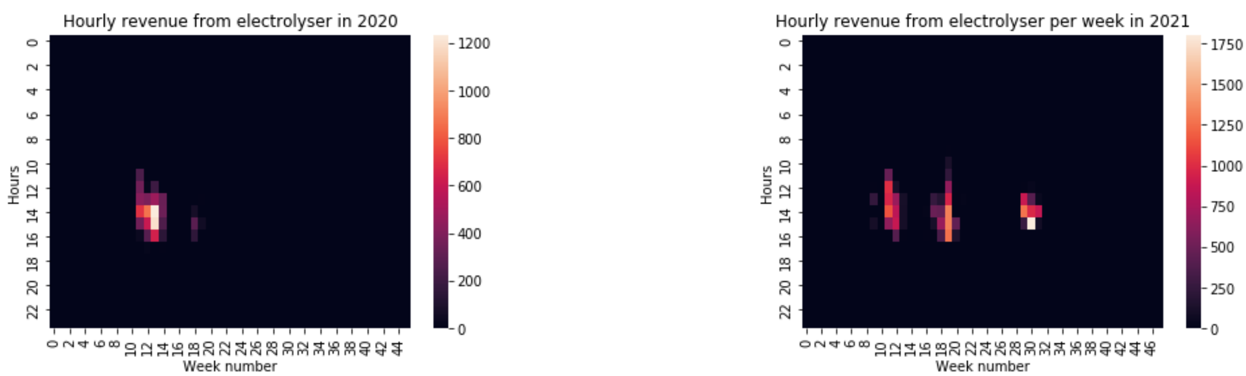
Table 2: Results of the simulations

Simulation period	2020	2021	semester 1 2020	semester 1 2021	semester 1 2022
Time electrolyser is used [hours]	47	68	47	56	79
Number of cold starts	13	19	13	14	18
Days that the electrolyser is used [%]	4.0	5.6	8.1	8.4	12.1
Total revenue [1000 €]	3970	10295	1719	3989	12240
Revenue only imbalance [1000 €]	3955	10252	1703	3950	12148
Compensated electrolyser revenue [1000 €]	16	44	16	39	93
Electrolyser added value [%]	0.4	0.4	0.9	1.0	0.8
Standby time [hours]	14	26	15	24	42
Standby time [%]	31	39	31	42	54
Full power electrolyser [%]	77	75	77.6	75.9	67.2
Hydrogen produced [kg]	10986	13442	10985	10645	11551

The prices in the first semester of 2021 were still on a more stable level, while the prices from 2022 reflect the crisis situation. It is important to take into account that in 2020 and 2021 almost all revenue from the electrolyser has been generated in the first semester, therefore by looking at the results of the scenarios during the first semester this might give a more optimistic image and can not be copied to the second semester.

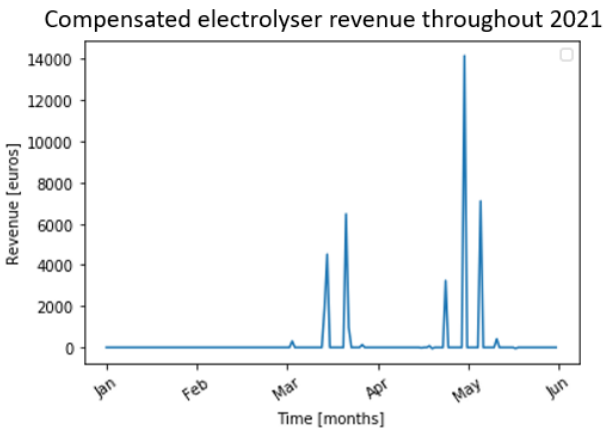
Figure 2 shows the difference in revenue for the different types of electrolysers during the first semester of 2021. A similar difference can be seen for 2022. This shows a lower revenue for a PEM electrolyser, both caused by lower peaks and less days. The time the electrolyser is used has increased more than the number of days the electrolyser used, in 2022 the number of days the electrolyser is used is even equal for both types of electrolysers. The higher added value of the electrolyser is therefore mainly caused by the fact that the electrolyser is used for longer and the higher hydrogen production. This is caused by a higher efficiency and lower life cycle costs of the alkaline electrolyser. The results also show that the PEM electrolyser is almost always at full power, which can be explained by the more flexible behaviour of the PEM electrolyser. Using this EMS, the alkaline electrolyser gives better results, and the more flexible behaviour of the PEM electrolyser doesn't seem to outweigh the higher efficiency and longer lifetime of the electrolyser. However, this EMS is developed based on the behaviour of an alkaline electrolyser. Since the cold start of a PEM electrolyser is only five minutes, the two step optimization might not be necessary. When the electrolyser behaviour can be fully based on the imbalance price, the PEM electrolyser might give better results because of the more fluctuating character of the imbalance market.

The scenarios with and without standby of the

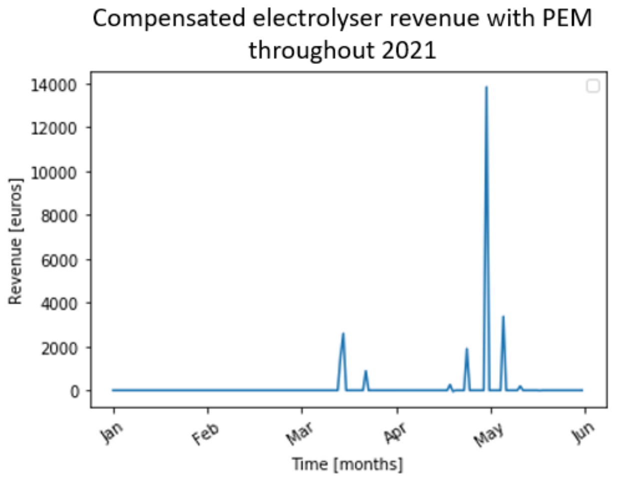


(a) Heatmap of 2020 (b) Heatmap of 2021

Figure 1: Heatmap with revenue from the electrolyser per hour and week in 2020 and 2021, the total revenues of the week per hour is displayed



(a) Alkaline electrolyser for 2021



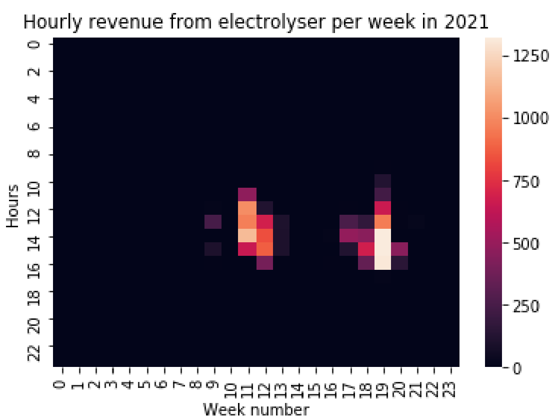
(b) PEM electrolyser for 2021

Figure 2: Hydrogen revenue, compensated with the imbalance price, for the different types of electrolyser in 2021 and 2022

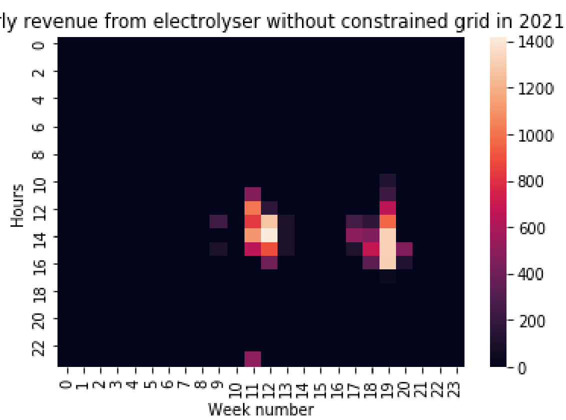
electrolyser have been compared. Since the first optimization step is for both scenarios the same, the number of cold starts and the time the electrolyser is on is not changed. The total revenue is for both 2021 and 2022 higher when the electrolyser can go to standby. However, this effect is larger in 2022, that can be caused by the more fluctuating imbalance prices. Without standby, more hydrogen is produced, however, this extra hydrogen is generated when it would be more profitable to sell the energy to the grid, leading to the lower revenue. When the imbalance prices are higher, the electrolyser that can not go to standby will operate at the minimum operating point, leading to a lower full power percentage, while otherwise the electrolyser will go to standby. The compensated electrolyser revenue is sometimes negative, while that is not the case with standby.

