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Review

Review of Energy Portfolio Optimization in Energy Markets Considering Flexibility of Power-to-X

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Abstract: Power-to-X is one of the most attention-grabbing topics in the energy sector. Researchers are exploring the potential of harnessing power from renewable technologies and converting it into fuels used in various industries and the transportation sector. With the current market and research emphasis on Power-to-X and the accompanying substantial investments, a review of Power-to-X is becoming essential. Optimization will be a crucial aspect of managing an energy portfolio that includes Power-to-X and electrolysis systems, as the electrolyzer can participate in multiple markets. Based on the current literature and published reviews, none of them adequately showcase the state-of-the-art optimization algorithms for energy portfolios focusing on Power-to-X. Therefore, this paper provides an in-depth review of the optimization algorithms applied to energy portfolios with a specific emphasis on Power-to-X, aiming to uncover the current state-of-the-art in the field.

Keywords: ancillary service; dynamic efficiency; electricity market; electrolysis; electrolyzer; flexibility; hydrogen; optimization; Power-to-X

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1. Introduction

Society is currently on the verge of one of the biggest transitions seen in the energy industry since the changeover to oil and natural gas starting in the early 1950s [1]. The war in Ukraine and the subsequent energy crisis have even intensified the focus on transitioning away from fossil fuels into a more sustainable energy system. After only one year, the renewable energy target in the EU was substantially increased from 40% (2021) to 45% (2022) by 2030 in the so-called *REPowerEU* plan. The targeted renewable generation capacity in the EU is 1236 GW by 2030 according to the plan [2]. A large share of renewable energy generation is expected to be coming from wind turbines and solar photovoltaic (PV) systems [3]. These two technologies intermittently produce electricity due to the dependency on weather conditions. As weather conditions cannot be controlled, nor perfectly forecasted, introducing larger shares of these technologies will inevitably introduce more imbalances to the electricity grid. Maintaining and balancing the grid frequency is of the utmost priority to ensure a well functioning power supply and avoid any brown or blackouts. Thus, it is important to find a suitable and sustainable way to account for the issues created by introducing large shares of these particular renewable technologies into the grid.

One of the topics in the energy industry with the most prosperity at the moment is Power-to-X, which has the possibility to be a cornerstone for addressing the downsides of introducing large shares of intermittently producing units into the electricity grid [4]. Power-to-X is a term for converting power into something else (e.g., sustainable fuels) or back to electricity at another point in time using fuel cell technology. The main component used in the Power-to-X term is the electrolyzer, which is expected to be an essential part of the sustainable energy system moving forward. The electrolysis technology is both controllable and can quickly be ramped up and down to suit the current need [5,6]. This property of the electrolyzer makes it a good candidate to provide demand response (DR), which counters the effects of fluctuating power production from renewable energy (RE). This flexibility of the electrolyzer is similar to that of EV (electric vehicle) charging. An extensive study of the synergy in energy storage coupled with RE for standalone EV charging stations has been done by authors of [7].

Based on the current literature and published reviews, none of them adequately showcase the state-of-the-art optimization algorithms for energy portfolios focusing on Power-to-X. Therefore, this paper contributes an in-depth review of the optimization algorithms applied to energy portfolios with a specific emphasis on Power-to-X, including a taxonomy table of central aspects covered in the reviewed optimization algorithms.

The structure of the paper is as follows: Section 2 covers the current and future need for flexibility and control. Section 3 covers the technical parameters for operating the most commonly known electrolyzer at the current time. Section 4 highlights the importance of optimization for operating a flexible energy portfolio and explains various aspects for consideration. In Section 5, the recent trend in the use of programming type and the development of publications within the field of review is presented. In Section 6, a review of the current state-of-art optimization models for energy portfolios with a focus on Power-to-X is conducted.

2. Current and Future Need for Flexibility and Control

One of the most significant barriers towards the introduction of large shares of RE technologies into the energy mix is the control and flexibility of production, and the loss hereof [8].

The control and flexibility of dispatchable units to keep the production and demand in balance are vital to have a stable and well functioning electricity grid. However, replacing traditional dispatchable units with large shares of RE technologies on the production side, one must look at the demand side for flexibility and control. The RE technologies can, to some extent, be operated flexibly, however, not to the same extent as the traditional dispatchable technologies. As mentioned in the first section, the large increase in RE in the electricity grid is expected to be generated from wind turbines and solar PVs. Since perfect foresight of weather conditions is not possible at the moment, complications arise. Imbalances in the system will increase due to the deviation between the forecasted and the actual production [9,10]. These imbalances are handled in reserve markets, where the market-participating assets are required to meet the qualification demands for providing any services in these markets.

In Denmark, wind turbines and solar PVs can participate in the reserve markets for capacity and energy activation. A requirement for participation from the Danish TSO is a certain qualification for the forecast of production [11]. The volatile production from the RE technologies will lead to hours with high production and hours with low production. In hours with high production, curtailments might be necessary due to the limitations of large-scale energy storage possibilities and grid constraints. These curtailments can be seen as a wasted potential to produce RE. Furthermore, the effects of the volatile production would be transferred to the electricity market prices as most markets are determining the clearing price using merit dispatch order and marginal pricing, c.f. Figure 1. The merit order is based on the short-term marginal prices of the producing units, where RE technologies, such as wind turbines and solar PVs, have low short-term marginal costs and thus out-compete traditional power plants.

This has also gained attention lately with DR and demand side management (DSM) being some of the keywords alongside Power-to-X as a solution to the loss of flexibility and control on the production side.

