The Need for Dynamic Process Simulation: A Review of Offshore Power-to-X Systems

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The integration of offshore wind energy into Power-to-X (PtX) process chains offers opportunities for the efficient use of renewable energy. This article analyzes different PtX process chain configurations and their adaptation to the offshore environment. However, direct coupling of PtX platforms with fluctuating electrical energy poses major challenges. Dynamic process simulation is presented for analysis of different plant configurations and operating strategies. The article emphasizes the need for interdisciplinary research to consider technological as well as economic and environmental aspects.

Keywords: Dynamic operation, Energy storage, Hydrogen, Renewable energy, Power-to-X

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1 Introduction

Man-made climate change is one of the greatest challenges and threats of the 21st century and must be tackled for the benefit of all inhabitants of the planet. However, studies on carbon dioxide (CO_2) concentration in the atmosphere show only a very slow leveling off of emissions. Therefore, science, society and politics must work together to accelerate defossilization.

In addition to the necessary expansion of renewable energies, European legislation is pursuing the goal of supplying citizens and industries with large quantities of hydrogen (H_2). Ten gigawatts of electrolysis capacity for green H_2 are to be built in Germany by 2030 [1]. This is accompanied by a deployment of 40 GW of electrolyzer capacity by 2030 in the EU and a further 40 GW of supply capacity from other countries [2]. The hydrogen can be used by industry to heat heat-intensive processes, as fuel in fuel cells or as an energy storage option. However, there are CO_2-intensive applications that cannot be easily substituted with hydrogen, such as aircraft. Therefore, the conversion of hydrogen into chemical energy carriers like LNG, FTS (eFuels, synthetic kerosene), ammonia or methanol is being targeted to support these so-called "hard-to-abate" sectors in defossilization.

This concept is called Power-to-X (PtX) and describes a process in which variably available electrical energy (Power) is converted into another energy carrier (X). The "X" can in turn be subdivided into the superordinate product groups Power-to-Liquid (methanol, eFuels, e.g., synthetic kerosene, ammonia) and Power-to-Gas, e.g., synthetic natural gas. According to the definition, these conversion processes are categorized as indirect electricity use, as the electrical power must first be converted into hydrogen which is subsequently used in the synthesis processes [3]. The products have been part of everyday life for decades and are used as base chemicals in industry. The complete infrastructure including transport routes, storage possibilities and environmental protection regulations are known and successfully applied. The products can be used as fuel and help to close the carbon cycle or as a substitute in industry using the example of green methanol and ammonia.

The challenges of producing large quantities of green hydrogen and transporting it in the form of other energy carriers are currently being intensively researched, for example in the hydrogen flagship project H2Mare of the German Federal Ministry of Education and Research [4]. A promising approach for this is the direct offshore production of PtX products at sea, where the electrical energy does not have to be transported to land via submarine cables first [5]. For this, offshore wind farms are directly coupled with electrolyzers and synthesis plants installed on central platforms and operated as isolated systems. This means that there is no grid connection and thus the entire fluctuations of the wind turbines are imposed on the process chain. This results in the major challenge of operating the chemical production plant dynamically and designing the process chains in such a way that they can follow the natural fluctuations. This is accompanied by significantly more complex

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process control strategies and higher demands on the plant technologies.

Compared to hydrogen, the PtX products have a significantly higher volumetric energy density and are therefore well suited for transport via ship or pipeline. Since significantly higher amounts of energy can be transferred via this and with lower losses than direct transmission of electrical energy via underwater high-voltage lines, these PtX platforms are particularly suitable for developing remote offshore wind sites and do not compete with nearshore sites for connection to the existing power grid [5].

This article provides a comprehensive insight into two main areas: Offshore energy generation and PtX technologies, as well as their integration to a dynamically operated offshore production platform on the high seas. Sect. 2 examines the global potential of offshore wind energy. Sect. 3 is dedicated to the fundamentals and technologies of water electrolysis and syntheses including different storage concepts for volatile input variables. Sect. 4 discusses the challenges and research prospects of offshore PtX production by bringing the two areas together. Sect. 5 provides an outlook on the use of dynamic process simulations for the detailed investigation of dynamic plant operation as well as the design and integration options for increasing overall efficiency. The article concludes in Sect. 6 with a summary of the content discussed.

2 Offshore Wind Power Potential

There is considerable potential for offshore wind energy in Europe and especially in the North Sea, as wind speeds are consistently high throughout the year and the North Sea, with its shallow water, also offers large development areas in the future [6]. Compared to onshore wind, higher wind speeds are achieved on average and are subject to lower. For the same installed capacity, more electrical energy can be generated with offshore wind than with onshore wind turbines or photovoltaics and thus higher annual full load hours can be realized [7, 8]. The choice of mounting technologies is strongly dependent on the respective ground conditions and water depth. Basically, a distinction is made between monopiles, jackets, tripods and floating [9].

As technology continues to evolve and energy companies demand larger turbine designs, new turbines continue to be unveiled and today are reaching outputs of 15 MW and announced 18 MW [10, 11]. Most turbines installed in the past are in the 3–9 MW range and newly planned offshore wind farms are installing 9.5–15 MW turbines [12]. In addition to turbines, costly power electronics are also required for conversion to DC or transformation to higher voltage levels to reduce transmission losses [13].

With the North Sea, Germany has a very suitable offshore wind energy access due to the shallow water and constant wind speeds. This is expected to increase overall capacity to 30 GW by 2030 and to about 70 GW by 2045, with a current installed capacity of 12 GW. The European Union has set a target of installing 160 GW by 2030 and 300 GW by 2050 [14, 15].