Comparing the results of the scenarios with and without use of the grid, the electrolyser is used for only a few extra days and hours. The heatmaps in Figure 3 show the difference. The heatmaps are comparable. The electrolyser was almost not used more. The electrolyser is used a few more days in the same week as the electrolyser was already on, causing a higher revenue in that week. Next to this, the electrolyser is once used in the night. This could be caused by the wind energy. When the share of wind energy increases, this could lead to larger differences in results.

Figure 4 shows the difference in hours the electrolyser is used for the different green premiums. This clearly shows that in 2021 the green premium has a much larger effect in 2021. This is because



(a) With grid contraint in 2021



(b) Without grid constraint in 2021

Figure 3: Heatmaps with revenue from the electrolyser per hour and week without grid constraint

the prices in 2022 are significantly higher and since the green premium is the same in both years, in percentages the green premium is lower. For 2021 and 2022 at the baseline of 20 €/ MWh the electrolyser is used more often in 2022. For the higher green premiums the use is much higher in 2021, the electrolyser is already used more with 40 €/ MWh in 2021 than with 60 €/ MWh in 2022. Also for the scenario without green premium the difference with the baseline is higher in 2021 than in 2022. Looking at the added revenue of the electrolyser this is still a small percentage.

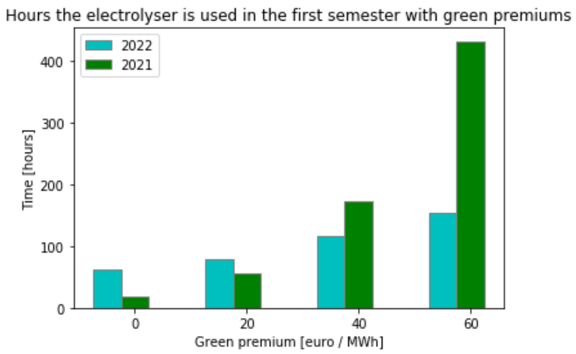


Figure 4: Hours the electrolyser is used for the different green premiums

One of the reasons this is still small is because the added value is only the difference between the imbalance market and the hydrogen that is sold. Next to this, the electrolyser has a maximum capacity that is during most days that the electrolyser is used, lower than the power that is generated by the solar panels. This means that even when the electrolyser is on its full capacity, electricity is still being sold on the imbalance market. Also, the electrolyser has more constraints. The efficiency and the start up time prevent that all used electricity is used to generate revenue. However, at that time the electrolyser is used, this is still more profitable than using the imbalance market. When interpreting these results it is important to take into account that the average natural gas price including the CO_2 emission tax in the first semester of 2021 was 27.64 €/ MWh, therefore adding a green premium of 60 €/ MWh would triple the average price of green hydrogen compared to the natural gas price. Comparing this to 2022 the natural gas price including CO_2 emission tax was 106.85 €/ MWh, for which the highest green premium is about 60% extra.

5 Conclusion

This research shows that a real-time EMS for this system can be developed. This is done using a two-step optimization taking into account two different electricity markets using MILP. The use of the electrolyser is too low under these conditions, the effect of changing the specifications of the electrolyser was limited. The different green premiums to affect the hydrogen market however, influence the system and higher green premiums increased the use of the electrolyser.

This real-time EMS is a step towards a supply-based energy system. It contributes to the energy transition in two ways. The first, it contributes to the ability of an alkaline electrolyser to respond to the sudden changes in the grid and by doing this making it possible to use alkaline electrolysers for balancing of the grid. And the second is by producing green hydrogen for the industry for a competitive price. Next to this, the research into the influence of different specifications of the electrolyser and the hydrogen market created focal points for further research into the alkaline electrolyser at a solar energy site.

Research has to be done to determine what parties would be willing to pay on top of the natural gas price for green hydrogen. Next to this, a cost analysis for the electrolyser has to be done to determine when the electrolyser use becomes feasible. To be able to generate more hydrogen for a competitive price, it is important that research is done to improve the current electrolyser technologies and to develop new technologies to increase the competitiveness of an electrolyser. Integrating the electrolyser with other assets and more electricity markets could also increase the use of the electrolyser and improve the reliability of the grid. At last, research has to be done into the effect of uncoupling the electricity and natural gas prices on the electrolyser use for future use and for ways to accommodate this.

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B
Literature assignment

Abstract

Energy management systems (EMS) are crucial for wide implementation of renewable energy and to work towards climate neutrality. Hydrogen can be used for storage of electrical energy or it can replace fossil fuels in, for example, industrial applications or transportation. Because of this, it can play an important role in EMS. To ensure a transition towards renewable energy, the renewable energy systems should be able to compete against fossil fuels economically. Therefore, only EMS with a hydrogen system and an economic objective are reviewed. The different systems and optimization methods that are used in the literature are analysed. The literature shows that the choice for the optimization method depends on the requirements of the system. Mixed integer optimization models is used represent most of the systems. For single-objective optimization problems linear programming is used the most, while for multi-objective optimization problems mainly non-linear programming is used. Further research is needed to determine which factors influence the feasibility of hydrogen in an EMS. Research into EMS with a supply perspective is needed to maximize the use of generated renewable energy and increase the competitiveness of renewable energy.

1 Introduction

The European Union has proposed the European Green Deal in 2019, in which it actions to reach climate neutrality of the EU economy by 2050 [1]. To reach this we will have to become more dependent on renewable energy. However, some of the main renewable energy sources have a highly intermittent nature. This causes for a high strain on the national grid and when high penetration levels of renewable energy are reached it can compromise reliable energy supply [2].
This can be solved by storage of the electric energy. The electrical energy can be stored in different ways. Technologies for storage of energy are pumped-storage hydropower, compressed air energy storage, thermal energy storage, batteries, hydrogen and flywheels. Each technology has its own strengths and weaknesses, and some technologies are further developed than others. Lithium-ion batteries are currently the most used for energy storage from renewable energy. [3] Next to storage, it is also possible to convert the energy to gas (P2G), the energy can be converted to hydrogen or methane. [4] P2G can be used in applications where it is hard or even impossible to electrify. Industrial applications are currently one of the largest consumers of energy, in which fossil fuels are often used as chemical feedstock.[5]

Hydrogen is an interesting component, because it can be used for both mentioned purposes. Electrical energy can be converted into hydrogen with an electrolyser. The hydrogen can then be stored in a storage tank and when the energy is needed the hydrogen will be converted into electrical energy again with a fuel cell. But the hydrogen can also be used for different applications. Hydrogen has the ability to replace fossil fuels or can be converted further into other compounds for use in many industrial applications. [5] It can also be used for transportation and it can be added to the natural gas network.

Multiple technologies can be used to combine the strengths of the technologies. The renewable energy is often connected in a system with multiple options. The system can consist of different types of storage and conversion methods and can be connected to different loads and/or the grid. The use of those components is controlled by an energy management system (EMS). An EMS determines how the energy is distributed at each moment. The EMS can have different objectives to which it will optimize, which can result in different behaviour of the system. [6]

The research into EMS with hydrogen is already quite extensive. The research in this field covers a broad range, from research into the sizing of the system, to research into specific components and to research with the development of an optimization model. This article focuses on this last topic. This research can still be split into multiple categories. In 2018, Vivas et al. have written an extensive review with a broad scope on EMS with hydrogen storage, which categorizes all articles into several subjects [6]. This review focuses on research that is done on EMS that are done where an economic objective is taken into account. The focus will be on articles published in 2018 or later, because articles before this are discussed in the review of Vivas et al. Also, because of a more narrow focus of this review, a more in depth analysis of these articles will be made. This review takes into account all uses of hydrogen when converted from renewable energy, therefore it can be used as storage but also used for other applications. This leads to the following research question:

What energy management systems with an economic objective are developed that use a hydrogen electrolyser for energy conversion from renewable energy and in which way is the optimal use of the electrolyser controlled?

Some articles that have been written that develop optimization model for an EMS start with a literature study. However, the extent of this research is often limited. Therefore, the additional value of this review is mainly on the systematic overview of all included articles. This makes it possible to get a better insight in the systems and optimization models that are developed and on the gaps in the literature.

This review is structured as follows: the methods for finding articles have been described in Section 2. In Section 3 the specifications of the systems analysed in the articles are reviewed. In Section 4 the optimization methods found in the literature are reviewed. At last, the Discussion and Conclusion are compiled in Section 5.