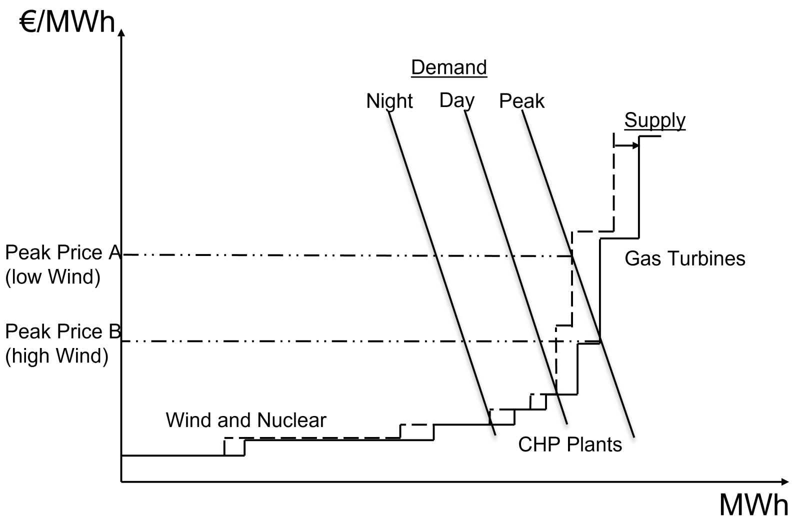

Figure 1. Merit order dispatch in electricity markets.

3. Parameters Influencing the Efficiency of the Electrolyzer Technologies

Electrolysis and Power-to-X are viewed as positive reinforcement for grid stabilization. This is because of its ability to regulate power consumption fast in regard to its hydrogen production. The dynamic operation of the electrolysis affects the efficiency and internal heat generation of the electrolyzer. This section will focus on the technological aspect of an electrolysis system and which parameters influence the selection of the electrolyzer. At the moment, there are four different well known technologies—alkaline electrolyzer cell (AEC), proton exchange membrane electrolyzer cell (PEMEC), solid oxide electrolyzer cell (SOEC), and anion exchange membrane electrolyzer cell (AEMEC) [12]. Some of the technologies are more proven than others which the technology readiness level evaluation (TRL) of the respective technology indicates. The International Energy Agency (IEA) ranks the technologies by their TRL, cf. Figure 2.

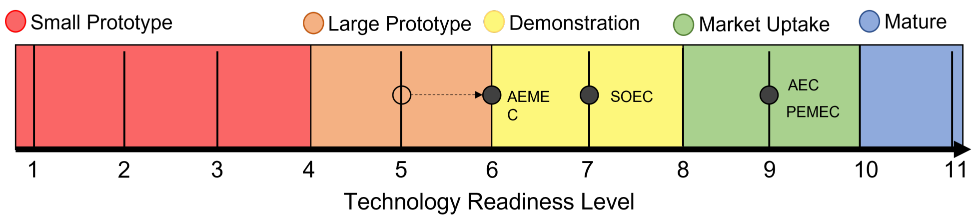

Figure 2. Technology Readiness Level of Electrolyzers [13].

AEC is the oldest electrolyzer technology and therefore also the most economically favourable [14,15]. The PEMEC technology has seen great development and has reached the same TRL as the AEC. PEMEC is still not at the same economic level as the AEC, but it is moving towards competitive price levels [16,17]. With AEC and PEMEC being more established and in operation around the world [13], the next technology on the TRL scale is SOEC. This technology is acquiring a lot of attention due to its synergy in sector coupling. The electrolyzer operates at high temperatures and is directly integrated with the process of renewable fuels [18]. The technology reaches higher efficiencies compared to AEC and PEMEC but requires a lot of heating input, which ideally should come from other processes [18]. The newest technology in the field is AEMEC, which is a hybrid version of the AEC and PEMEC. However, due to it still being developed, there does not exist a lot of data on it, nor have any specifications been published yet [19]. Thus, this paper will focus on the AEC, PEMEC, and SOEC technologies, as they are more proven, and the literature on the technologies is available.

Figure 3 is an illustration of the electrolyzer cells and their working principles. Since the technologies are operating differently, the parameters influencing the efficiency are also different. In general, the process of producing hydrogen is done by passing a direct current (DC) between two electrodes separated by a medium of water, splitting it into its compound elements of hydrogen and oxygen [12].

3.1. Alkaline Electrolysis Cell

The AEC is an aqueous electrolysis operating with 30% potassium hydroxide (KOH) to maximize ionic conductivity [12]. Water is delivered at the cathode and the separator transfers the OH^- ions. Schalenbach et al. [20] investigated how to model an electrolyzer and which parameters affect the efficiency. The overall efficiency is denoted as the cell efficiency, which contains voltage efficiency, current efficiency, and heat balance. In general, to improve the efficiency of the cell, the energy necessary for splitting the water molecules must be reduced [21].

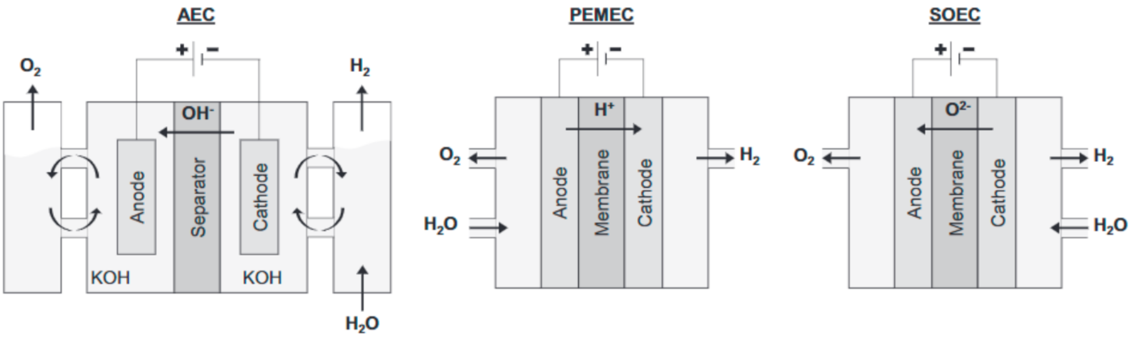

Figure 3. Operating principle of AEC, PEMEC and SOEC [22].