The current largest European wind farms are offshore wind farm Hollandse Kust Zuid with 1.5 GW , Borkum Riffgrund 1, 2 and 3 with 1.66 GW and Hornsea 1 and 2 with 2.6 GW installed capacity and planned 5.5 GW, which would make it the world's largest wind farm [16–18]. Other parts of Europe are also favored due to the Atlantic coast with plenty of wind and long coastlines on the Mediterranean Sea [19]. However, the sea depths there are significantly deeper, making expansion more difficult and expensive. Floating turbines could provide a remedy for this in the future [20]. The share of offshore wind energy is also increasing strongly in other parts of the world, as China is able to realize a fast expansion and large amounts of capital are available for offshore wind energy in the USA. Besides the Southwest of North America, there is also high potential in Brazil, Indonesia, Namibia, South Africa, Australia and Chile [5, 21, 22]. Fig. 1 shows that the technical wind energy potential of some industrialized countries exceeds their own electricity demand. In this context, PtX can be seen as a method of storing volatile electrical energy and making it transportable. This makes it possible to benefit globally from the favorable conditions and the technically possible energy surplus of some countries.

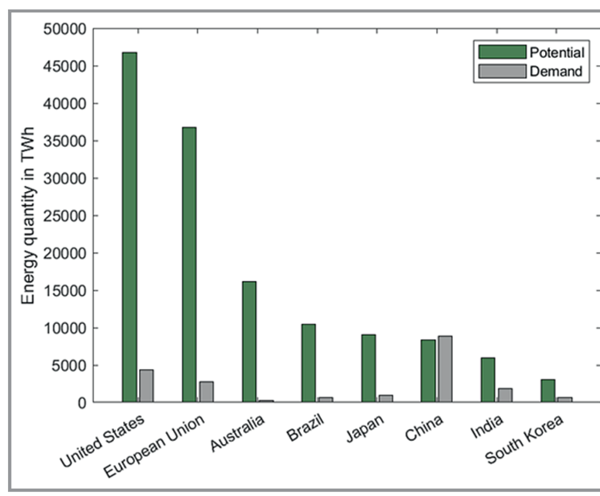

Figure 1. Comparison of offshore wind technical potential (2018) and electricity demand (2022) for various countries and the European Union, based on data from [23, 24].

3 Power-to-X Technologies

PtX process chains are used to convert the electrical energy into chemical energy carriers. These process chains are coupled from individual process steps and basically consist of four higher-level steps: an energy source for renewable electricity, reactant supply, synthesis and upgrading/processing. Hydrogen (H_2) required for all syntheses can be produced via water electrolysis technologies (alkaline (AEL), proton exchange membrane (PEM), anion exchange membrane (AEM) and solid oxide electrolysis (SOEC)). Carbon dioxide (CO_2) provision can be obtained in-situ or delivered from onshore point sources. For the syngas-based processes, the process route can be taken via Co-SOEC (CO_2 and H_2O electrolysis) or via the two-step process by coupling electrolysis with a Reversed Water Gas Shift (RWGS) reactor. Fig. 2 shows the schematic layout of the PtX process chains and the structure of the chapter: Sect. 3.1 first deals with the supply of reactants (desalinated water, carbon dioxide, syngas and nitrogen), followed by Sect. 3.2, which is dedicated to hydrogen production by water electrolysis. Sect. 3.3 to 3.6 provide an overview of the various synthesis routes, including Fischer-Tropsch for eFuels, liquefied natural gas (LNG), methanol and ammonia.

3.1 Offshore Provision of Reactants, Utilities, and Periphery

The provision of fresh water for electrolysis is a significant variable in offshore PtX production. Different synthesis processes and electrolysis methods require different quality standards for the water used, with proton exchange membrane electrolysis (PEM electrolysis) having the highest water quality requirements [26]. Water treatment technologies can be divided into membrane-based, thermal, and hybrid or emerging technologies [27]. Membrane-based processes include the widely used reverse osmosis, which uses a semi-permeable membrane and requires high pressures. Nanofiltration operates analogously to reverse osmosis but at lower pressures. Electrodialysis, on the other hand, uses electric potentials to induce the directed migration of salt ions. In the area of thermal processes, multi-stage flash (MSF) involves passing heated salt water through multiple pressure chambers to promote evaporation of the water. Hybrid systems are also possible, for example a combination of MSF and reverse osmosis, to use waste heat from the MSF process to preheat the feed water in the reverse osmosis system. In the context of emerging technologies, zero liquid discharge technology is relevant [28]. Here, all feed water is separated into usable water and solid salt, enabling complete resource utilization [29]. Even if the thermal processes are more energy-intensive (MSF with 13.5–25.5 kWh m^{-3} versus RO with 3–4 kWh m^{-3}), a higher energy efficiency of entire process chains can still be achieved by using waste heat from, e.g., synthesis plants [30].

In addition to the treatment of fresh water, the treatment of process wastewater (wastewater treatment) is of crucial importance for the entire process chains in isolated systems. Within this category, a basic distinction is made between chemical, physical, physicochemical, mechanical, and biological treatment methods [31]. The selection of the appropriate technology depends on the specific type and quantity of contaminants in the wastewater.

The carbon dioxide (CO_2) required for the synthesis processes can be provided either by marine tank transport or via a CO_2 pipeline from onshore point sources or generated in-situ. In the context of in-situ technologies, direct air capture (DAC) and direct ocean capture (DOC) are important [32]. In the case of DAC technology, CO_2 is adsorbed directly from the air. By applying negative pressure and thermal energy, the adsorbed CO_2 is desorbed and made available for subsequent synthesis processes. A limiting factor of this method is the low concentration of CO_2 in the atmosphere, which makes it difficult to provide more than 13 tons of CO_2 per hour required for a 100 MW electrolysis plant for methanol synthesis. Since the oceans absorb about 25 % of atmospheric CO_2, DOC technology offers the possibility of harnessing some of the CO_2 dissolved in seawater [32]. Combining DOC and seawater desalination could provide synergistic benefits, for example, by using a single pumping unit for both processes. In addition, hybrid approaches could provide thermal integration opportunities that would increase the overall efficiency of the process chain.

