Simulation Based Techno-Economic Evaluation of Self-sufficient Microgrid Systems with Renewable Energy and Power-to-X

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Abstract. Because of the renewable energy's weather dependence (e.g. wind, solar) as well as the normally mismatched load profile of energy consumption, the deployment of energy storages in Microgrid system is mandatory for an autarky. The Power-to-X (PtX) technology with Hydrogen or Synthetic gas will be one of the particularly relevant solutions. Self-sufficient (Off-Grid) microgrids incorporating renewable energy sources, Power-to-X and Combined Heat and Power (CHP) were created and investigated. A set of different system designs was sized to fulfill the load demand and analyzed by using a rule-based operating strategy whilst respecting predicted price changes of Hydrogen, Synthetic gas and components. The results show that the deployment of microgrid system using renewable energy, Power-to-X and CHP on the example of the selected industrial site might be a competitive solution for reaching not only decarbonization or carbon dioxide neutrality but also achieves a similar range of the household's electricity price before 2022.

Keywords: Renewable Energy · Renewable Energy storage · Power-to-X · Power-to-Gas · Microgrid · Hydrogen · Synthetic gas · Techno-Economic Evaluation · Decarbonization · Carbon Dioxide Neutrality · Simulation Investigation

1 Introduction

1.1 Background

The successful implementation of the energy transition and climate protection goals represents one of the central social tasks for the coming decades e.g. the earth average temperature increase must be limited below 1.5 °C in consideration of 2015 Paris Climate Agreement. According to the amended Climate Protection Law 2021 in Germany, a reduction of CO_2 emissions by 65% compared to 1990 has been decided, and greenhouse gas neutrality should even be achieved until 2045 [1]. In order to achieve these goals, beside the complete transformation of the electricity sector towards 100%

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renewable energy sources, other sectors, e.g. heat, must also be de-fossilized. Against this background, the prevailing opinion meanwhile in science, industry and politics is that a purely electricity-based energy world is not expedient for technical and economic reasons and so that the implementation of the energy transition should be succeed with the help of different cross-sectoral concepts for being able to achieve the set goals.

Integrating of renewable energy in the conventional energy supply system is one of the key measurements to tackle the climate change challenge. Because of the renewable energy's weather dependence (e.g. wind, solar) as well as the normally mismatched load profile of energy consumption, the deployment of energy storages in microgrid system is mandatory for an autarky. The Power-to-X technology with hydrogen or synthetic gas could be one of the particularly relevant solutions.

1.2 Project Description

For investigating this solution, a cooperative research and development project MethQuest financed by Federal Ministry for Economic Affairs and Energy of Germany has been carried out. This cooperative project consist of 6 projects, within the two projects MethPower and MethGrid self-sufficient microgrids incorporating renewable energy sources, Power-to-X and CHP were created and investigated. These concepts which differ in terms of the fuel, i.e. the chemical energy storage, and the system layout are either carbon free or carbon neutral.

2 Methodology

2.1 Approach

The investigations have been carried out according to the following procedures described below.

Firstly, the self-sufficient microgrid concepts with Power-to-X as well as CHP have been created. The dimensioning followed by technical and economic evaluation of every microgrid concept respectively is conducted by using an inhouse developed automated simulation- and evaluation-toolchain giving the technical valid and economic optimal variant. The technical evaluation is carried out with focus on the system power and energy balance given by the real life electrical and heat demand of the selected locations. The economic evaluation is conducted with the focus on the lowest system Net Present Cost (NPC) and Levelized Cost of Electricity (LCOE). The respective steps in the mentioned approach are in the following parts further described.

2.2 Toolchain

The concepts are created based on expert knowledge. One of the challenges is the dimensioning of the subsystems, therefore a two-step approach consisting of nested optimization loops is decided to apply.