2 Methods

To find the most relevant literature for this research question, all concepts from the research question are analysed and the different synonyms in literature are used. This lead to the following search query: ("hydrogen generator*" OR "electrolys*" OR "electrolyz*" OR "green hydrogen" OR "alkaline" OR "AEL" OR "pem el" OR "PEMEL") AND ("energy management system*" OR "energy management" OR "energy distribution" OR "multi energy system*" OR "multi-energy system" OR "P2P" OR "P2G" OR "P2X") AND ("conver*" OR "storage" OR "store*" OR "microgrid" OR "micro-grid")

Adding an economic factor to this search query would lead to relevant literature not being found, therefore articles that do not have an economic objective are excluded by hand. This search query is used to find literature in Scopus and Web of Science. As mentioned in Section 1 articles published in 2018 or later are included. After removing duplicates 282 articles are found.

To determine whether these articles are relevant for this review, the following exclusion criteria are set up:

- Review, background article or other not original articles
- Full text not available in English
- No (optimization) model developed
- Research into the layout or sizing of the energy management system
- Research into a specific component
- EMS for other purposes than energy conversion to hydrogen from renewable energy
- Different objective for optimization
- EMS based on another type of energy than electricity

The abstracts of the articles are read and are excluded according to the exclusion criteria. This leaves 83 articles. In the next step, for the articles that are left, the full text is read. This leaves 28 articles that are included. These articles are analysed and reviewed in the following sections.

3 Systems

In literature EMS with hydrogen can be categorised in different ways. The first distinction that can be made, is in the system layout. Articles without a hydrogen system are not taken into account and therefore, the systems that are studied can be divided into the following categories. The EMS can consist of only a hydrogen system, a hydrogen system with a battery system, a hydrogen system with a heat system and a hydrogen system with both a battery system and a heat system. Other types of systems are not found in the literature in combination with a hydrogen system.

The most common layout is a hydrogen system and a battery system [7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18], followed by a hydrogen system and a heat system [19, 20, 21, 22, 23, 24] and only a hydrogen system [25, 26, 27, 28, 29, 30] and the least research is done into EMS that combine all three [31, 32, 33, 34]. Langeroudi et al. compared the results of an EMS with only a hydrogen system with the results of an EMS a hydrogen system and battery storage in electric vehicles. Farahani et al. combined hydrogen storage and hydrogen demand with battery storage in vehicles. In both articles, they found that adding the battery storage led to an increase in flexibility, reliability and a decrease in the daily costs. [18, 34] Pang et al. designed an EMS with a battery system, heat system and used hydrogen for storage and hydrogen demand. They compared the combination of all systems to every type separately and they found that combining hydrogen, electrical and heat storage led to lower costs and less carbon emissions than each system separately. However, hydrogen alone led to better results than battery or heat storage alone. [23] These results are of course highly dependent on the different systems. Pang et al. used an solid oxide electrolyser cell (SOEC). This is a promising technique, with higher efficiency than PEM or alkaline electrolysers. However, this technique is not commercial yet. Before this technique can be used in a commercial project, the battery and heat storage will also be developed more. Comparing the SOEC with the other storage methods that are currently commercial is therefore not an accurate representation of the current or future situation.

Langeroudi et al. and Farahani et al. do not mention the type of electrolyser that is used. Also, none of the articles mention the size of the electrolyser or sizes of other components that are used. These specifications of the electrolysers can highly influence the results. Since the efficiencies and flexibility are different for different types of electrolysers [35], it is not possible to determine if the results that are found would not be solved by using a different type of electrolysers.

What also can be noticed is different use for hydrogen, it can be split into hydrogen storage and hydrogen demand. The hydrogen for hydrogen demand can be used for hydrogen vehicles, industrial application, added to the gas distribution network or further conversion into other compounds. In most articles, hydrogen storage and hydrogen demand is combined [12, 13, 14, 15, 18, 19, 20, 21, 22, 23, 24, 26, 27, 31, 33, 34]. Other articles only use hydrogen for storage [7, 8, 9, 11, 16, 17, 25, 28, 29]. Research into systems with conversion into hydrogen only for hydrogen demand is limited, only a few articles only used hydrogen for hydrogen demand [10, 30, 32].

However some articles found that the the use of the fuel cell, and thus hydrogen storage, was not profitable. Yamashita et al. only researched hydrogen for storage in combination with battery storage and they found that the cost of electrolyser and fuel cell use was too high to use with the current capital cost and French grid reward [9]. Roy et al. started with a sizing problem and with that optimal configuration, the optimization was done. They intended to use hydrogen for storage and demand in combination with battery storage, however a fuel cell was not included in the optimal configurations because of the high investment cost and low energy efficiency. Therefore, the optimization was done with only hydrogen for hydrogen demand. [12] Roy et al. also found that when the fuel cell was included in the configuration and another optimization method was used

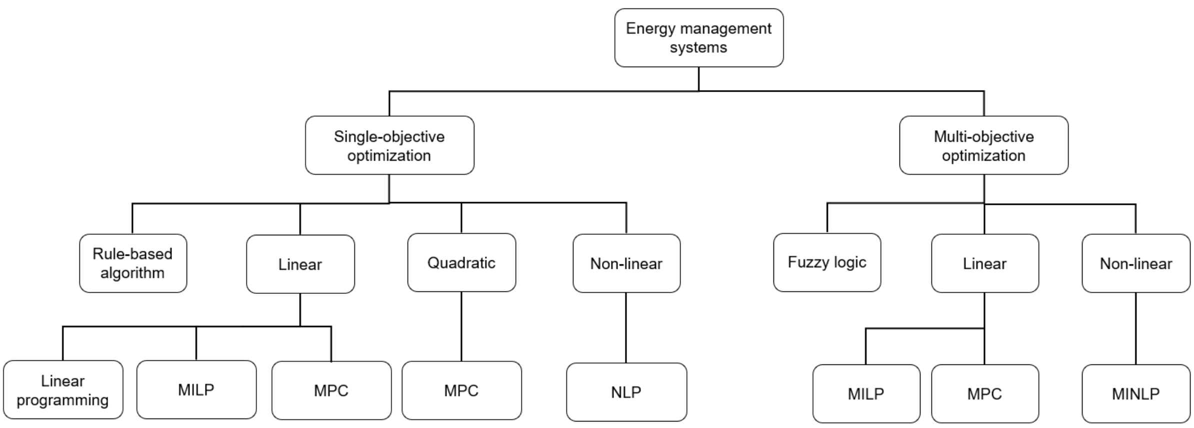

Figure 1: Flowchart optimization methods

for the same system, the fuel cell was again never used because it was not profitable to use hydrogen for electricity instead of hydrogen demand [14]. Moghaddas-Tafreshi et al. combined hydrogen storage, hydrogen demand, battery storage and a heat system and they found that it was not profitable to use hydrogen for storage [33]. Beshr et al. researched an islanded site with no connection to the grid. Hydrogen was used for storage and a diesel generator as backup. They found that hydrogen storage was economically infeasible, it could not compete against the fuel cost of the diesel generator. [28] From those articles only Yamashita et al. mentioned that they used a PEM electrolyser, the other four articles did not mention the type of electrolyser. Yamashita et al. and Maghaddas-Tafreshi et al. used a small electrolyser of respectively 25 kW and 30 kW, while Roy et al. and Beshr et al. used a large electrolyser of respectively 2.3 MW and 3.5 MW. As mentioned before, the specifications of the electrolysers are again important to draw conclusions from those results. Next to this, for storage, the specifications of the fuel cell also influence the feasibility of the system. When the hydrogen can be either sold or used for storage, the demand for hydrogen, and therefore the price of hydrogen, will determine if the hydrogen is solved or used for storage. In the systems of Roy et al. and Moghaddas-Tafreshi et al. the demand for hydrogen was high enough to be more profitable than storage.

When comparing the feasibility of hydrogen storage compared to a diesel generator or a direct grid connection, several things should be taken into account that will influence the comparison in the future. The articles are all published between 2018 and 2021. However, a lot of research is done into electrolysers and battery storage. Both technologies are potentially well-suited for mass manufacturing and cost reductions like those experience through the large-scale production of solar PV are not inconceivable and already underway. The progress of battery technology is more advanced than that of electrolysers. However, that makes the scope for significant near-term cost reductions even larger. Besides, batteries and electrolysers apply the same scientific principles of electrochemistry, therefore the development of electrolysers may benefit from the knowledge acquired from scaling up of batteries. [36] The specifications, and thus strengths and limitations, of these technologies can therefore completely shift in the coming years. Next to this, in a lot of countries, there is a large possibility of a CO_2 tax in the coming years and the congestion on the grid will increase as the percentage of renewable energy will keep increasing. Next to hydrogen, also oxygen and heat is generated when an electrolyser is used. When this can also be sold, will this make using the electrolyser also more profitable. None of the reviewed articles used the generated oxygen and only a few articles used the generated heat, from the articles that found the that hydrogen storage was not feasible, only Beshr et al. used the generated heat. Finding buyers for the residual heat and the oxygen, will improve the results for using the electrolyser and thus make it more competitive.