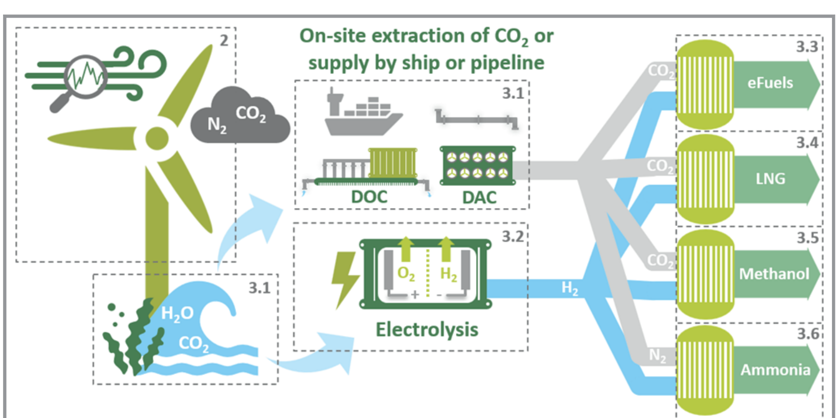

Figure 2. Schematic representation of the offshore PtX process chain, adapted from [25].

The nitrogen (N_2) required for ammonia synthesis can be extracted using cryogenic air separation unit (ASU), which are considered industry-proven technologies [33]. However, these are typically designed for high capacities. An alternative method for lower capacities is pressure swing adsorption (PSA), which isolates nitrogen by adsorption at high pressures and desorption at lower pressures [33]. This technology is characterized by high dynamic capabilities due to its cyclic process flow and is capable of achieving high nitrogen qualities, depending on the specific design and operating mode. Furthermore, PSA technology has already been successfully applied in offshore environments, especially on oil tankers, but their capacity is typically too low for large-scale industrial processes. Alternatively, technologies exist for nitrogen production by membrane processes or use a HT-SOEC directly for ammonia synthesis gas production with air [34]. In addition to the utilization of nitrogen as a feedstock, it is also used as an inert gas for purging applications or as an extinguishing agent in offshore contexts.

3.2 Technologies for Water Electrolysis

In water electrolysis, a direct electric current induces a controlled redox reaction in an electrochemical cell consisting of at least two electrodes, an electrolyte, a voltage source and a diaphragm. The electrolyte serves as the medium for ion transport, and the membrane acts as a selective barrier, allowing ion diffusion but preventing electrolyte mixing. The magnitude of the molar hydrogen current is proportional to the applied electric current, and the reaction requires a minimum cell voltage. The thermoneutral voltage represents the energetic point at which the reaction neither releases nor consumes heat. Loss mechanisms, including ohmic losses and bubble formation at the electrodes, increase the total voltage required [35].

The most prominent electrolysis technologies are alkaline electrolysis (AEL), proton exchange membrane electrolysis (PEM), anion exchange membrane electrolysis (AEM), and solid oxide electrolysis (SOEC). PEM uses an acidic, proton-conducting polymer membrane as the electrolyte, which separates the cell into two half-cells. At the anode, water is oxidized, while at the cathode, the proton-conducting membrane allows hydrogen to form. A major advantage of the PEM is the very high current densities of up to $3\,A\,cm^{-2}$ and it exhibits very large load gradients and can be operated over a wide dynamic range [36]. For AEL, an aqueous solution of KOH or NaOH is usually used as the electrolyte, with a porous separator to separate the half cells. The AEL has current densities up to $0.6\,A\,cm^{-2}$ and therefore a higher space requirement compared to the PEM [36, 37]. In the SOEC, an ion-conducting ceramic serves as a solid electrolyte and separator. The high temperature SOEC is operated at 600–850 °C and uses water vapor [30]. Here, the thermal energy is additionally used to split the water, resulting in higher efficiency (provided that the heat is available) [38].

In addition to HT-SOEC, there are two special forms that will be of interest in the PtX in the future: Co-SOEC and rSOC. In Co-SOEC, carbon dioxide is split in addition to water vapor, producing synthesis gas that can be used directly for subsequent synthesis processes [39]. The rSOC can be operated in one direction as electrolysis and in the other direction as a fuel cell. If the system was designed mainly for water electrolysis, the round-trip efficiency is about 30–40 % [40]. The AEM combines the PEM and the AEL and reduces the use of rare earths on the PEM membrane as catalysts. Another interesting technology for offshore use is direct seawater electrolysis. this technology uses seawater directly as an electrolyte and as a feed for hydrogen production [41, 42]. However, the TRL is currently in the range of 3 [43].

Due to fluctuating wind energy, it is necessary to operate electrolysis processes in PtX process chains dynamically. These dynamics require high flexibility of the plants to respond to varying electrical input currents. Such flexibility minimizes the need for extensive electrical and hydrogen storage, the operation of which is associated with energetic losses and additional costs. Characteristic metrics for quantifying the flexibility of chemical plants, and electrolyzers in particular, include the duration for cold and warm starts, heating dynamics, and the ability to operate transiently at part load. While in a cold start the system must first be heated to operating temperature, in a warm start it is already in a standby state and is maintained at operating temperature and pressure without any production taking place. Another critical parameter is the load gradient, which describes the percentage change in power in relation to the rated power per unit time. A higher load gradient allows faster adjustment to changes in input power [44].

Lange et al. have compared the flexibility parameters of different types of electrolysis in the literature, according to which PEM electrolyzers have high load gradients of up to $40.6\,\%\,s^{-1}$, which makes them particularly suitable for use in systems with fluctuating power [44]. While the cell can react to electrical fluctuations almost without delay, peripheral components such as pumps or gas-liquid separators limit the overall dynamics of the system. Load flexibility varies from 0 % to temporarily up to 300 %, giving the PEM the ability to respond adequately to short-term load peaks. The high load gradient of 10–90 % per second enables adaptation to rapid load fluctuations [44]. The start-up time from hot standby is less than 10 s until full load is reached and is accordingly extremely fast. In comparison, the start-up time from the cold standby state is in the range of about 10 to 15 min, which is in the same range of the AEL. AEL operation is only possible in a load range between 20 % and 100 %. Operation below this limit would risk hydrogen diffusing through the lye and diaphragm, potentially creating an explosive mixture [39]. In terms of dynamic operation of the SOEC, longer periods without electrical power should be avoided. With low heating and cooling ramps, the start-up and shutdown can take several hours, and cold start-up can also take up to 60 min [44].