In the first step, a rule-based rough configuration and dimensioning is carried out based on empirical values and rules of thumb. During the optimization loop of the inhouse developed tool in the next step, the dimensioning of the individual subsystems

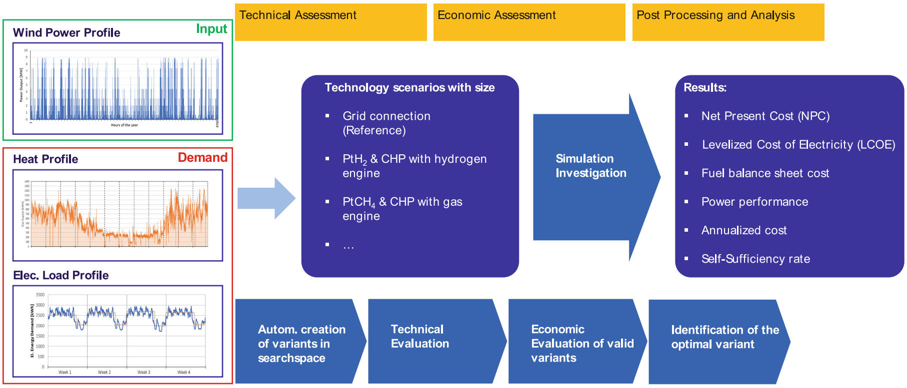


Fig. 1. Developed tool for automatic creating variants and identifying the most economic variant

and components is optimized with the help of rule-based operating strategy. The target here is the minimization of the capital costs over the whole lifetime (Net Present Costs).

The internal developed simulation tool consists of 4 modules described below. The hourly resolved load profiles of electricity and heat demand, the generated profiles of renewable energy sources for one year as well as the technical and economic parameters of the applied technologies can be imported in the module 1. All possible variants of respective concept are automatically created in the module 2 and operated for the whole year and in the following step verified regarding the compliance with technical constraints e.g. coverage of the electricity and heat demand at each time step. The economic evaluation and identification of the most economical variant is carried out in the module 3. Finally the results of evaluations are post-processed and presented in the module 4 (Fig. 1).

2.3 Operating Strategy

The system operating strategy conditioned by the control concept of the individual subsystems refers to the Fig. 2 as an example. In case of electricity surpluses, battery is charged firstly, followed by operation of the electrolyser and after that operation of the power-to-heat plant. In case of shortages, the battery is discharged firstly and the CHP is operated next. The heat supply is ensured by the CHP and the power-to-heat plant, which can be supplied temporally by using heat storage system, decoupled from heat producer. In addition, heat supply can also be supported by a boiler.

3 Off-Grid Concepts

3.1 PtH$_2$ & H$_2$-CHP

In the Power-to-H$_2$ (PtH2) & Hydrogen CHP (H$_2$-CHP) concept (Fig. 3), electrical energy storage and coupling with the heat sector is achieved by generating hydrogen in an electrolyser from surplus electricity, storing the hydrogen and feeding it back

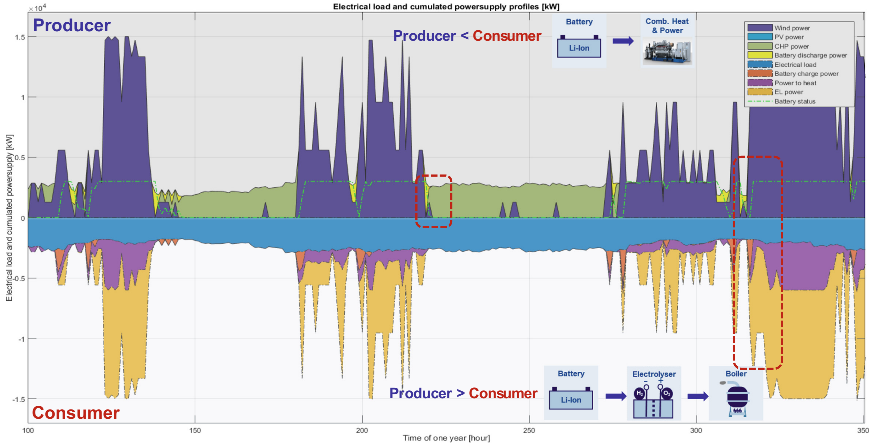


Fig. 2. Sample of power supply and energy storages performance of SI site

into electricity on demand in an innovative H_2-CHP unit. Optionally, it can further be combined with a battery storage system to achieve an optimal combination of short- and long-term storage.