All systems are built for different applications, in different locations and therefore have different sizes as well. However, almost all reviewed articles have the same perspective. The research is focused on reaching the demand that is needed for the application. Only two articles looked at the supply and optimize what is done with the generated energy from the renewable intermittent sources. Yamashita et al. took a supply perspective, however they added a self-consumption mark to the system. If the required self-consumption mark is not reached, this is penalized in the objective function and a reward is added for self-consumption. [9] Cheng et al. also looked at the supply. The EMS is build to determine what can best be done with the excess wind generation. [22]

A portion of the articles do not mention the application of their system, or only partly. The articles that do mention the country in which their system is based, vary throughout the world. The difference in for example the weather, grid connection and hydrogen demand between different countries can lead to different results. Therefore, it is very relevant to name the country in which the study is done. Next to the country, the application will also affect the results. The application can say something about the size of the system, for example an EMS in the area of the South Australian electricity network around the city of Port Lincoln [11], will have very different results than an EMS in an Amsterdam office building [18]. Also, it will affect the demand, the size and variability of the hydrogen demand for a charging station for electric and hydrogen vehicle [26] will be different than for a parking lot with electric vehicles where the hydrogen can be sold to the industry [34].

4 Optimization methods

Each reviewed article has developed an optimization model for the researched system. For this review, articles with an economic objective are reviewed. When this only objective for the optimization, it is a single-objective optimization problem. The model consists of only one objective function that needs to be optimized with constraints that represent the behaviour and boundaries of the system. It is also possible to have a multi-objective optimization problem. In some articles, a second objective is determined, next to the economic objective. Two objective functions can then be set up. These objective functions are often conflicting, which leads to a trade-off between the objectives. A pareto front can be made with multiple optimal solutions.

Most literature combined an economic objective with an environmental objective [13, 16, 23, 24, 27]. Beshr et al., Farahani et al. and Vivas et al. combined the economic objective with a technical objective. Beshr et al. combined the economic objective with and objective to minimize the line losses [28], Farahani et al. with an objective to minimize the degradation of the battery and the fuel cell [18] and Vivas et al. with an objective to maximize the lifespan of the components [7]. Albogamy et al. combined the economic objective with three other objectives, an environmental objective, the peak-to-average ratio minimization and user discomfort minimization [15]. A multi-objective optimization problem will result in different outcomes compared to a single-objective optimization problem. Kholardi et al. combined hydrogen demand and hydrogen storage. They researched different weighting coefficients for both their objectives, economical and environmental. The results show an equal use of the electrolyser for each scenario. However, when the economic objective had a higher weighting coefficient the fuel cell was used little and most hydrogen was sold for hydrogen demand. For a high weighting coefficient for the environmental objective, the fuel cell was used more, to limit the electricity bought from the grid. [24] Ruiming compared the results of multi-objective and both single-objective optimizations. For multi-objective the optimal compromise solution is taken from the pareto front. The multi-objective optimization reduced the carbon emissions by 3.5% with an increase of 2.6% of operating cost compared to the economic single objective. Comparing to the environmental single objective, the multi-objective optimization reduced the operating cost by 5.12% with an increase of 2.6% of carbon emissions. [27] This shows that choosing for multi-objective optimization and choosing the objective will influence the results, and that this choice has to be thought through carefully to determine what the goal is and what is best for the application.

The economic objectives found in the literature can have two different goals, either to minimize the costs or to maximize the profit. The majority of the literature minimized the cost. The costs that are minimized depend on the article, most articles minimized the operational costs [8, 9, 10, 13, 16, 17, 19, 20, 21, 22, 23, 24, 25, 27, 29, 31, 32, 34]. The other articles minimize the cost of energy [7, 15, 18, 26, 28]. The last reviewed articles have the objective to maximize the profit [12, 14, 25, 30, 33].

Stable operation of the electrolyser can increase the running life and the efficiency of the electrolyser [27]. Some articles take into account the operation state of the electrolyser. This can be done in multiple ways. Vivas et al. uses an alkaline electrolyser and has the lifespan of the components as the second objective in their multi-objective optimization problem [7]. Abomazid et al. implemented a varying electrolyser efficiency based on the operation state and constraints were added to guarantee stable and accurate operation of the electrolyser. They found that their model reduced the hydrogen production cost and total system cost compared to the conventional model without stable operation of the electrolyser. The type of electrolyser is not mentioned. [10] Ruiming added a constraint for stable operation. By setting a threshold before the PEM electrolyser can be turned on or off, the number of switching times decreased largely from 512 to 198 times, while keeping similar operational and environmental costs. [27] According to the report from the International Renewable Energy Agency

Reference	Optimization method	Algorithm	Program
[14]	Rule-based algorithm	Not mentioned	Matlab
[20]	Rule-based algorithm	Not mentioned	TRNSYS18
[32]	Linear programming	Not mentioned	Not mentioned
[30]	Linear programming	Not mentioned	Matlab - fmincon
[19, 22, 26, 29, 31, 33, 34]	MILP	Branch-and-bound	GAMS - CPLEX
[12]	MILP	Branch-and-bound	Matlab -intlinprog
[11] [21]	MILP	Branch-and-bound	Not mentioned
[9]	MPC - MILP	Branch-and-bound	CPLEX
[17]	MPC - Fuzzy logic / TOPSIS	Not mentioned	Matlab - Gurobi
[8]	MPC - Quadratic programming	Not mentioned	Matlab Simulink
[10]	Non-linear programming	Not mentioned	Matlab - optimization toolbox
[25]	Non-linear programming	Harmony search	Matlab

Table 1: Optimization methods for single-objective optimization

the degradation of alkaline electrolysers is not really affected by the operating conditions or variable loads, while for PEM electrolysers a variable load might add additional corrosion of the stack components, thus decrease the lifetime. However there is little evidence yet. [35] The flexibility of a PEM electrolyser however, is higher than that of an alkaline electrolyser. The articles found beneficial results using the different types of electrolysers.

Different control algorithms can be used to solve this optimization problem. Roy et al. and He et al. used an rule-based algorithm to control the optimal use of the system [14] [20]. Vivas et al. used fuzzy logic. [7] Both types of algorithm do not need to develop a model of the system or forecasting assumptions, but use expert knowledge. The other control algorithms do develop a model for optimization. The models of an optimization problem can be classified in multiple ways.

The first way optimization problems can be classified is by constrained or unconstrained optimization. All models found in the literature are constrained optimization problems.

The optimization problems can also be classified by deterministic optimization or stochastic / robust optimization. In deterministic optimization it is assumed that all data that is used are known accurately, while in stochastic optimization uncertainty is taken into account. Some

Reference	Optimization method	Algorithm	Program
[24]	MILP	Branch-and-bound	GAMS - CPLEX
[18]	MPC - MILP	Not mentioned	Matlab - optimization toolbox / Gurobi
[7]	Fuzzy logic	Not mentioned	Matlab Simulink
[23]	MINLP	ε-constraint method	GAMS - DICOPT solver
[16]	MINLP	E_NSGA-II	Not mentioned
[27]	MINLP	Improved NSGA-II	Matlab
[28]	MINLP	GA + NSGA-II / FPA	Matlab
[15]	MINLP	Ant colony optimization	Matlab
[13]	MINLP with Fuzzy logic	Not mentioned	GAMS

Table 2: Optimization methods for multi-objective optimization

articles take into account the uncertainty from the demand and/or the generation from renewable energy and have built an stochastic model [9, 13, 15, 25, 26, 29, 32, 33, 34].

Another way of classifying is by single and multi-objective optimization. As mentioned, single-objective and multi-objective problems are found in the literature. Multi-objective optimization problems can be solved in multiple ways. It can be solved by combining the objectives into one objective function with weight factors and then solve it as a single-objective optimization problem or it can be solved by solving both objective functions independently and then combine them, which can be done using different algorithms.

Optimization problems can also be classified in continuous, integer or mixed-integer optimization problems. For integer variables different optimization methods need to be used than for continuous variables. Mixed-integer optimization problems both have continuous and integer variables. Most literature modelled their systems as mixed-integer optimization problems [9, 11, 12, 13, 15, 16, 18, 19, 21, 22, 23, 24, 26, 27, 28, 29, 31, 33, 34]. Some articles use only continuous variables [8, 25, 30]. In [10, 32] it was not mentioned what type of variables were used.