3.2. Proton Exchange Membrane Electrolysis Cell

PEMEC is an acid-based electrolyzer. It consists of two electrodes separated by a perfluoro sulfonic acid (PFSA) membrane [22]. The main difference between the AEC and the PEMEC technology is the current density. This property of the electrolyzer affects the flexibility of the system, especially when coupling the electrolyzer with fluctuating renewable energy resources (RES). Hernández-Gómez et al. [23] have reviewed this property to be [0.2–0.4 $A \cdot cm^{-2}$] for AEC and [2 $A \cdot cm^{-2}$] for the PEMEC. A downside compared to the AEC is the choice of raw materials for the PEMEC. Platinum is applied for the catalyst, whereas AEC utilizes nickel. This is a bigger contributor to the price difference between the two technologies.

3.3. Solid Oxide Electrolysis Cell

As can be deducted from the name, SOEC consists of an oxide ion conducting solid phase component [22]. The SOEC technology has seen great development in the recent decade. Both the electrochemical performance and the long-term resilience have been improved to where the technology has become ready for commercial use [18]. A property of this technology, which has made it especially attractive, is its possibility of direct sector coupling. AEC and PEMEC stop their processes after generating H_2. The water is vaporized in the SOEC process, which makes it possible to perform a co-electrolysis, where the steam is converted together with CO_2 to generate syngas [22]. This process requires the electrolysis to run at temperature levels of 600–850 °C. For comparison, AEC and PEMEC operate in the temperature range of 50–85 °C. Additionally, the current density of the SOEC is 1.5 $A \cdot cm^{-2}$. The data necessary for an in-depth review of the SOEC technology have not been made available yet, and therefore computer models have been preferable. Ba et al. [24] made a study of efficiency parameters with empirical data and computer modelling. The computer model performed with a relative error range of −0.33% to −1.03% compared to the empirical data. A main factor affecting the efficiency is preheating the water. The study showed that external water vaporization will lessen the power load and increase the efficiency from 68% to 83%. Synchronization of the gas flow, from the anode and cathode, will yield higher hydrogen production. Thus, it will increase efficiency.

3.4. General Efficiency Parameters

From Hernández-Gómez et al. [23], a general understanding of the efficiency of the electrolyzer process can be deducted. The efficiency can be depicted as the correlation between electric power and the hydrogen production rate [25]. The electric power of the electrolysis can be expressed as cell power and stack power, as seen in Equations (1) and (2).

$$P_{cell} = V_{cell} \cdot I_{cell} \tag{1}$$

$$P_{stack} = V_{stack} \cdot I_{stack} \tag{2}$$

The cell voltage can be formulated as the sum of the reversible potential and its over-potentials. The reversible potential V_{rev} is the minimum voltage level required to operate the electrolysis. This is generalized as 1.23 V [16]. The activation over-potential η_{act} is the over-potential required to initiate the proton transfer. The Ohmic over-potential η_{ohm} is generated from the flow of electron and their resistance. Concentration over-potential η_{con} occurs when H_2 and O_2 are generated at a higher rate than they are removed.

$$V_{cell} = V_{rev} + \eta_{act} + \eta_{ohm} + \eta_{con} \tag{3}$$

The cell voltage is a part of the voltage efficiency, which is:

$$\eta_v = \frac{V_{th}}{V_{cell}} \tag{4}$$

where V_{th} is the thermoneutral potential. This is related to V_{rev}, and, at standard condition, it can be assumed to be 1.48 V.

To model the energy consumption of the electrolyzer, Faraday efficiency is required. The Faraday efficiency is also known as the current efficiency, which is the ratio between ideal and real electric charge or ideal and real hydrogen production.

$$\eta_f = \frac{Q_{id}}{Q_{re}} = \frac{H_{id}}{H_{re}} \tag{5}$$

A common decrease in the Faraday efficiency is caused by low current densities [26]. The Faraday efficiency is directly related to the gas flow rates of hydrogen and oxygen.

$$f_{O_2} = \frac{N \cdot I_{cell}}{4F} \cdot \eta_f \tag{6}$$

$$f_{H_2} = \frac{N \cdot I_{cell}}{2F} \cdot \eta_f \tag{7}$$

where N is the number of cells connected in series, I_{cell} is cell current, F is the Faraday constant, and η_f is the Faraday efficiency.

As a result of this, the specific energy consumption of the electrolyzer can be concluded as:

$$C_E = \frac{\int_0^{\Delta t} N \cdot I_{cell} \cdot V_{cell} \cdot dt}{\int_0^{\Delta t} f_{H_2} \cdot dt} \tag{8}$$

The system efficiency is the proportion of the higher heating value (HHV_{H_2}) of hydrogen produced and the energy consumption of the system (C_E). The HHV_{H_2} can be found to be 39.4 kWh·kg^{-1}. The system efficiency becomes:

$$\eta_{ele} = \frac{HHV_{H_2}}{C_E} \cdot 100 \quad (9)$$

4. Importance of Optimization for the Flexible Energy Portfolio

The optimization of an energy portfolio can be done in various ways and includes different elements depending on the role of the owner. The optimization becomes more complex when acting as a prosumer, where several assets besides the electrolyzer are introduced. The aim of this section is to introduce some of the key areas, which could be accounted for in an optimization algorithm related to an energy portfolio. Figure 4 is a sketch of a possible scenario for an energy portfolio.