3.3 Fischer-Tropsch Synthesis

Power-to-Liquid is a collective term used to describe energy conversion into liquid energy carriers, with particular focus here on the products of Fischer-Tropsch synthesis (FTS). In FTS, a specified end product does not result directly, but rather a spectrum of hydrocarbons of different chain lengths [45]. Consequently, downstream processing is required to optimize the yield of the target product on the one hand and to achieve the specified product properties on the other. In the context of eFuels or synthetic kerosene production, long-chain hydrocarbons can be cracked by hydrocracking under hydrogen addition and isomerized in hydrotreatment reactors [46]. The main products are waxes, oils, process water and a gas mixture that can be recycled into the FTS reactor to increase process efficiency. In Fischer-Tropsch synthesis, a differentiation is made between high-temperature FTS, operating at 300–350 °C and using iron catalysts, with increased productivity in terms of C2-C4 olefins for aviation fuel, and low-temperature FTS with cobalt catalysts at an operating temperature of around 200–250 °C to produce middle chain hydrocarbons [47, 48]. The processing of the product streams can be realized by means of separators or distillation columns.

3.4 Power-to-Gas/LNG

Methanation can be accomplished by heterogeneous, gas-phase catalytic synthesis of hydrogen and carbon monoxide or carbon dioxide [49]. The underlying chemical reactions include the Sabatier reaction, the water gas shift conversion, and consequently the reaction of CO_2 and H_2. The Boudouard reaction can appear as an undesirable side reaction and lead to the formation of elemental carbon. In addition to the product gas, steam, carbon monoxide, and unreacted reactants usually exit the reactor, requiring further processing and separation. Reactor options include fixed-bed reactors, where special care must be taken with respect to hot spots due to the exothermic reaction characteristics. Cascade reactors can be implemented to minimize this risk. Operating temperatures within the reactor are in the range of 250 to 300 °C, while reactant gases are heated to temperatures of 400 to 500 °C [49]. Alternative reactor configurations may also include microreactors, fluidized bed reactors, bubble column reactors, and honeycomb reactors [50]. The methane is liquefied by cooling it to temperatures below –162 °C, and about 5–15 % of the natural gas energy content must be consumed for liquification [51].

3.4 Power-to-Methanol

Methanol synthesis can be carried out either by direct hydrogenation of CO_2 or by using synthesis gas [52]. Commercial catalysts based on $Cu/ZnO/Al_2O_3$ are used at operating temperatures in the range of 200 to 270 °C. Reaction conditions include operating pressures of 50 to 80 bar and a H_2/CO_2 feed ratio of 3:1 [53]. Alternatively, other catalyst systems and process parameters are conceivable. The reaction is exothermic and characterized by a reduction in molecular numbers; therefore, lower temperatures and higher pressures favor the reaction process. The overall efficiency of the process chain is highly configuration-dependent and varies between 39 % and 75 % in the scientific literature [54]. Various reactor typologies, including fixed bed reactors, fluidized bed reactors, membrane reactors and microreactors, can be used [54]. In addition, distillation columns are used to achieve the required product purity and for the separation of water.

3.5 Power-to-Ammonia

Ammonia is typically synthesized on a large industrial scale by the Haber-Bosch process, which requires high thermodynamic conditions and significant purity of the hydrogen and nitrogen feedstocks. Conventional ammonia synthesis plants operate under conditions of 400 to 450 °C and 100 to 150 bar with an H_2/N_2 feed ratio of 3:1 [55]. Iron- and ruthenium-based catalysts are primarily used in heterogeneous catalysis [56]. The usual separation of the produced ammonia is carried out by means of phase separators, in which cooling processes separate the liquid ammonia from the gaseous components nitrogen and hydrogen.

4 Challenges of Direct Coupling of Offshore Wind Parks with Power-to-X Process Chains

The implementations of the different synthesis routes in an offshore environment face similar challenges originating from the volatile energy supply to a highly integrated system. The requirements for dynamic offshore PtX production systems can be divided into three main categories: Process chain configuration (I), dynamics of the process chain and its operating modes (II), and integration into the offshore system environment (III). Fig. 3 summarizes the key challenges discussed in this chapter.

For conversion of offshore generated electrical energy into PtX products, interconnectivity of the plants is required (I). Several approaches are conceivable for the spatial arrangement of the process components: a) coupling wind turbines with offshore transformer stations to transport electrical energy via submarine cables to shore for chemical conversion; b) building PtX plants on a central platform near the wind farm; and c) integrating modular, decentralized PtX plants directly into the wind turbine structures [5, 20, 57]. In scenarios with offshore production (b and c), the produced chemicals and fuels can be transported either by pipeline or marine transport. A main pipeline to the mainland can either be connected directly to the central platform (b) or connected to the respective PtX-producing wind turbines via several secondary "feeder lines" (c). In the case of ship transportation of ammonia, methanol, eFuels or LNG, specific ship engines can be used that are powered directly by the product being transported.