The last way to classify the model is by determining if the system is linear, quadratic or non-linear. Linear and quadratic optimization models can use exact algorithms, those will reach the optimum within a finite number of steps. For non-linear optimization models, this can not be guaranteed and they can only find approximations of the optimum. For these optimization problems, it is also possible to get stuck in a local optimum. Most articles use linear optimization for their model [9, 11, 12, 18, 19, 21, 22, 24, 26, 29, 30, 31, 32, 33, 34], one article uses a quadratic model [8] and the other models are non-linear optimization [10, 13, 15, 16, 23, 25, 27, 28].

These classifications determine what kind of optimization methods can be used. The optimization methods that are used in the literature are shown in the flowchart in Figure 1. This figure shows how different optimization methods follow from the classifications. First the optimization methods for the single-objective optimization problems are reviewed. Table 1 shows the control algorithms for all single-objective optimization problems reviewed. As mentioned before, linear programming is used the most in the literature. In these studies, mixed-integer linear programming (MILP) is used the most and is used by ten articles. Continuous linear programming is also used twice. Another method that is used multiple times is model predictive control (MPC). This method can be combined with an optimization method. In [9] MPC is combined with MILP, Li et al. with fuzzy logic and the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) [17]. Gonzalez-Rivera et al. combined MPC with quadratic programming [8]. The last two reviewed articles use a non-linear optimization method to reach the optimum. In [25] harmony search is used.

Some articles compared different optimization methods. Gonzalez-Rivera et al. compared their MPC-based EMS to a state-based EMS, which uses a rule-based control algorithm. They found that the MPC-based EMS resulted in lower costs and a better efficiency was obtained. This also led to a lower chance on loss of power. [8] Yamashita et al. also compared their MPC-based EMS to a rule-based algorithm. They found that the MPC-based EMS could reach a higher self-consumption rate, while still decrease the operational cost slightly by 9% for public buildings. Li et al. compared MPC in combination with fuzzy logic to MPC with TOPSIS, TOPSIS can take more attributes into account than fuzzy logic. They found that TOPSIS resulted in lower operational costs and lower degradation. [17] Roy et al. compared the MILP to a rule-based algorithm, they found slightly lower performance for the rule-based algorithm [14]. Cheng et al. compared the MILP model to a MINLP model, they found slightly lower costs with the MILP model and a great reduction in computation time [22]. These results show that the right optimization method for a system is not always the same. It can depend on the requirements of the system, for example whether a slight increase in results is important or that the computation time may not be too high. These factors will influence the choice of optimization method.

The multi-objective optimization problems are shown in Table 2. Kholardi et al. and Farahani et al. combined both objective functions into one objective function with weighting coefficients, effectively solving the multi-objective problem like a single-objective problem. It can be seen that all other reviewed articles have developed a non-linear optimization model. Albogamy et al. used ant colony optimization to solve the multi-objective optimization problem [15]. All other reviewed articles first solved both mixed-integer non-linear programming (MINLP), which is done with a mixed integer genetic algorithm in [28]. The other articles did not specify which algorithm was used. Next, the optimal solution from the Pareto front is determined using different algorithms. In [16, 27, 28] this is done with different variations of the non dominated sorting genetic algorithm II (NSGA-II). In [23] this is done with the ε-constraint method and in [13] with fuzzy logic. Albogamy et al. found that their proposed algorithm with ant colony optimization improved the energy costs compared to MILP [15]. Beshr et al. compared the NSGA-II with a flower pollution algorithm (FPA), they found that FPA improved the results slightly by 2-6%, but the computation time was also 10 times lower than NSGA-II [28].

Table 1 and 2 also show the program that is used for the optimization algorithm. Almost all reviewed articles use either a toolbox from Matlab or from GAMS. Their is no clear relation between the type of optimization and the program that is used, this is probably based on the preference of the authors.

5 Discussion

A review has been carried out on energy management systems with a hydrogen system and an economic objective. In Section 3, the systems modeled in each article have been reviewed. This showed a large distribution on the types, sizes and applications of the systems. Therefore it is not possible to compare the results from the articles one on one. Differences in the use of hydrogen, the types of energy storage and conversion and the perspective can result in different use of the EMS. However, similarities in the articles can be used to come to more general conclusions and gaps in literature can be found.

In this review is aimed to answer the research question:

What energy management systems with an economic objective are developed that use a hydrogen electrolyser for energy conversion from renewable energy and in which way is the optimal use of the electrolyser controlled?

The different energy management systems that are developed are analysed and the optimization methods are discussed. The energy management systems can be divided into different classes based on specifications of the system and on optimization choices. These factors influence the choice of optimization method and the results. Articles that compared different optimization methods, showed often a trade-off between computational time and results. In the articles that are reviewed, different optimization methods were chosen based on different focus points of the study. This shows that the choice for a optimization method therefore should depend on the requirements of the system, and that there is not one type of optimization that should always be used for energy management systems with a hydrogen system.

In this review the importance of further research into this field is shown. The studies that are reviewed show that an EMS is a promising solution for peak shaving and to remove the congestion on the grid. The current EMS show that in some situations the renewable solutions are not yet feasible or competitive, however the techniques that are used are promising, and it is important that the research into the different techniques continues. It is necessary to continue developing algorithms for EMS but also to compare the different methods. The optimal use of the current techniques will improve the competitiveness of the renewable energy sources and help reach the climate goals. Therefore, the research into and development of models for the allocation of renewable energy should be done to maximize the use of renewable energy and to compete against non-renewable sources.

The research in this review raises new questions, the following questions should me answered in future research in this field.

Which factors influence the feasibility of hydrogen in an EMS and specifically the feasibility of hydrogen for storage?

In the research is shown that the results for energy storage with hydrogen is dependent on the specifications of the system. To be able to predict if hydrogen storage is beneficial for a specific system, it is important to map the factors that influence the results of the energy management system, and the amount of that influence. This can generate an overview of applications for which conversion hydrogen might be useful.

How to develop an energy management system with a supply perspective?

Almost all literature focused on reaching a certain demand. Research should be done into EMS with this perspective to optimize the use of generated energy and to prevent curtailment and low selling prices. Taking the perspective of a renewable energy park to determine the most profitable way to allocate the generated energy can increase the competitiveness of renewable energy.

Is stabilising the operation of an electrolyser, by limiting the fluctuations, beneficial?

In literature is found that dynamic use of electrolysers increases the degradation of an electrolyser. Some articles have looked into stable operation of the electrolyser, but this is still limited. More research should be done into the effect of dynamic operation compared to a more stable operation on the degradation. If this research shows that it is beneficial to limit the fluctuations of the use of the electrolyser, research should be done on how the stable operation can be added into the energy management system.

Some other aspects in the literature can be noticed. Before developing an EMS, it is important do determine what should be the objective or objectives. The other objectives in a multi-objective optimization problem influence the behaviour of the EMS. By adding a second objective, the economic objective usually performs somewhat less, to increase the other objective. For example, Kholardi et al. stated that because of the emission objective, the use of the fuel cell increased, to prevent the use of the grid [24]. Therefore, it is important that adding an objective is thoroughly considered. The emission objective might be very interesting in a system with a demand perspective and a sustainable ambition, while for a system with a supply perspective all the energy that is handled is renewable energy, so adding a emission objective might be less useful. Also, all the currently developed EMS with multiple objectives are solved with non-linear programming, which has a higher solving time than linear programming. This should be taken into consideration when deciding if a second objective should be added.

What also can be noticed, is that often in the literature, critical information to compare different articles is not mentioned. The size of components of the system, the type of electrolysers and other components or the application and location is not always discussed, but also the optimization method or algorithm that is used is not always mentioned or the objective function and constraints are only partially discussed.

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C

Mathematical model

The two optimizations have different mathematical models, that have some overlap. In the following sections C.1 and C.2 the mathematical models for both optimizations are discussed.