3.2 PtCH$_4$ & CH$_4$-CHP

In the Power-to-CH$_4$ (PtCH$_4$) & Methane CHP (CH4-CHP) concept (Fig. 4), electrical energy storage and coupling with the heat sector is achieved by generating hydrogen in an electrolyser from surplus electricity, optional intermediate storage of the hydrogen, conversion of H_2 and CO_2 in a synthesis (also called methanation) to CH_4, and storage of the synthetic natural gas as well as demand-based reconversion to electricity in a conventional natural gas CH_4-CHP unit. The CO_2 is separated from the CHP exhaust gas with a CO_2 scrubber, stored, and then fed back to the synthesis. Overall, apart from slight loss, this concept can achieve a closed CO_2 cycle. The CO_2 losses can be compensated by slight use of external natural gas/biomethane.

3.3 PtCH$_4$ & CH$_4$-Oxy-CHP

The Power-to-CH4 (PtCH$_4$) & Methane-Oxygen-CHP (CH$_4$-Oxy-CHP) concept (Fig. 5) drives from the concept PtCH4 & CH4-CHP, besides the same components the CH_4 is fed back into an innovative Methane-Oxygen-CHP unit for a demand-oriented reconversion from natural gas to electricity. By combustion with pure oxygen, the exhaust gas of the CHP consists of water and CO_2, which can be stored after condensation of the water and then fed back into the synthesis (so called oxyfuel process). In this case, intermediate storage of the oxygen produced as a by-product during the electrolysis process is essential. The system contains no CO_2 scrubber due to the composition of exhaust gas. Apart from slight loss, a closed CO_2 cycle can be achieved. The CO_2 loss can be compensated by minor use of external natural gas/biomethane.