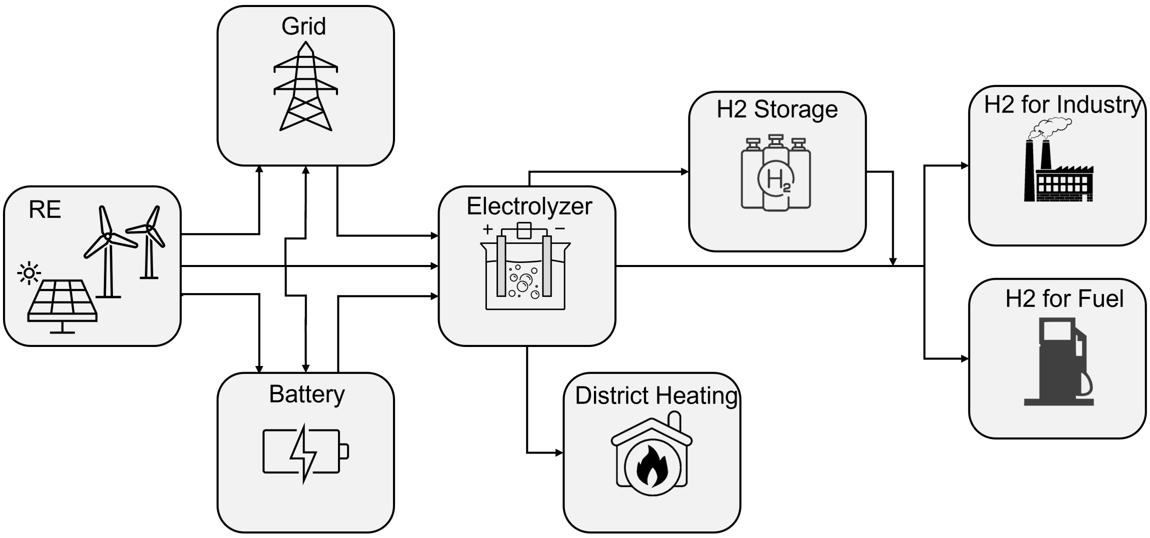

Figure 4. Possible pathway for green hydrogen production for an energy portfolio.

4.1. *Ancillary Service Participation*

Ancillary service participation or also often referred to as reserve market participation is one of the elements an owner of an energy portfolio could look into when trying to optimize revenue and profit.

Participation in reserve markets necessitates compliance with various technical requirements, as these services aim to maintain grid stability and functionality.

Some of the most common technical requirements are response times (both up and down regulating), minimum offer capacity, and minimum time of activation [11,27,28]. By providing ancillary services, the portfolio owner receives payment for the specific ancillary services provided, where some services consist of both availability- and energy-delivery payments. Thus, participation in this market will influence the business case of the energy portfolio.

In an energy portfolio consisting of an electrolyzer, the market might become very attractive due to the technical features of the electrolyzer. The response times of the electrolyzer technology are very quick, meaning the consumption can be changed almost immediately. In [29], the response time of a 40 kW PEM electrolyzer was tested. The results showed a nonlinear relationship between the size of the electrolyzer and the ramp rate. The ramp rate of this particular study and electrolyzer was 0.1 MW/s (2.5 pu/s). In another study [6], a 1 MW electrolyzer ramp rate was tested, which resulted in a ramp rate of 0.5 MW/s (0.5 pu/s). As large electrolyzers consist of multiple smaller units in parallel, the response time of the accumulated units does not change significantly [6]. Thus, it can be concluded that a large-scale electrolyzer consisting of multiple units, with similar technical characteristics as the ones tested in [6,29], is eligible to provide all the different ancillary services in Denmark [11]. Even with a fixed demand for hydrogen that must be provided by the electrolyzer, operating it flexibly with storage possibilities can be beneficial and lower the levelized cost of hydrogen (LCOH) [30]. However, before participating in the Danish ancillary services market, the unit must be approved by the Danish TSO, Energinet. Additionally, the flexible operation of the electrolyzer affects the lifetime of the components, which must be accounted for in the business case evaluation [31].

The future outlook of the ancillary services markets is looking into an international standard and market for trading these services across borders within continental Europe. The current timeline given by the Danish TSO, Energinet, is that in Q2 2024, there will be a common market for manual frequency restoration reserve (mFRR) with energy activation using the manually activated reserves initiative (MARI) and automatic frequency restoration reserve (aFRR) with energy activation in the platform for the international coordination of automated frequency restoration and stable system operation (PICASSO) [10]. By introducing this change, the market not only becomes larger, but also more liquid in the sense of more market participants can be allowed in the same market. This will most likely drive the payment of ancillary services down and the business case of participants in such a market might change.

4.2. Spot Market Participation and Storage

Market participation strategies for participation in the spot market (also known as the day-ahead market) are important when dealing with an energy portfolio with a focus on electrolysis technology. The cost of electricity is one of the most significant cost drivers for the production of green hydrogen [32,33]. Thus, combining hydrogen production with RE production and strategically buying electricity at hours with low cost is essential in providing hydrogen at the lowest cost possible. Additionally, storage for hydrogen can be advantageous for adapting to the volatile prices in the spot market. Especially when having a contractual agreement of a fixed amount of hydrogen, which needs to be produced, the necessity of producing hydrogen becomes more flexible, and the differences in prices can be further exploited.

4.3. Forecast and Market Uncertainties

Forecast and market uncertainties are important elements when dealing with the optimization of an energy portfolio. Particularly, this occurs when the energy portfolio consists of both production and consumption technologies. There are a considerable amount of forecasts that are interdependent within the electricity and reserve markets [34]. The production forecast of the RE technologies is dependent on the weather forecast and the accuracy hereof. As many of the markets are based on merit order dispatch and short-term marginal prices, the accuracy of the forecasted production can affect the prices in such markets [35]. Additionally to the forecast, there are also market uncertainties related to unexpected outages of production plants, large consumers, etc. [36].

Hedging options could be used to eliminate some of the forecasting uncertainties, but by using this strategy, the flexibility of the optimization model would decrease [37]. Thus, hedging options can be used to ensure price stability, but they could lead to a sub-optimal solution dependent on the price development in the different markets.

4.4. Optimal Sizing of Energy Portfolio

There should naturally be a focus on finding the synergies between the technologies within an energy portfolio. With the focus on the electrolyzer technology connection with RE generation, sizing of the different units is essential to avoid any under- or over-investment in capacities. The portfolio should be accessed and optimized based on the synergies between the technologies wanted in the portfolio, so a fitting ratio between the capacities invested in is found.