C.1. Mathematical model global planning

Sets and indices

i	Component	$i \in I$, I = [grid offtake [kWh], grid feed in [kWh], Hydrogen [kWh], Oxygen [kg]]
t	Minute	$t \in T$, $T = [0, 1, ..., 1439]$
		$t \in T^{pos}$, T^{pos} consists of all minutes where $P^{gen} \geq P^{site}$
		$t \in T^{neg}$, T^{neg} consists of all minutes where $P^{gen} < P^{site}$
		$t \in T^1$, $T^1 = [1, 2, ..., 1439]$
		$t \in S$, $S = [30, 31, ..., 1439]$
		$t \in S^{begin}$, $S^{begin} = [0, 1, ..., 1409]$
		$t \in S^{end}$, $S^{end} = [1409, 1410, ..., 1439]$
k	Minute	$k \in K$, $K = [0, 1..., 20]$
j	Minute	$j \in J$, $J = [0, 1, ..., 10]$
g	Minute	$g \in G$, $G = [0, 1, ..., 10]$

Parameters

$c_{i,t}$	Cost of component i in minute t
$c^{lifecycle}$	Lifecycle cost
η	Efficiency of the electrolyser
E_t^{gen}	Solar energy generation in minute t
E^{site}	Energy demand at the site
E^{loss}	Energy losses during start of the electrolyser
P^{cap}	Maximum operating power of the electrolyser
P^{ramp}	Maximum ramp rate per minute of the electrolyser
P^{min}	Minimum operating power of the electrolyser
$P^{opt,start}$	Last value of p^{opt} from previous optimization interval
$P^{el,start}$	Last value of p^{el} from previous optimization interval
D^{switch}	Total start up or shut down time of the electrolyser
D^{begin}	First phase of start up time of the electrolyser

Decision variables

$y_{i,t}$	Amount of energy from component i at minute t
p_t^{el}	Electrolyser power at minute t [kW]
p_t^{opt}	Temporary decision variable electrolyser power at minute t [kW]
U_t	Binary state of the electrolyser, 1 if electrolyser is on, 0 if electrolyser is off
Y_t	Binary variable, 1 if electrolyser is turned on at minute t, 0 otherwise
Y_t^{start}	Binary variable, 1 if electrolyser is starting up at minute t, 0 otherwise
Y_t^{first}	Binary variable, 1 if electrolyser is in the first phase of starting up (without hydrogen generation) at minute t, 0 otherwise
Z_t	Binary variable, 1 if electrolyser is turned off at minute t, 0 otherwise
Z_t^{stop}	Binary variable, 1 if electrolyser is shutting off at minute t, 0 otherwise

Objective function

$$max \sum_{i \in I} \sum_{t \in T} c_{i,t} * y_{i,t} - c_t^{lifecycle} * U_t = min \sum_{i \in I} \sum_{t \in T} -c_{i,t} * y_{i,t} + c_t^{lifecycle} * U_t \qquad \text{(C.1)}$$

Because this problem is a maximization problem, it is rewritten as minimization of the negative of this problem. The objective function C.1 multiplies the costs of each component with the amount. This is compensated with the costs of the use of the electrolyser in terms of a decrease in lifetime, when the electrolyser is on. The amount of each component is a decision variable that can be optimized, to reach the highest value of the objective function. The matrix $c_{i,t}$ consists of costs of the components, that are discussed in Section 3.2.

Constraints

The constraints can be divided into groups that model a specific part of the electrolyser. For each group of constraints is explained why these constraints are added.

$$y_{i,t} \geq 0 \qquad \forall i \in I, \quad \forall t \in T \qquad \text{(C.2)}$$
$$p_t^{el} \geq 0 \qquad \forall t \in T \qquad \text{(C.3)}$$
$$p_t^{opt} \geq 0 \qquad \forall t \in T \qquad \text{(C.4)}$$

Constraints C.2 - C.4 are the non-negativity constraints for the decision variables.

$$y_{0,t} - y_{1,t} + \frac{p_t^{el}}{60} = E_t^{gen} - E^{site} \qquad \forall t \in T \qquad \text{(C.5)}$$

Constraint C.5 ensures the energy balance for every time t. The amount of energy bought from or sold to the grid together with the energy consumed by the electrolyser must be equal to the energy generated at the solar park minus the energy demand from the site, at a given time t. The electrolyser power is divided by 60 to get the electrolyser energy of that minute.

$$y_{0,t} = E^{max,grid} * 60 \qquad \forall t \in T \qquad \text{(C.6)}$$
$$y_{1,t} = E^{max,grid} * 60 \qquad \forall t \in T \qquad \text{(C.7)}$$
$$y_{1,t} = 0 \qquad \forall t \in T^{pos} \qquad \text{(C.8)}$$
$$y_{1,t} \leq E^{site} - E_t^{gen} \qquad \forall t \in T^{neg} \qquad \text{(C.9)}$$

Constraint C.6 - C.9 limit the use of the grid. Constraint C.6 and C.7 prevent the use of the grid connection over its capacity. Constraint C.8 and C.9 limit the use of the grid to prevent use of the grid to operate the electrolyser. The time set T is split into two different sets. Time set pos consists of every minute where the generated solar energy is more than or equal to the site demand, time set neg

consists of every minute where the generated solar energy is less than the site demand. Constraint C.8 sets the grid feedin to zero when the generated energy can provide the energy demanded by the site. Constraint C.9 limits the grid feedin to the use for the energy demand by the site.

$$y_{2,t} \leq \eta * \frac{p_t^{el}}{60} - Y_t^{start} * E^{loss} \qquad \forall t \in T \qquad \text{(C.10)}$$

$$y_{2,t} \leq (1 - Y_t^{first}) * M^{start} \qquad \forall t \in T \qquad \text{(C.11)}$$

Constraint C.10 and C.11 represent the relation between the power of the electrolyser and the hydrogen that is produced. The first part of constraint C.10 represents the relation between the electrolyser power and hydrogen under normal operating conditions. During start up of the electrolyser, this is not an accurate representation of the system. When the electrolyser is starting, the electrolyser starts using power and also already starts producing hydrogen. As discussed in Section 3.2, the assumption is made that the start up time can be split into two parts, to be able to take this behaviour into account with a linear optimization problem. During the second part of starting up, the hydrogen that is produced at a time is less than during normal operation. An adjustment of the efficiency for this state is not possible with linear optimization. Therefore, the simplification is made that during this state, the hydrogen is generated with more losses than with normal operation conditions. This can be seen in the second part of constraint C.10. During the first part of starting up, the electrolyser does not produce any hydrogen yet. This is modeled in constraint C.11. The big-M method is used to turn this constraint on or off depending on the state, where M_{start} is a large number. [26] At a time that the electrolyser is in the first part of starting up, the constraint is on, because the right side of the constraint equals zero. When this is not the case Y_t^{first} is zero and therefore the right side from the constraint has a large value, which results in the hydrogen amount not being limited by this constraint.

$$y_{3,t} = \frac{y_{2,t}}{LHV_{H2} * 2} \qquad \forall t \in T \qquad \text{(C.12)}$$

Constraint C.12 is the relation between the generated hydrogen and oxygen. The amount of hydrogen in kWh ($y_{2,t}$) is converted to kg by dividing over the LHV in kWh/kg. By the molar equation of the electrolyser, the amount of oxygen generated is half of that of hydrogen.

$$p_t^{el} \leq P^{cap} * U_t \qquad \forall t \in T \qquad \text{(C.13)}$$

Constraint C.13 limits the power used by the electrolyser to the maximum capacity of the electrolyser.

$$p_t^{opt} - p_{t-1}^{opt} \leq P^{ramp} * U_t \qquad \forall t \in T \qquad \text{(C.14)}$$

$$p_t^{opt} - p_{t-1}^{opt} \geq -P^{ramp} * U_t \qquad \forall t \in T \qquad \text{(C.15)}$$

$$p_0^{opt} - P^{opt,start} \leq P^{ramp} * U_0 \qquad \text{(C.16)}$$

$$p_0^{opt} - P^{opt,start} \geq -P^{ramp} * U_0 \qquad \text{(C.17)}$$

$$p_t^{el} = P^{min} * U_t + p_t^{opt} \qquad \forall t \in T \qquad \text{(C.18)}$$

The constraints C.14 - C.18 limit the ramp up and down from the electrolyser every minute with the minimum and maximum ramp up or down time. The variable P_t^{opt} is a temporary value that is used to compare the electrolyser power with the one before and limits this to the maximum or minimum ramp rate in constraint C.14 and C.15 and is set to zero when the electrolyser is off. These constraints are based on the model of Zhang et al. [41]. Next to this, constraint C.16 and C.17 are added for $t = 0$, using the power and state from the last timestep of the optimization before. Constraint C.18 is based on the model of Zhang et al. and uses P_t^{opt} to set the electrolyser power, when the electrolyser is on, the minimum power of the electrolyser is added to this.

$$U_t - U_{t-1} = Y_t - Z_t \qquad \forall t \in T^1 \qquad \text{(C.19)}$$

$$\sum_{k \in K} Y^{start}_{t+k} \geq D^{switch} - M * (1 - Y_t) \qquad \forall t \in S^{begin} \qquad \text{(C.20)}$$

$$\sum_{j \in J} Y^{first}_{t+j} \geq D^{begin} - M * (1 - Y_t) \qquad \forall t \in S^{begin} \qquad \text{(C.21)}$$

$$\sum_{g \in G} Z^{stop}_{t+k} \geq D^{switch} - M * (1 - Z_t) \qquad \forall t \in S^{begin} \qquad \text{(C.22)}$$