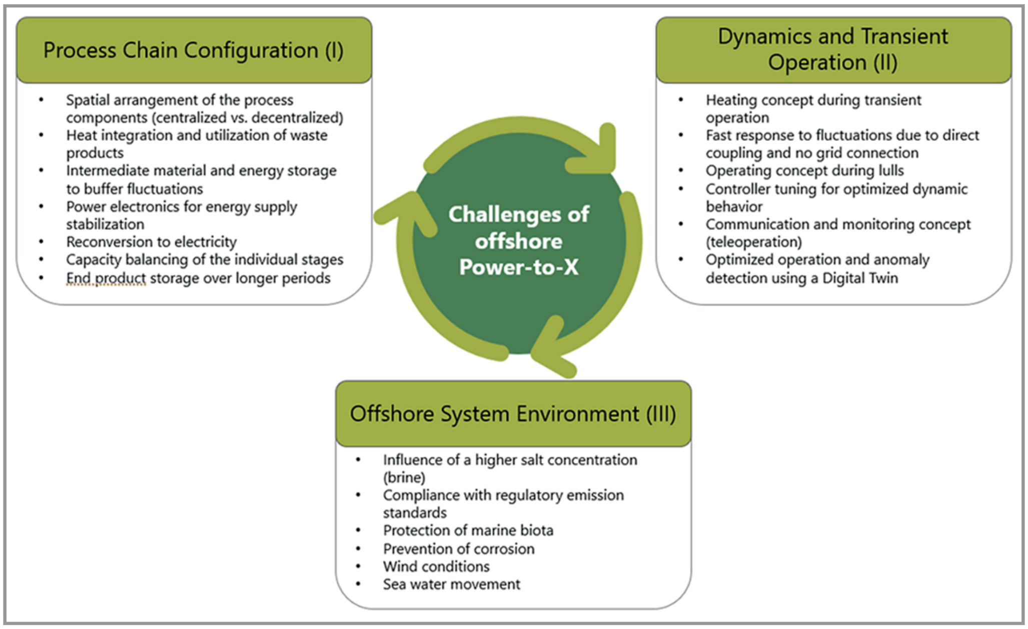

Figure 3. Summarized overview of the challenges of offshore PtX, grouped into the 3 categories presented: process chain configuration (I), dynamics and transient operation (II) and offshore system environment (III).

Compared to onshore PtX production approaches, offshore production offers potential savings in terms of pipeline losses and costs, which depend on the specific connection method and distance to shore [5]. Studies show that pipelines have a much higher capacity for energy transport compared to submarine cables and have lower energy losses (0.2 % for pipelines compared to 6–8 % in electricity grids, depending on the transport method in medium or high voltage as well as alternating or direct current) [58–60]. However, a comprehensive analysis must also take into account the transportation losses that occur in substations or due to compressors on the PtX platforms. Offshore production also eliminates transformer stations, which can cause costs of around €2 billion, as well as the costs of submarine cables, which amount to around €1.5 million per km [20, 60]. However, these savings are offset by increased additional costs for the offshore suitability of the systems, processes and control technology. Therefore, a detailed cost analysis and efficiency assessment will be required in future in order to take into account not only the transportation losses but also the efficiency of the synthesis processes.

The implementation of central offshore platforms, as outlined in option b), has significant advantages, especially in the context of transporting the liquid end products via centralized loading stations. In addition to the economies of scale, centralized facilities enable optimized processes for heat integration as well as the utilization of by-products or waste products to increase the overall process efficiency (I). An exemplary scenario for such a synergy would be the use of waste heat generated in the synthesis plant for heating seawater desalination plants or to generate steam for a HT-SOEC. In addition, required peripheral units, such as water treatment and combined steam and cooling systems, can also benefit from centralization and process integration. Fig. 4 schematically shows the in-depth integration potential of the individual stages of the process chain using energy and material streams. Nevertheless, the implementation of heat integration concepts poses significant challenges compared to conventional plant designs. Especially in transient operating conditions, the availability of process heat from certain process steps for subsequent steps is not continuously guaranteed (II). For example, the use of waste heat from the electrolysis unit for water treatment processes would only be feasible when the electrolysis unit is in operation mode. In such cases, a central heat and cooling management system for the entire process chain could be beneficial to ensure continuous energy efficiency and electric heater must be installed as a reserve.

From an ecological perspective, decentralized plants (option b) could offer benefits in terms of dispersion of saline solutions (brine) in the marine ecosystem (III). More efficient mixing of brine would reduce the likelihood of localized, elevated salt concentrations ('hotspots') that could pose both ecological risks to marine fauna and increased corrosion risks to metallic infrastructure [24]. In addition, the transmission of electrical energy would be completely eliminated, as the wind turbine would directly output PtX products.

With respect to the use of offshore wind energy for PtX conversion, the direct coupling of wind turbines with electrolysis processes presents a technical challenge because this approach leads to the transient operation of the plants to cope with the fluctuation of wind energy production (II). In the absence of a balancing power grid that could buffer such