5. Trend in Publications

For this review, a search in trends has been performed. This has been done to get an idea of how intensive the subject is being researched and if there seems to be a gap in the research. The methodology applied to investigate the trend in publications is based on a structured search in ScienceDirect. The process consists of applying several search strings to cover the field of research and quantify the development in publications within the field. The main keywords used in the search strings are as follows:

- Electricity market
- Hydrogen
- Electrolyzer
- Optimization

The conducted searches showed a significant increase in published articles in 2019 and forward to 2022. This growth is due to political activities and the presentation of roadmaps around this period for renewables and decarbonized gases [38]. Figure 5 shows the development of published papers in the field in the last decade. Another separate search was conducted where ancillary services were incorporated. This particular search string only listed 10% of the original search. From the original papers, the focus has been on the optimization type for the models.

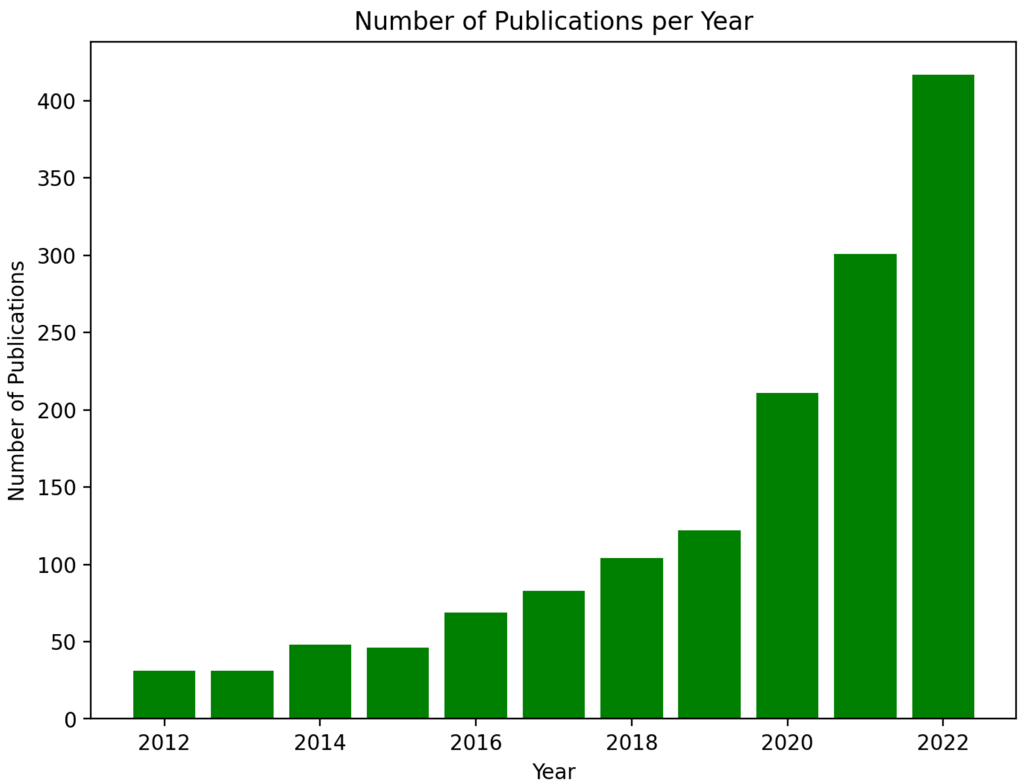

Figure 5. Development of research in the field of energy portfolio optimization with a focus on hydrogen production from electrolyzer technologies.

When differentiating the searches, four programming types are occurring consistently. The programming types are linear programming (LP), non-linear programming (NLP), mixed integer programming (MILP), and mixed integer non-linear programming (MINLP). Figure 6 showcases the publication of papers and their optimization types. Here, a clear trend of developing optimization models based on either LP or MILP is preferable to NLP and MILNP. This choice of using either NLP or LP is based on the complexity of the objective function and its constraints. Another factor, especially for models with big datasets, is the computation time.

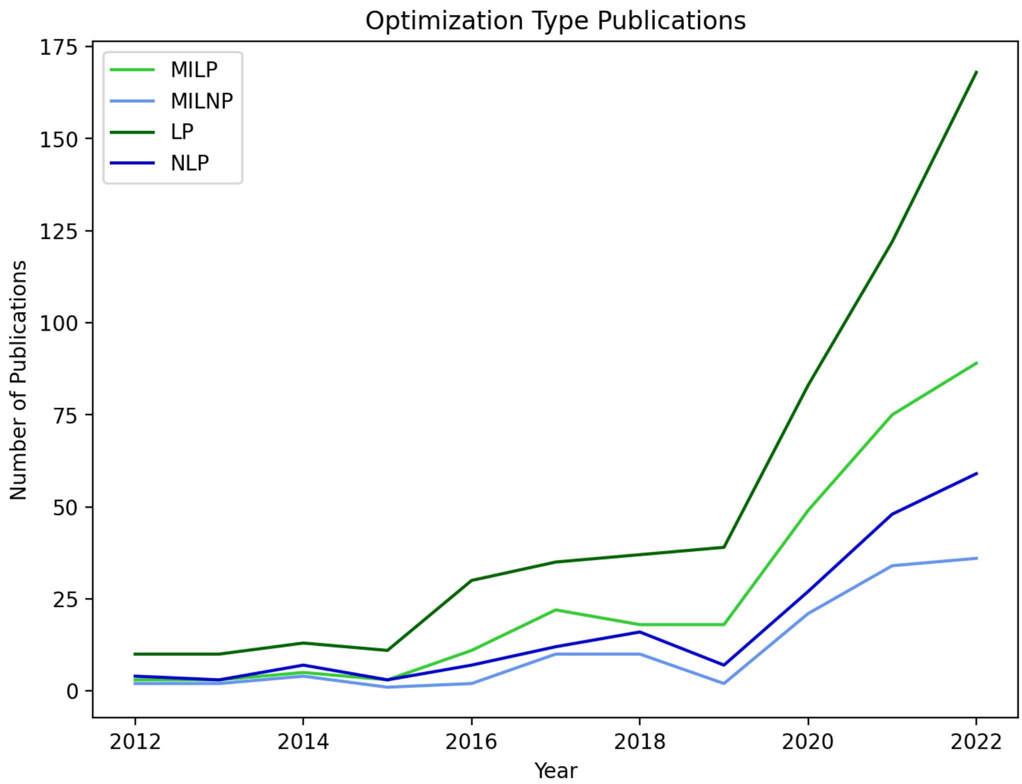

Figure 6. Development of different optimization types found in state-of-the-art research.