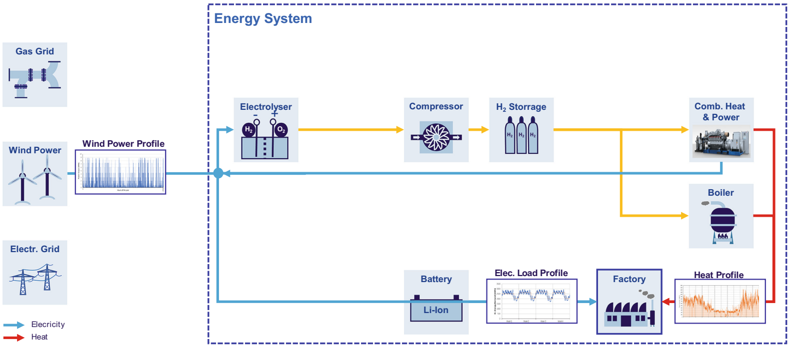


Fig. 3. Off-Grid concept with Power-to-H_2 & H_2-CHP

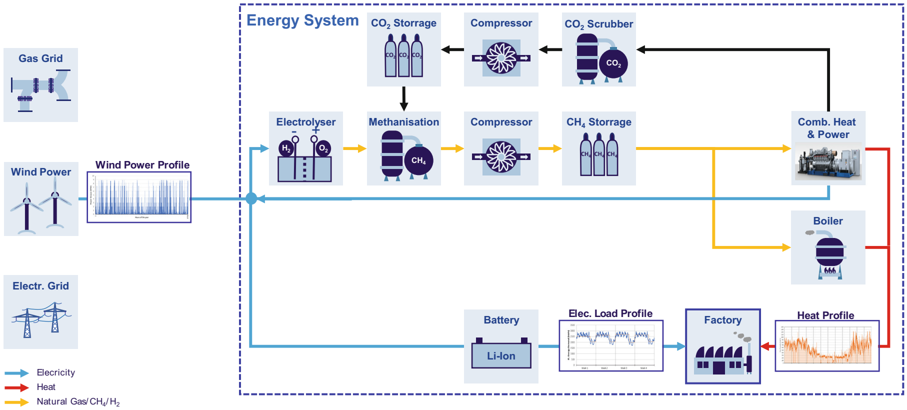


Fig. 4. Off-Grid concept with Power-to- CH_4 & CH_4-CHP

3.4 PtH$_2$ & H$_2$-Oxy-CHP

The Power-to-H_2 (PtH$_2$) & Hydrogen-Oxygen-CHP (H_2-Oxy-CHP) concept corresponds to a mixture of the PtH$_2$ & H_2-CHP and the PtCH$_4$ & CH$_4$-Oxy-CHP concept. Compared to the PtCH$_4$-Oxy concept, synthesis and CO_2 capture and storage are omitted. Only oxygen and hydrogen generated by electrolyser have to be stored and fed back into an Hydrogen-Oxygen-CHP (H_2-Oxy-CHP) unit (Fig. 6).

4 Results

The description for the selected results consists of the following parts. Firstly, the technical and economic simulation-investigations including the automated creation of variants, optimization of dimensioning and techno-economic evaluation for identifying the most economic variant are accomplished both for the selected industrial (SI) site and for the Karlsruhe harbour (KAH) with condition data of MethPower and MethGrid for the years 2022, 2030, 2040. Apart from this, the investigation for the selected industrial site with

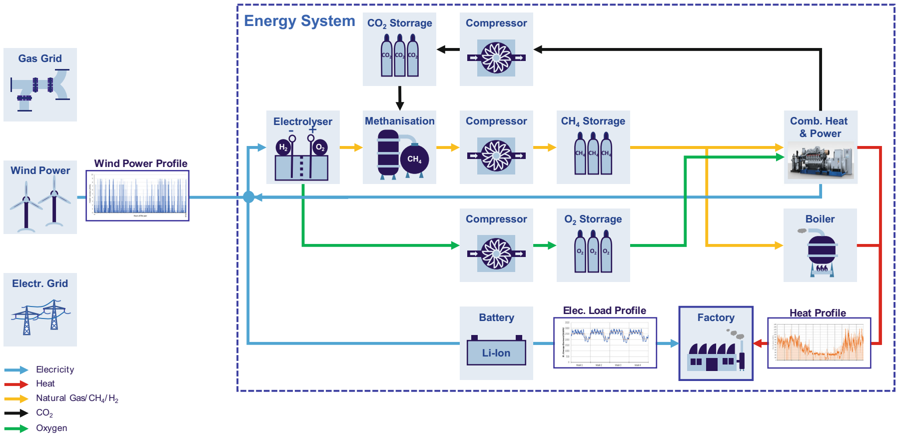


Fig. 5. Off-Grid concept with Power-to-CH_4 & CH_4-Oxy-CHP

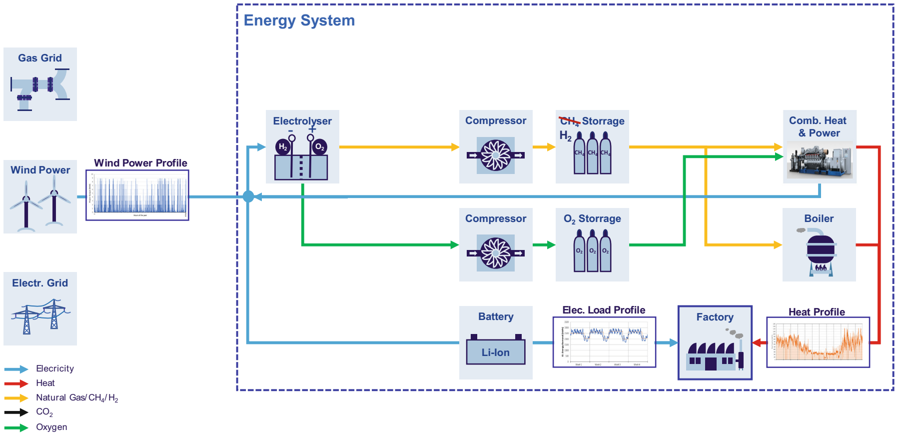


Fig. 6. Off-Grid concept with Power-to-H_2 & H_2-Oxy-CHP

internal condition data (load profiles and all parameters needed for conducting the investigation) has also been accomplished. Selected results of that are described subsequently below.