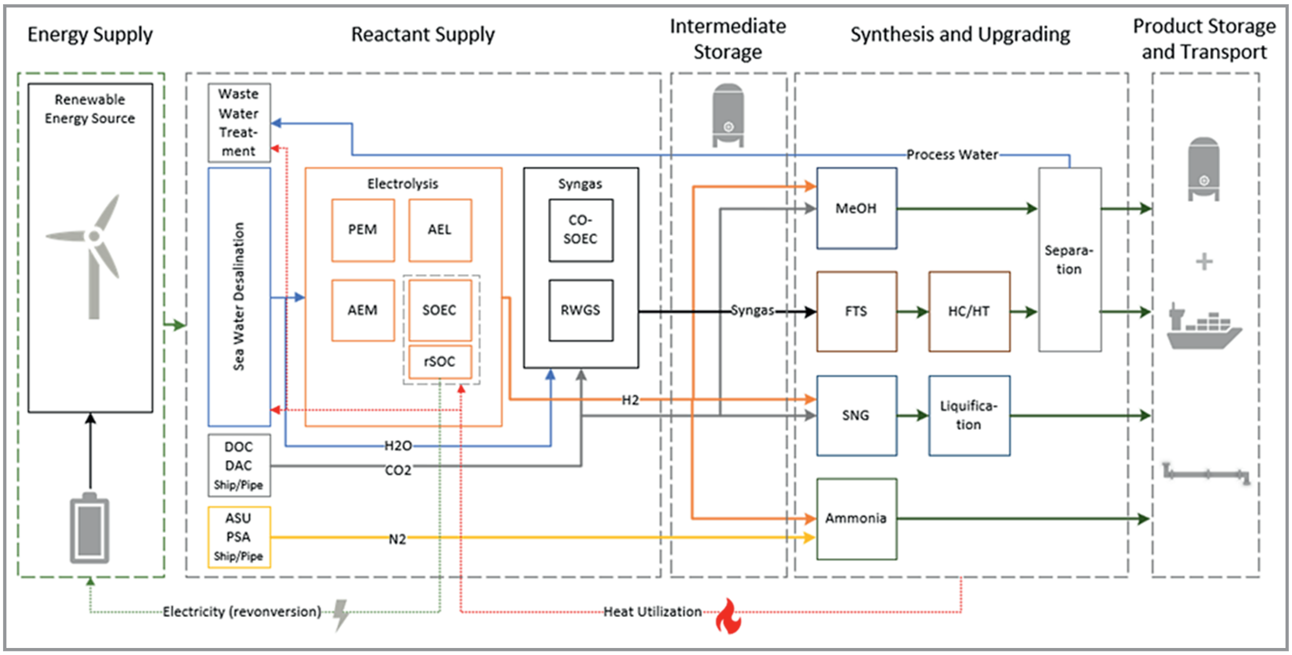

Figure 4. Possible process chain configurations and integration potentials of the different PtX technologies, adapted from [61].

fluctuations, this implies the transfer of all wind energy variability to the PtX process chain. To meet this requirement, storage systems need to be integrated, differentiating between energetic and product storage and buffers (I). These act as intermediary elements between the system components to absorb rapid fluctuations and thus ensure process stability. In theory, these buffer systems can be viewed as low-pass filters that filter high-frequency fluctuations. The challenge is to match the storage capacities and plant capacities so that production is as high as possible even during lulls without unnecessarily increasing the investment costs of the storage facilities. From another idealized point of view, the buffer system can be completely omitted, if the electrolysis dynamics align with the synthesis dynamics and only the amount of H_2 is produced that is actually required by the synthesis (II).

Energetic buffers, such as lithium-ion batteries, are used for short-term stabilization of the electrical supply (I). Other control elements, such as power electronics and rectifiers, are also required for input power stabilization. Long-term energy requirements can theoretically be met by batteries but are less suitable for techno-economic reasons. Complementary to battery systems, technologies for reverse power generation, such as reversible solid oxide cells (rSOCs), can be used. Combined approaches, for example, an 80 % use of PEM and 20 % rSOC for hydrogen production would provide a potential reverse power generation capacity of 6.7 % of the nominal electrolysis capacity, with the assumption of 30 % SOFC power share (I).

Optimizing the dynamic capabilities of the process chain requires careful tuning of the capacities of the individual plant components (I). This includes the ratio between the capacity of the electrolysis unit and the wind farm, and between the storage systems and the downstream PtX processes. Control loops, both at the level of the individual stages and in the higher-level process chain, have a significant influence on the dynamics of the system. Therefore, optimized controller tuning is required (I, II).

The dynamics of the process chain depend on the individual dynamic characteristics of its individual stages and can be evaluated using parameters such as load limits, turndown ratio and ramp rates. Operating modes such as full load, transient operation and various standby/shutdown states influence the energy demand of the individual stages and consequently the optimal operation of the overall plant (II).

Another challenge is the communication and monitoring of an offshore production platform to ensure its safe and efficient operation (II). It is crucial that data on the status of the system and production is either forwarded to the operators on site or, in the case of a largely autonomous platform, to a central control center on land. This can be implemented using a teleoperation system. In addition, a digital twin, which serves as a virtual model of the platform, can be integrated to detect anomalies and optimize operational management [62].

Integration into the offshore system environment includes compliance with regulatory emission standards and protection of marine biota. In particular, the removal of concentrated brine after the desalination process and the control of corrosion by the marine environment pose specific challenges (I, III). In addition, logistical aspects are also relevant, such as the need to plan for reactant and product storage facilities that provide sufficient capacity even under adverse ship delivery conditions (I).

There are overlaps between the categories, which often makes a clear categorization difficult. The challenges of each category are interdependent, making the process of system design and evaluation an iterative one. One possible solution strategy could be to modularize the system, allowing partial shutdown of system components during periods of low energy input.

5 Dynamic Process Simulations as a Method to Overcome the Challenges

For the evaluation of optimal plant configurations and operating modes, dynamic process simulation is a valuable tool. This allows detailed case studies to be carried out without the need to implement complex physical plants in advance. The simulative approach also allows the integration and evaluation of different control strategies in terms of their suitability for transient operation. To this end, this chapter focuses on gaining insights and formulating requirements for a dynamically operated PtX process chain. Particular attention is paid to the short- and long-term fluctuations of the wind and the resulting dynamic processes of hydrogen production. These findings form an essential basis for future investigations of the entire integrated process chain, which includes wind turbines, electrolyzers, synthesis plants and processing and treatment technologies.

The wind sometimes fluctuates by more than 30 % in the minute range and within one hour, in extreme situations, 75% of the installed power can be lost, but seasonal fluctuations can also occur [63]. For an overestimate calculation of wind fluctuations, we analyzed the freely available data sets of the reanalysis ERA5 with $1\,h^{-1}$ measured values for the site SEN-1, which was tendered by the Federal Maritime and Hydrographic Agency of Germany (BSH) as a special area in the North Sea for e.g., PtX projects [64, 65]. Fig. 5 illustrates typical wind patterns over a week in 2022, showing both the week with the strongest and the week with the lowest fluctuations and the lowest energy output. This figure underlines the challenge that the PtX plants must be able to operate flexibly under fundamentally varying conditions. On the other hand, Fig. 6 illustrates that there are also significant differences in the wind conditions on a monthly and seasonal level, which makes a long-term operating strategy necessary. In the summer months, lower average wind speeds can be expected than in winter, which is why maintenance operations are carried out in these months due to calm seas and lower downtime losses of the turbines. Long-term lulls of up to 3 days must also be expected, especially during the summer months.