Table 1 presents the distribution of the programming methods within the field. The use of either LP or MILP has been substantial compared to the use of NLP and MINLP.

Table 1. Cumulative number of research published between 2012–2022 using the different optimization types.

Type	No. Articles
LP	558
NLP	193
MILP	296
MINLP	124

6. Literature Review of State-of-the-Art Optimization Models

In the following section, an analysis of the literature is conducted to determine the current state-of-the-art in the field and to disclose any research gaps found in this review. Table 2 comprises a taxonomy of the reviewed papers to indicate and highlight which aspects have been considered in the different optimization algorithms presented. In addition to this, a graphical representation of the no. of times an aspect is considered in the models reviewed can be found in Figure 7.

In [39], different bidding strategies for an energy portfolio consisting of a wind farm, water electrolysis, and storage facilities are investigated. The objective is to maximize the profit of an already situated wind farm in Texas, USA by introducing a hydrogen pathway in the form of a water electrolysis and storage facility. Additionally, the study also considers fuel cells to reconvert the hydrogen back into electricity and batteries to reduce the electrolyzer capacity. In [40], a two-stage stochastic program is developed in order to optimize the bidding strategy for energy-intensive enterprises in both the day-ahead market and the primary balancing market in Germany. The prices in the different markets are forecasted. In [41], a wind–electrolytic hydrogen storage system is investigated. The model considers uncertainties in production from the wind turbine and conditional value at risk (CVaR) as a measure of financial risks. Simultaneous participation in an ancillary service market with a pay-as-bid mechanism and a day-ahead market has been considered in [42]. This can be used to monetize the flexibility of an electricity consumer. The simultaneous strategy development is not bound to a specific technology or consumer type, but can be used by flexible energy consumers. In [43], flexible operation of a switchable chlor-alkali electrolysis is considered for DSM purposes. Furthermore, the effects of having a decreased lifetime due to the switchable operation of the electrolyzer are investigated. The lifetime reduction is based on assumptions. Ref. [44] focuses on optimizing the size of a hydrogen system with the objective of minimizing the levelized cost of hydrogen. Various scenarios, including fuel cell, electrolyzer, and storage technologies, are investigated. Both external and internal suppliers of hydrogen are used, where external suppliers are not necessarily producing green hydrogen. The hydrogen supplied is based on hydrogen market conditions and which type of hydrogen is the cheapest to buy. In [9], the production price of hydrogen from an electrolyzer located in an area with high wind penetration is investigated. The investigation is based in Denmark, where wind power makes up significant portions of the power in the grid. The study consists of multiple scenarios testing different levels of wind power penetration in the grid from which the electrolyzer is buying electricity. Additionally, a parameterization of the power price variations is conducted.

Table 2. Taxonomy of the reviewed literature, where x is indicating the aspects considered in the optimization algorithms presented.

Source	Optimal Sizing	Storage	Electricity Market	Ancillary Services	Availability	Market Uncertainties	Forecast	Optimization Approach	Country
[39]	x	x	x					Linear optimization	USA, Texas
[40]			x	x			x	Two-stage stochastic program. First stage (NLP) second stage (MILP)	Germany
[41]		x	x		x			MILP	Denmark
[42]			x	x		x		MINLP	Germany
[43]	x	x	x					MILP	Germany
[44]	x	x	x					Not explicit stated	Denmark
[9]			x					Not explicit stated (simple optimization)	Denmark
[45]		x	x		x		x	The predictive approach incorporates non-linear simulation models	Germany, Berlin
[46]	x	x	x	x				MINLP	Belgium
[47]		x	x					MLNP	UK
[48]	x	x	x			x		Stochastic energy management algorithm, MILP	
[49]	x	x	x		x			Not explicit stated	Iran, Ekbatan
[50]		x	x	x		x		Not explicit stated	Iran
[51]	x	x	x					Sequential quadratic programming method Adaptive particle swarm optimization (APSO)	Denmark
[52]	x	x	x			x		MILP	USA, Califonia
[53]		x	x	x				Combined Interior Point nonlinear programming and Newton Trust Region techniques	
[54]		x	x	x				MILP	Norway
[55]		x	x	x				MILP	Italy
[56]			x					Schedule-based	
[57]		x	x				x	Mixed-integer stochastic linear programming (MISLP)	Canada
[31]	x	x	x	x				MILP	Denmark
[58]			x		x			Grey wolf and crow search optimization (GWCSO)	
[59]		x	x		x			Enhanced normalized normal constraint (ENNC) strategy based on game theory (GT) and Fuzzy compromising (FCP) method	