4.1 Results of SI Site with Internal Condition Data

In order to analyse the effects of intermittent power generation on the operation, design of the concepts and furthermore on the investment costs as well as the operating costs, the investigation for annual operation with a lifetime of 20 years is carried out by using the in-house developed tool, which can also optimize the system dimensioning. Based on these results, the defined PtX-CHP concepts are compared regarding their economic indicators.

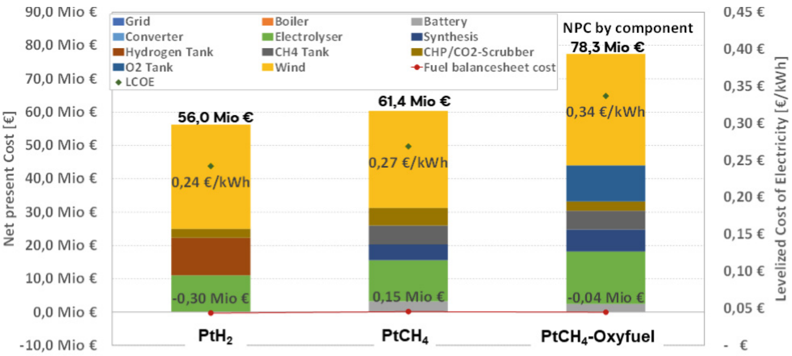


Fig. 7. Comparison of evaluated economic indicators of selected concepts for SI site

The PtX-CHP concepts have costs in a range of 55–63 million €. The costs are dominated by the required installation of wind energy. In case of the PtH_2 & H_2-CHP concepts, besides the electrolyser, the investment costs of the hydrogen storage system are particularly significant. In contrast, the costs of methane and CO_2 storage are significantly lower in case of the $PtCH_4$ & CH_4-CHP concept. Overall, the costs of H_2 storage and H_2-CHP combined are similar to the price of CO_2 storage, CH_4-CHP with CO_2 capture and synthesis combined in case of $PtCH_4$ & CH_4-CHP concept. The $PtCH_4$ & CH_4-Oxy-CHP concept suffers from low engine efficiency compared with other concepts. O_2 storage costs added, the NPC of $PtCH_4$ & CH_4-Oxy-CHP concept is much higher than PtH_2 & H_2-CHP and $PtCH_4$ & CH_4-CHP concept, which leads to that this concept within the scope of the investigation has not been further considered (Fig. 7).

In contrast, approximately only half of O_2 storage capacity is required for the PtH_2 & H_2-Oxy-CHP concept compared to the $PtCH_4$ & CH_4-Oxy-CHP concept due to the combustion stoichiometry (lower stoichiometric O_2 demand for H_2) and the higher efficiency of the PtH_2 & H_2-Oxy-CHP, separately shown in the Fig. 8. The PtH_2 & H_2-Oxy-CHP concept could therefore achieve similar NPC as PtH_2 & H_2-CHP.

The relations of the NPC are also reflected in the LCOE Fig. 8. The on-grid industrial electricity price is in the range of 12–15 ct/kWh before 2022. In combination with Power-to-Gas (PtG) CHP and battery, the LCOE of an off-grid solution can reach 24–28 ct/kWh, which is already in the scale of household's electricity price. And the concepts can become even more competitive due to a most likely rising market electricity price. The results show the potential of combining short-term storage via battery and long-term storage in the form of H_2, CH_4.

The PtH_2 & H_2-CHP, $PtCH_4$ & CH_4-CHP and PtH_2 & H_2-Oxy-CHP concept have similar LCOE. In case of $PtCH_4$ & CH_4-CHP, the costs of CH_4 storage are much lower than the costs of H_2 storage, which leads to the similar LCOE. In case of PtH_2 & H_2-Oxy-CHP, the additional costs of O_2 storage can be compensated by the expected higher efficiency of the H_2-Oxy-CHP compared with H_2-CHP (Fig. 8).