In the next step, based on the dynamic wind patterns, both the power output of the wind turbine and the resulting trend of hydrogen production are analyzed and evaluated.

Due to the inertia of the mechanical systems of the entire wind turbine, fast wind fluctuations are transmitted to the generator to a lesser extent than the slower fluctuations.

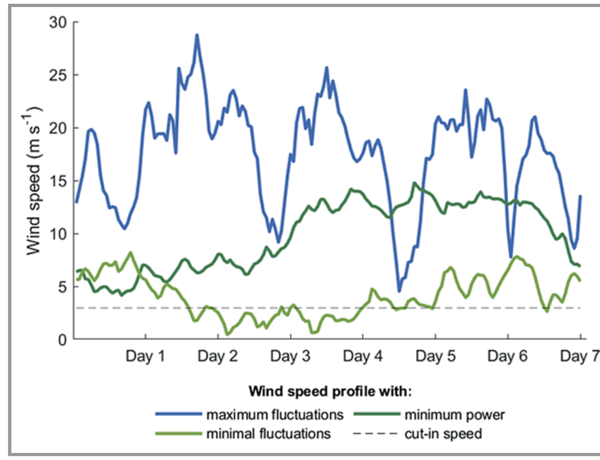

Figure 5. Comparison of exemplary characteristic daily courses of wind speeds within one week in 2022. Maximum fluctuations in the period from 15.-22. February, minimal fluctuations from 29. November-06. December and minimum power output from 06.-13. August. Cut-in minimum wind speed above which power generation starts.

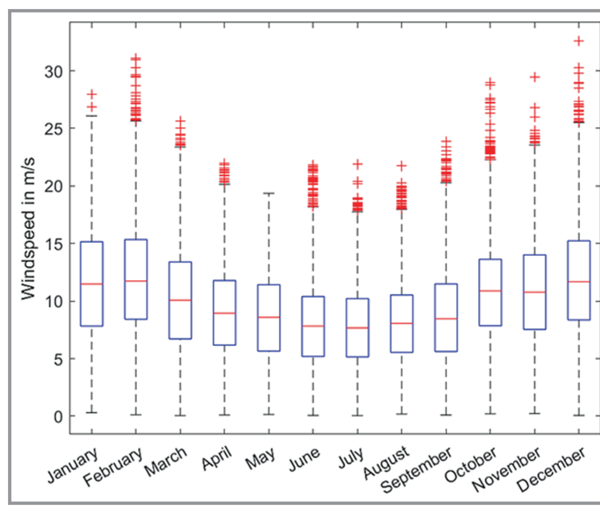

Figure 6. Boxplot of wind speeds for PtX special area SEN-1 in the North Sea over 40 years, based on ERA5 reanalysis data [65].

This behavior can be described by a low-pass filter, where all frequencies below the cut-off frequency are removed. This means that fluctuations in the wind at higher frequencies are filtered out by the wind turbine and do not transfer to the output electrical energy. According to Farmer and Rix, frequencies above 1.2 mHz are filtered out by synchronous generator's rotor inertia so that fluctuations in the seconds range are not relevant to the dynamics of the electrical energy [66].

Using the wind profiles previously studied, a simulation of the dynamic pattern of electricity production was carried out using a power curve for offshore wind turbines. Fig. 7 illustrates the power generation on the days with the highest dynamics in the SEN-1 area for the year 2022, based on the

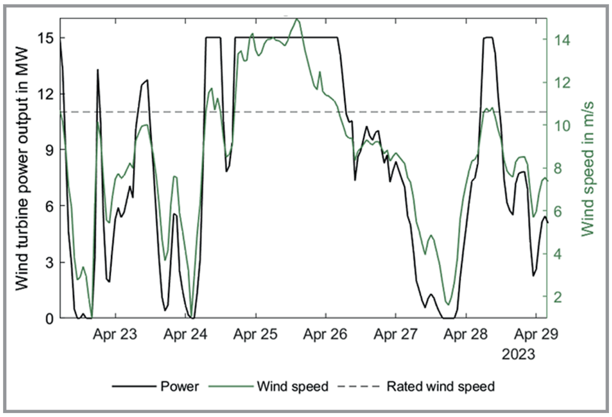

Figure 7. Simulated power generation curve based on the IEA 15 MW reference wind turbine in the SEN-1 area. Above the nominal wind speed of the turbine, it outputs almost constant maximum power.

power curve of an IEA 15 MW reference wind turbine mentioned in the literature [64, 65, 67]. Since the study focuses on the direct coupling of the wind turbine with an electrolyzer for hydrogen production, this dynamic curve of electrical energy serves as the basis for the subsequent simulation of dynamic hydrogen production.

To simulate the dynamic hydrogen production, a dynamic PEM electrolysis model was created as a flowsheet simulation. The basis for the model is a PEM container plant with 100 kW installed power, whereby two of the four stacks of the plant were simulated. The simulated plant layout can be seen in Fig. 8. The dynamic pressure-driven simulation was carried out in Aveva Process Simulation and contains, in addition to the wind turbine and electrolysis models, pumps, heat exchangers, drums and various control loops for pressure and flow control [68].

Fig. 9 shows the simulated hydrogen flow as a function of wind speed, where the maximum output power of the turbine was limited to 70 kW to match the nominal power of the electrolyzer. From the result, it can be seen that the hydrogen production follows the fluctuations of the wind input almost without delay and there is a smoothing of the fluctuations due to the peripheral components such as the H_2 separator vessel.