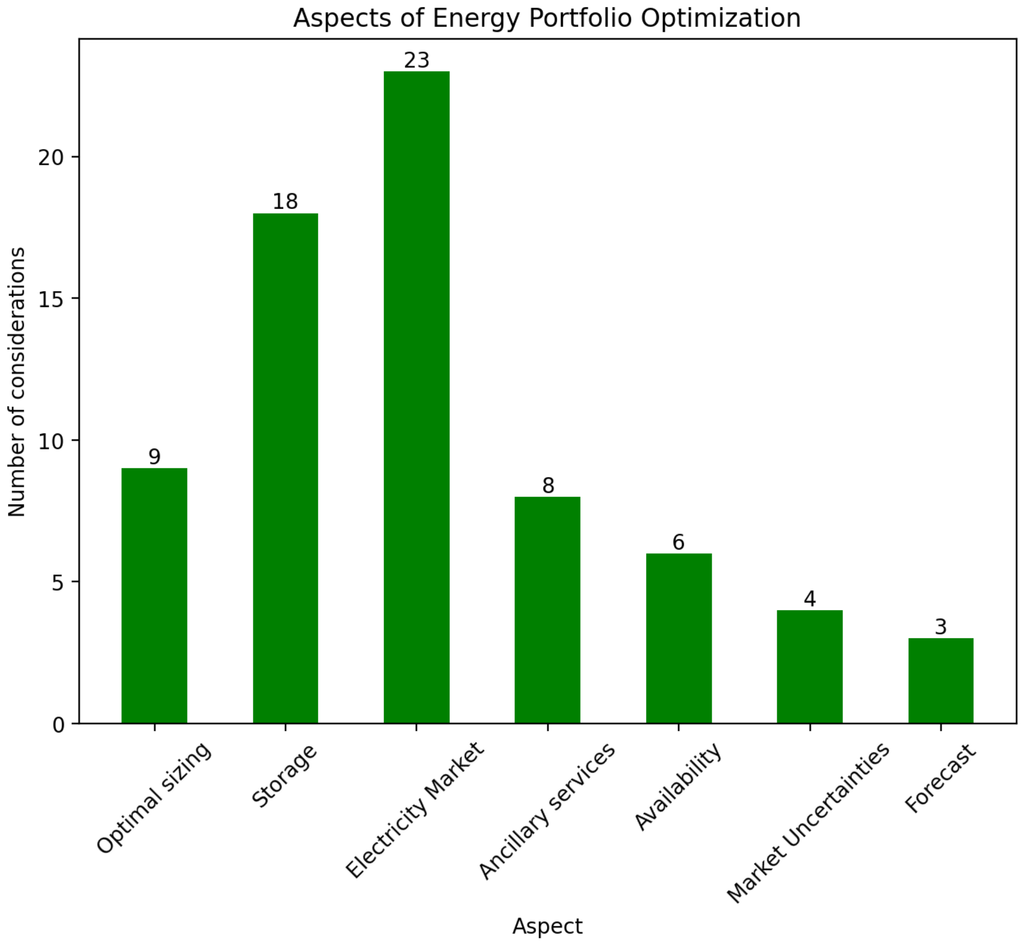

Figure 7. Number of times each of the investigated aspects are considered in the reviewed literature.

The authors of [45] consider the case of a hydrogen refuelling station (HRS) combined with a wind farm and how the day ahead market can be exploited to maximize profit. The study introduces imperfect forecasts instead of using perfect foresight. The imperfect forecast is carried out for the energy prices, wind energy availability and hydrogen demand. The model employs a nonlinear component model in the optimization. Ref. [46] does also consider a HRS system, such as [45]. However, it does not consider the direct link to the wind farms as a part of the optimization. Instead, it considers the ancillary services of frequency containment reserve (FCR), which can be provided by the electrolyzer. Ref. [47] examines an optimisation routine developed for a HRS in Rotherham, UK. The system consists of a PEM-type electrolyzer with a power rating of 270 kW and a wind turbine varying in size based on scenarios tested. The Rotherham site is able to operate at 0 and 100% of full power output, but, for extended periods of 6 h or more, a minimum load of 12.5% of the max load must be maintained. The objective function of this study aims to minimize the cost of hydrogen production and the amount of hydrogen demand not met. The optimisation algorithm is used for half-hour time steps over 30 days. The optimisation is based on 48 periods (24 h), and thus it may restrict the ability to take advantage of long periods with low electricity prices using hydrogen storage. Ref. [48] investigates the possibilities of optimizing a microgrid (MG) consisting of intermittent RE technologies, electrolyzer, fuel cells, etc. The market clearing price is found using a game theory model and Cournot equilibrium, which highlights that they are modelling the MG as a price maker unit and not as a price taker unit. In short, it means that the MG can affect the electricity market and the market clearing price in their model. Ref. [49] considers a MG similar to [48], but also introduces a reliability assessment. The reliability assessment is based on probabilities for outages of the wind turbines, solar PVs, and DC/AC converters. Ref. [50]

also considers a MG, where an optimal bidding strategy is proposed for participation on both the power and spinning reserve markets mainly to avoid high surplus power produced by certain weather conditions. The strategy considers uncertainties of the output power from the RE technologies, as well as the active power of loads and electricity prices using the unscented transformation approach. Ref. [51] proposes an optimized strategy for improving the investment of an offshore wind farm by producing hydrogen. Additionally, the trade-off between selling the hydrogen directly to the customers or using it as a storage medium to re-generate electricity using fuel cell technology is investigated. Ref. [52] investigates a renewable-electrolysis system, including solar PV and an electrolyzer under various market conditions, as well as connections. The connections include scenarios of island modes, wholesale market, retail market connections, etc. Furthermore, the financial mechanism in the state of California is considered including taxes. Ref. [53] examines the operational optimization of distributed and central electrolysis-based hydrogen generation and storage systems. The optimization algorithm considers both the electricity market, as well as multiple ancillary services. The ancillary services considered are reactive power support, demand response, and operating reserve. Moreover, it accounts for the physical limits of the power grid.