The constraints C.19 - C.29 determine the start and stop behaviour of the model. Constraint C.19 is based on the constraint in the model from Zhang et al. [41] and sets the binary variable Y_t or Z_t to one when the state of the electrolyser U_t changes, from zero to one or from one to zero respectively. Constraints C.20 - C.22 set the variables to one during the different starting and stopping times, when the electrolyser starts or stops. This is again done with the big-M method. When Y_t or Z_t is zero, the right hand side of the equation will be smaller than zero and therefore the variable can be zero. Otherwise, variable needs to be bigger than or equal to the starting or stopping time. Because the variable can only be zero or one, the maximum value all variables together can have during this period is the starting or stopping time, and therefore it will always be equal to this time.

$$\sum_{k \in K} Y_{t-k} * M \geq Y^{start}_t \qquad \forall t \in S \qquad \text{(C.23)}$$

$$\sum_{j \in J} Y_{t-j} * M \geq Y^{first}_t \qquad \forall t \in S \qquad \text{(C.24)}$$

$$\sum_{g \in G} Z_{t-k} * M \geq Z^{stop}_t \qquad \forall t \in S \qquad \text{(C.25)}$$

$$\text{(C.26)}$$

Constraint C.23 - C.25 prevent the variables on the right from being one when the electrolyser has not been turned on or off during the starting or stopping time.

$$\sum_{k \in D^{switch} - t} Y^{start}_{t+k} = Y_t * (D^{switch} - t) \qquad \forall t \in S^{end} \qquad \text{(C.27)}$$

$$\sum_{k \in D^{begin} - t} Y^{first}_{t+j} = Y_t * (D^{begin} - t) \qquad \forall t \in S^{end} \qquad \text{(C.28)}$$

$$Y^{start}_t + Z^{stop}_t \leq 1 \qquad \forall t \in S^{end} \qquad \text{(C.29)}$$

The constraints C.27 and C.28 are the same as constraint C.20 and C.21 respectively, when the optimization is at the end and the starting time is longer than the end of the optimization. Constraint C.29 prevents that the electrolyser is starting and stopping at the same time.

C.2. Mathematical model given state

For the second step of the optimization the electrolyser state is an input and therefore this model has less decision variables and constraints. Since the state of the electrolyser is an input, this can't be altered. However, the electrolyser can be put into standby mode in this optimization, because the response time for the electrolyser in standby is much quicker.

Sets and indices

i	Component	$i \in I$, I = [grid offtake [kWh], grid feed in [kWh], Hydrogen [kWh], Oxygen [kg]]
t	Minute	$t \in T$, $T = [0, 1, ..., 1439]$
		$t \in T^{pos1}$, T^{pos} consists of all minutes where $P^{gen} \geq P^{site} + P^{standby}$
		$t \in T^{neg1}$, T^{neg} consists of all minutes where $P^{gen} < P^{site} + P^{standby}$

Parameters

$c_{i,t}$	Cost of component i in minute t
η	Efficiency of the electrolyser
E_t^{gen}	Solar energy generation in minute t
E^{site}	Energy demand at the site
E^{loss}	Energy losses during start of the electrolyser
P^{cap}	Maximum operating power of the electrolyser
P^{ramp}	Maximum ramp rate per minute of the electrolyser
P^{min}	Minimum operating power of the electrolyser
$P^{opt,start}$	Last value of p^{opt} from previous optimization interval
$P^{el,start}$	Last value of p^{el} from previous optimization interval
S_t^{el}	Given state electrolyser at minute t
B_t^{start}	Start up state electrolyser at minute t
B_t^{first}	First phase start up state electrolyser at minute t
$P^{standby}$	Power of the electrolyser when in standby

Decision variables

$y_{i,t}$	Amount of energy from component i at minute t
p_t^{el}	Electrolyser power at minute t [kW]
p_t^{opt}	Temporary decision variable electrolyser power at minute t [kW]
U_t^{st}	Binary variable, 1 if electrolyser is on standby at minute t, 0 otherwise

Objective function

$$min \sum_{i \in I} \sum_{t \in T} -c_{i,t} * y_{i,t} \tag{C.30}$$

Again, the objective function as represented in equation C.30, multiplies the negative costs of a component with the amount. However, because the state of the electrolyser has already been determined, the costs for the use of the electrolyser is a constant and therefore is not involved in the objective function.

Constraints

Some constraints are the same as for the global planning model, with the only difference that the state of the electrolyser is an input instead of a variable. Therefore, all constraints are listed here and only the constraints that are different from the global planning model will be explained here.

$$y_{i,t} \geq 0 \qquad \forall i \in I, \quad \forall t \in T \tag{C.31}$$
$$p_t^{el} \geq 0 \qquad \forall t \in T \tag{C.32}$$
$$p_t^{opt} \geq 0 \qquad \forall t \in T \tag{C.33}$$
$$y_{0,t} - y_{1,t} + \frac{p_t^{el}}{60} = E_t^{gen} - E^{site} \qquad \forall t \in T \tag{C.34}$$
$$y_{0,t} = E^{max,grid} * 60 \qquad \forall t \in T \tag{C.35}$$
$$y_{1,t} = E^{max,grid} * 60 \qquad \forall t \in T \tag{C.36}$$
$$y_{1,t} = 0 \qquad \forall t \in T^{pos} \tag{C.37}$$
$$y_{1,t} \leq E^{site} + \frac{P^{st}}{60} - E_t^{gen} \qquad \forall t \in T^{neg} \tag{C.38}$$

Constraint C.37 and C.38 limit the grid use. When the energy generation is not enough to reach the minimum power at that moment, because of the maximum ramp rate, the electrolyser can't be turned off as was possible in the first optimization. The electrolyser can be placed in standby if necessary. However, this also requires power. Therefore, the energy needed for standby is added to the energy demand for the site, to determine the maximum energy that can be used from the grid. The power for standby is divided by 60 to reach the energy needed for standby.

$$y_{2,t} \leq \eta * \frac{P_t^{el}}{60} - B_t^{start} * E^{loss} - U_t^{st} * \eta * \frac{P^{st}}{60} \qquad \forall t \in T \tag{C.39}$$
$$y_{2,t} \leq (1 - B_t^{first}) * M^{start} \qquad \forall t \in T \tag{C.40}$$
$$p_t^{el} \leq P^{cap} * S_t^{el} \qquad \forall t \in T \tag{C.41}$$
$$y_{3,t} = \frac{y_{2,t}}{LHV_{H2} * 2} \qquad \forall t \in T \tag{C.42}$$
$$p_t^{opt} - p_{t-1}^{opt} \leq P^{ramp} * S_t^{el} \qquad \forall t \in T \tag{C.43}$$
$$p_t^{opt} - p_{t-1}^{opt} \geq -P^{ramp} * S_t^{el} - M * U_t^{st} \qquad \forall t \in T \tag{C.44}$$
$$p_0^{opt} - P^{opt,start} \leq P^{ramp} * S_0^{el} \tag{C.45}$$
$$p_0^{opt} - P^{opt,start} \geq -P^{ramp} * S_0^{el} - M * U_t^{st} \tag{C.46}$$
$$p_t^{el} = P^{min} * S_t^{el} * (1 - U_t^{st}) + p_t^{opt} + P^{st} * U_t^{st} \qquad \forall t \in T \tag{C.47}$$

Constraints C.39, C.44, C.46 and C.47 have been adjusted to take into account the standby state. Constraint C.39 subtracts the standby energy from the energy that is used by the electrolyser, when the electrolyser is in standby. This ensures that no hydrogen is generated when the electrolyser power is in standby, since the power of the electrolyser is used to keep the electrolyser pressure and temperature. Constraint C.44 and C.46 use the big-M method, this enables the electrolyser to go to standby state. The downward ramp rate will be exceeded when the electrolyser goes to standby state, this constraint is lifted when the standby state is 1. In constraint C.47 the standby power is added when the electrolyser is in standby.

$$p_t^{opt} \leq (1 - U_t^{st}) * M \quad \forall t \in T \tag{C.48}$$
$$U_t^{st} \leq S_t^{el} \quad \forall t \in T \tag{C.49}$$

Constraint C.48 sets the P^{opt} to zero when the electrolyser is in standby. Constraint C.49 constrains the standby state of the electrolyser to when the electrolyser state that is determined in the global optimization is 1, so the electrolyser is on.