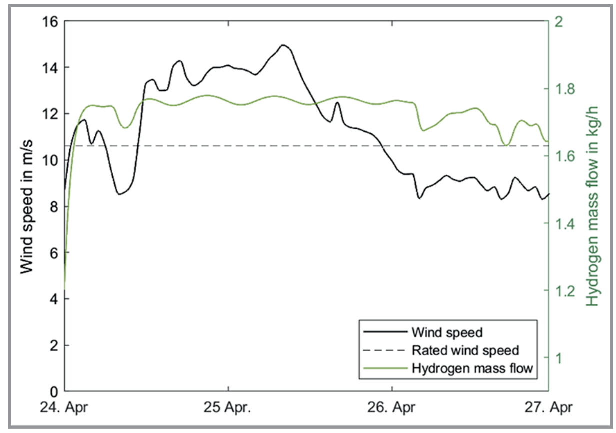

Figure 9. Simulation of hydrogen flow after the H_2 separator based on wind speeds for SEN-1 area.

The previously developed dynamic hydrogen trend serves as the basis for planning the downstream synthesis and processing steps in future dynamic flow sheet simulations. The next steps include modeling the PtX process chains based on existing container plants for electrolyzers and synthesis plants in the 100 kW range, which will be validated by experimental data. On a simulative level, the validated models will then be virtually coupled to investigate the optimization of plant configurations for transiently operated offshore process chains, including in-situ recovery of reactants, process integration and intensification. A further step involves upscaling the plant configurations to higher production capacities with a nominal electrolysis capacity above 100 MW. In addition, the investigation includes the development of modular operating concepts and the dimensioning of energy storage and product storage systems for transient and standby operation. Furthermore, the findings of the seasonal operating dependencies will be included in the future investigation of scenarios and use-cases in order to optimize the system configuration and storage design for long-term operating scales. This simulation method enables preliminary estimates of the annual production volume, which can be used for the economic evaluation of different plant configurations and the integration into energy system simulations.

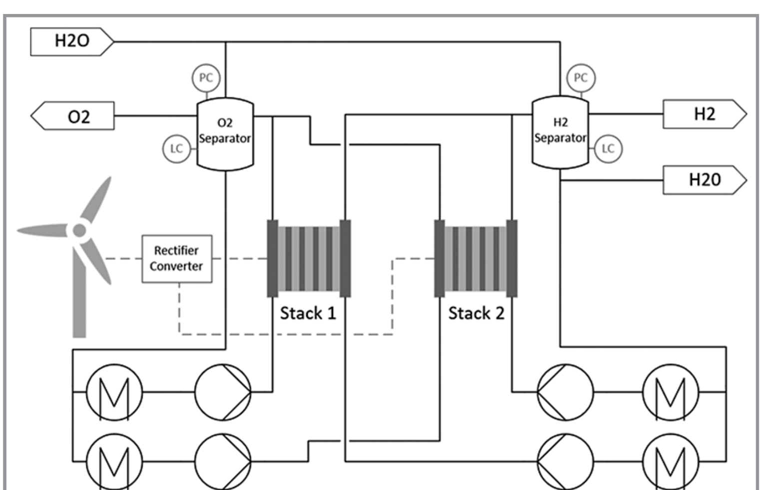

Figure 8. Configuration of the simulated electrolysis container with two of the four stacks of the plant coupled with a wind turbine.

6 Conclusion

The integration of offshore wind energy with PtX process chains represents a promising strategy for the efficient use of renewable energy sources. This study has presented several implementation approaches, including coupling wind turbines with centralized offshore PtX platforms, integrated PtX units and possible transient operation strategies.

The challenges in the context of dynamic offshore PtX production are complex and multi-layered. They relate not only to the process chain and its dynamics, but also to integration into the offshore environment. Key technical challenges include the need to effectively size and control buffer systems for product and energy, as well as control loops. In addition, the plants must comply with environmental regulations, particularly with respect to the protection of marine biota and the protection against corrosion.

The use of dynamic process simulation was presented as a method to address these challenges. Through these simulation approaches, it is possible to accurately evaluate both the technical and economic aspects of the various implementation approaches. The simulative approach allows a detailed case study without having to implement complex physical plants in advance. Validation of simulation results by matching them with experimental data provides additional reliability and accuracy.

Despite the promising possibilities, numerous questions remain, especially in the area of scalability and integration of heat utilization concepts. Furthermore, a detailed investigation of technical and economic feasibility is needed to make informed decisions. The interdisciplinary nature of these challenges requires a broad research agenda that considers technology, economics, and environmental aspects equally.

Overall, the research shows that direct coupling of offshore wind farms with PtX process chains is a promising but complex approach that requires thorough, multidisciplinary investigation and planning. However, through further research and the development of pilot projects, the concepts discussed here can contribute to sustainable energy supply and climate protection in the near future.

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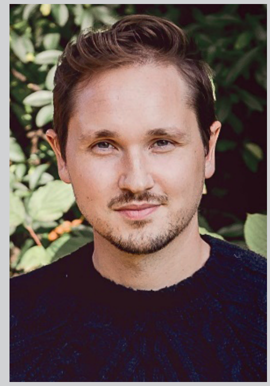

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Abbreviations

AEL	Alkaline electrolyzer
AEM	Anion exchange membrane
ASU	Air separation unit
DAC	Direct air capture
DOC	Direct ocean capture

FTS	Fischer-Tropsch synthesis
LNG	Liquified natural gas
HT-SOEC	High temperature solid oxide electrolyzer
MSF	Multi-stage flash
PEM	Proton exchange membrane electrolyzer
PSA	Pressure swing adsorption
PtX	Power-to-X
SOEC	Solid oxide electrolyzer
SOFC	Solid oxide fuel cell
rSOC	Reversible solid oxide cell

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The Need for Dynamic Process Simulation: A Review of Offshore Power-to-X Systems

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Review Article: When coupling offshore wind turbines with Power-to-X platforms on the high seas, the plants must be able to follow the wind and energy fluctuations without a grid connection. Dynamic process simulations can help to adapt the process chains to the offshore plant environment and to investigate transient operation.