Ref. [54] presents a general model for optimal energy storage operation under specific market conditions. The model focuses on maximizing income earned from energy arbitration and providing several ancillary services. The model considers various constraints and market rules, which must be obeyed in order to participate in the different markets. In this specific study, the model has been used for a battery and a pump storage hydropower plant. Ref. [55] investigates the economic profitability of the secondary frequency reserve market in Italy through an integrated generation-and-storage system. The objective of the optimization is to minimize the annual average electricity cost for an electrical load. The integrated generation-and-storage system accessed considers a solar PV field and a hydrogen-based power-to-power system using fuel cell technology. Ref. [56] develops a DR-oriented dynamic model (schedule-based) of an industrial-sized electrolyzer plant, incorporating the dynamics and phenomena related to DR participation of such a plant. It considers a high level of detail related to the dynamic operation of the electrolyzer. Multiple relationships are considered in the model, including cell temperature and voltage, current-voltage, and material balance. Furthermore, it describes the importance of monitoring the evolution of cell temperature, when dynamically operating the electrolyzer, to ensure safe operation. Continuous operation of the plant is considered and, with a minimum current density of 0.3 A/cm^2 and a maximum of 0.6 A/cm^2, Ref. [57] investigates the aspects of hydrogen production and storage in combination with mixed wind–nuclear power plants. Introducing the nuclear power plant in the optimization model is making it different from the other mentioned studies. Additionally, it considers the profit generated by selling oxygen and excess heat from the electrolyzer. The electricity prices used in the optimization model are based on a simple forecasting model. The model assumes a normal distribution of forecasted electricity prices around actual electricity prices. A maximum relative error of 30% is compared to the actual hourly Ontario electricity price. In [30], a case study related to the value of flexibility of an electrolyzer is investigated. The investigation is done by the Danish TSO, *Energinet*, and uses an optimization model they themselves have created. The model allows for testing an energy portfolio consisting of multiple RE technologies and a grid connection. The analysis is based on Danish regulations and prices for ancillary services. The optimization model was made publicly available in October 2022 [4]. In [58], an innovative home appliance scheduling framework based on a fusion of the grey wolf and crow search optimization algorithm is presented. The proposed technique is used to efficiently provide DR from household appliances by analyzing multiple areas, such as the cost of electricity, user comfort, and peak-to-average ratio for the home appliances based on real-time price signals. In the study, it is demonstrated that there is a trade-off between users' comfort considering the appliances waiting time and the electricity cost. Ref. [59] is an extension on the work presented in [58]. Besides only including home appliances into the optimization model, the presented work also considers distributed energy resources, such as wind turbines and solar PV, electrical energy storage, etc. Furthermore, a two-stage optimization model has been presented. The first stage is an enhanced normalized normal constraint strategy based on game theory with the objective to optimize consumption cost, end user comfort, and peak-to-average ratio. The second state is using the fuzzy compromising method to optimize the overall energy cost and gaseous emissions. In addition to this, CVaR has been incorporated in the objective function to resolve failures and reliability issues.

Research Challanges

Due to the area and field of research, there are a number of research challenges the reader should be aware of. Firstly, the literature revolving around the dynamic operation of an electrolyzer and the effects hereof in an optimization model are very limited. In addition to this, public data on state-of-the-art electrolyzers and their dynamic operational features are often not available due to the highly competitive market conditions at the moment. Therefore, the literature on the dynamic operation of an electrolyzer is typically based on smaller capacities, which might not be applicable to large-scale energy portfolios.

Secondly, market uncertainties and forecasts are aspects that a limited amount of optimization models have explored. A reason for this could be the numerous amount of uncertainties, which could be captured in a model to make it more realistic.

Lastly, Power-to-X and the usage of electrolyzers on a large-scale basis in energy portfolios consisting of multiple technologies are a fairly new topic in the field of research. The market is still developing with governmental entities working on international agreements. As a result of this, there is a limited amount of research available encapsulating the essence of operating a Power-to-X portfolio considering the different market dynamics in which it can participate. However, this research challenge is anticipated to be lessened during the next couple of years due to the pressure from governments and the market itself.

7. Conclusions

The focus on energy portfolio optimization with respect to power-to-X has increased immensely in recent years, and the trend in publications clearly identifies this. Energy portfolios consisting of the electrolysis technology are able to quickly change demand, making it a good candidate to provide ancillary services and generate a supplementary profit from providing these.

The state-of-the-art analysis showed various examples and methodologies used in order to optimize an energy portfolio consisting of one or more technologies, markets, and connections. The optimization models ranged from simple to highly complex models, including some dynamics of the electrolyzer technology used. All of the models have an interaction with the electricity market (also often referred to as the day-ahead market), where only a minor portion of the models introduced ancillary services as a possibility in their optimization algorithms. Modelling the dynamics of the electrolyzer and the effects of operating the electrolyzer dynamically is done in a very limited manner in the literature reviewed. Additionally, perfect foresight of prices in the different markets, as well as productions and faults for wind turbines, solar PVs, etc., is often used in evaluating models and their performance in the literature. Even though an optimization model performs optimally under perfect foresight conditions, the model performance would always be dependent on the accuracy of forecasts in real-life applications.

Thus, future research could focus on the perfect foresight, dynamic modelling, and providing ancillary services aspects, as these are the largest research gaps identified in the current literature.

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Abbreviations

The following abbreviations are used in this manuscript:

AC	Alternating current
AEC	Alkaline electrolyzer cell
AEMEC	Anion exchange membrane electrolyzer cell
aFRR	Automatic frequency restoration reserve
CVaR	Conditional Value at Risk
DC	Direct current
DR	Demand response
DSM	Demand sidde management
EV	Electric Vehicle
FCR	Frequency containment reserve
HRS	Hydrogen refuelling station
IEA	International Energy Agency
LCOH	Levelized cost of hydrogen
LP	Linear programming
MARI	Manually activated reserves initiative
mFRR	Manual frequency restoration reserve
MG	Microgrid
MILNP	Mixed integer non-linear programming
MILP	Mixed integer linear programming
NLP	Non-linear programming
PEMEC	Proton exchange membrane electrolyzer cell
PICASSO	Platform for the international coordination of automated frequency restoration and stable system operation
PV	Photovoltaic
RE	Renewable energy
SOEC	Solid oxide electrolyzer cell
TRL	Technology readiness level
TSO	Transmission system operator

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