D Verification and validation

The main focus of this verification section is on the verification of the overall code. The functions that are created for the import of data and the output of the electrolyser have also been verified separately by comparing the input data to the output data to check if the alterations that have been made in the functions are correctly implemented. These tests have all been passed and therefore the import and output functions could be used for the EMS and didn't need to be focused on for the rest of the verification.

The verification tests that have been worked out are:

- The optimization of both the global optimization and the optimization with given state must always be optimal. The status of the optimization is printed when this is 'infeasible', 'unbounded' or 'undefined'. The verification is done by testing 30 randomly selected days in 2021. For every day, the global optimization is run one time and the optimization with given state is run every minute. Each optimization was always optimal. Therefore this verification test has been passed by the EMS. An 'assert' function has been implemented in the code, such that the model gives an error when one of the optimizations is not optimal.
- The global optimization must only have the electrolyser on when the grid is not needed for the electrolyser. This is tested for 30 randomly selected days and for every day the power from the electrolyser was always below the solar generation. As an example, one of the tested days is shown in Figure D.1. This shows that the electrolyser power was at all times lower than the generated power from the solar field.
- The ramp up or down rate must not be exceeded unless the electrolyser is turned off or going to standby state. Therefore the difference between two minutes can't be bigger than the ramp power, unless the power is zero or the standby power in the second time step or when the minimum power has to be reached when starting up. By printing time steps that have larger steps in power than the ramp rate, the verification test can be performed. This is tested for 30 randomly selected days in 2021. The tests show that the ramp rate is only exceeded when going to standby, turning off and when starting.
- For the continuity tests multiple sets of two days have been chosen to compare the results. The sets are based on having a similar solar generation pattern and similar day ahead prices. The imbalance prices fluctuate more and therefore did not have to be similar, since this is not possible. The behaviour of the electrolyser for the global optimization for the days are compared to the other day from the set. In Figure D.2 the produced hydrogen for May 27, 2022 and May 28, 2022 are compared. This shows that the electrolyser has a similar behaviour for both days. The same was found for the other sets of days. Therefore this verification test is passed.

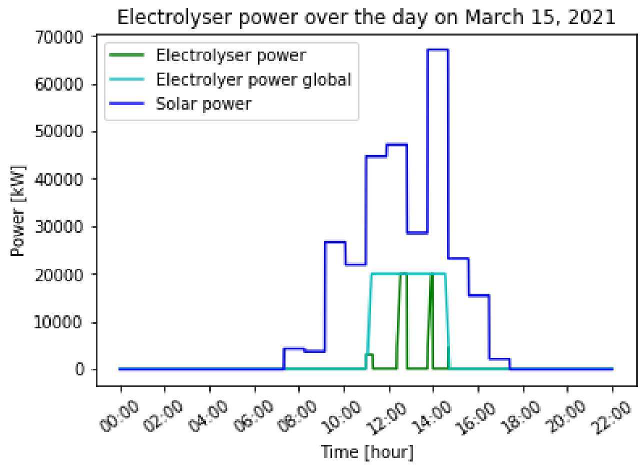


Figure D.1: Verification of the electrolyser never using the grid, the global electrolyser power is the power determined by the first optimization step

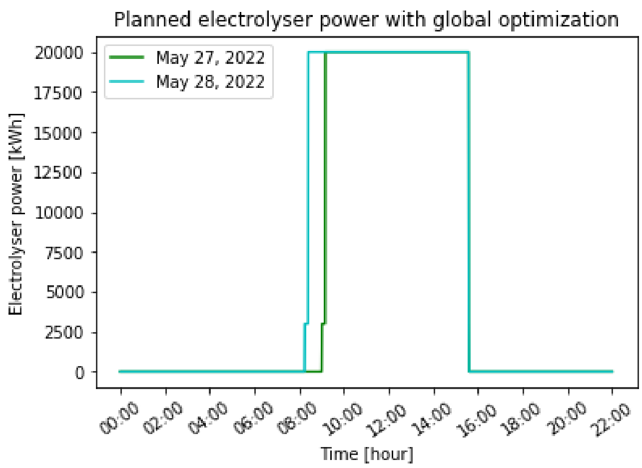
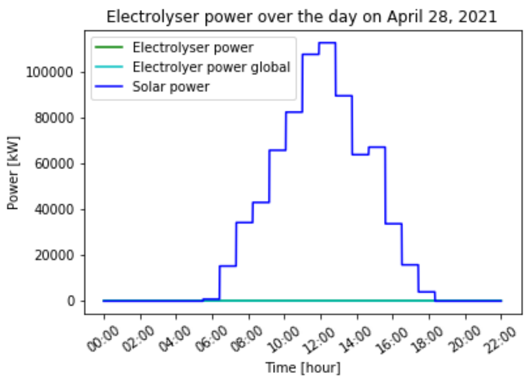


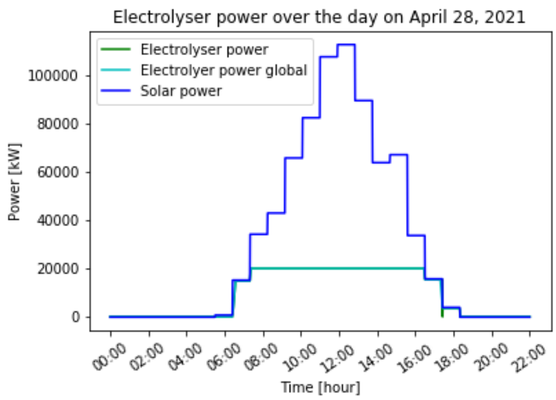
Figure D.2: Electrolyser power based on the global optimization of comparable days in 2022

- The system is tested on special inputs by changing the hydrogen price. For the first test, the hydrogen price is set at zero. Since the day ahead price is always higher than zero, the electrolyser should never be turned on. The other data is used from 30 randomly selected days in 2021. For every day, the number of minutes that the electrolyser is used is zero as expected. Figure D.3a shows the electrolyser use for April 28, 2021. For the second test, the hydrogen price is put artificially high at 500 €/ MWh. Since the highest prices of the day ahead in 2021 are around 100 €/ MWh, even taking into account the efficiency losses, the lifetime losses and imbalance peaks, using the electrolyser is more profitable than the day ahead market. Therefore, the electrolyser should be used whenever the solar generation is high enough. Again, 30 randomly selected days in 2021 are used. Figure D.3b shows the electrolyser use during the day at April 28, this shows that the electrolyser is on as long as the solar power is enough. The other tested days show the same behaviour. Therefore the special input tests have been passed.

Next to the verification test for the overall EMS, some hand calculations are done for verification of the optimization with given state. A few different situations are calculated by hand and compared to the result from the optimization in Python.



(a) Hydrogen price set at zero for April 28, 2021



(b) Hydrogen price at 500 €/ MWh for April 28, 2021

The first situation has the following inputs:

- The state of the electrolyser is 1 for the duration of the optimization
- The generated power from the solar park is 16000 kW for the duration
- The electrolyser power from the last minute before the optimization is 20000 kW
- The electrolyser is not starting, so $Y_{start} = 0$
- The hydrogen price is higher than the imbalance price, enough to compensate for the losses

Since the ramp rate can not be met, the electrolyser will be put on standby, even though it would be more profitable to use the electrolyser. Therefore the revenue generated will be $c_{imbalance} * (P_{gen} - P_{site} - P_{standby})$ for every minute.

The second situation has the following inputs:

- The state of the electrolyser is 1 for the duration of the optimization
- The generated power from the solar park is 60000 kW for the duration
- THe electrolyser power from the last minute before the optimization is 20000 kW
- The electrolyser is not starting, so $Y_{start} = 0$
- The hydrogen price is higher than the imbalance price, enough to compensate for the losses

The electrolyser will be used at its maximum capacity since the hydrogen price is high enough. The rest of the generated power minus the site demand, will be sold to the grid for the imbalance price. This will result in a revenue of $c_{imbalance} * (P_{gen} - P_{site} - P_{cap})$ per minute.

The third situation has the following inputs:

- The state of the electrolyser is 1 for the duration of the optimization
- The generated power from the solar park is 15000 kW for the duration
- THe electrolyser power from the last minute before the optimization is 10000 kW
- The electrolyser is not starting, so $Y_{start} = 0$
- The imbalance price is higher than the hydrogen price

The electrolyser will be put on standby, since it is more profitable to sell the energy to the grid. Therefore the revenue generated will be $c_{imbalance} * (P_{gen} - P_{site} - P_{standby})$ for every minute.

For all hand calculations, the optimization gave the same result.