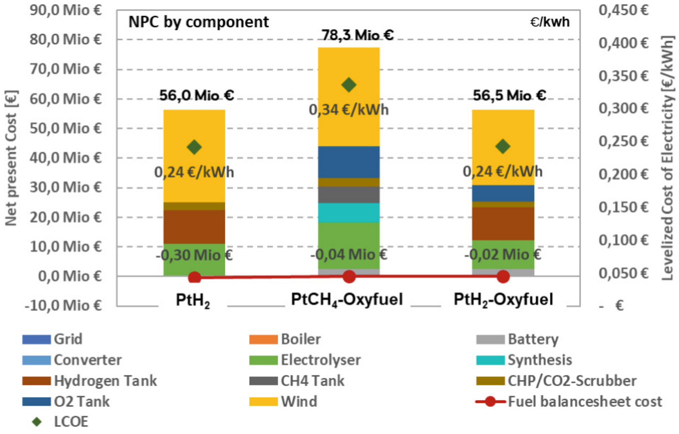


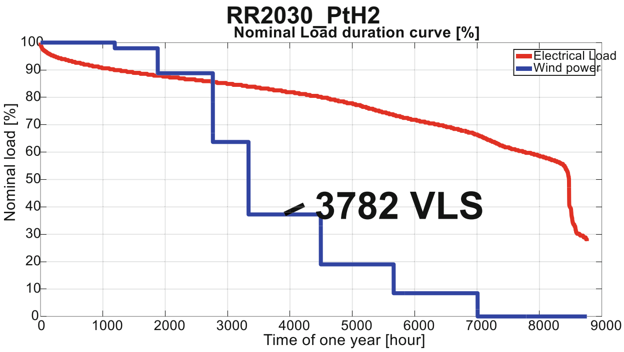
Fig. 8. Comparison of evaluated economic indicators of PtH_2 & H_2-CHP, $PtCH_4$ & CH_4-Oxy-CHP, PtH_2 & H_2-Oxy-CHP for SI site in the year 2030

4.2 Results of KAH Harbour with Condition Data of MethPower, MethGrid

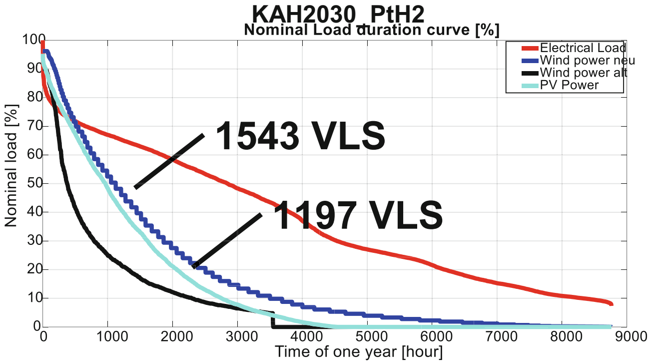
The same approach as for the SI site is also applied for KAH harbour. Unlike SI site as a good wind location, the KAH harbour is a medium wind location. This is obvious when analysing the wind energy full load hours of both locations as shown in Fig. 9. At the SI site the wind energy full load hours is almost 3800 h, in contrast to this the wind energy full load hours at KAH harbour can only reach 1543 h, less than half of the value of SI site. However, at the KAH harbour PV energy can be more utilized. Therefore, a system design incorporating both wind and PV energy can realize a self-sufficient microgrid system.

Due to the load profile of Karlsruhe harbour with a daily peak power around midday, a combination of PV and wind energy is found to be an optimal solution for supplying the system power demand. The good time correlation of PV electricity generation overcompensates the higher investment costs in PV per peak power compared to wind energy at a non-ideal wind location (Fig. 10).

The NPC and the LCOE of the individual concepts applied on both SI site and KAH harbour for the years 2022 2030 2040 respectively are summarized in Fig. 11. For comparison, the NPC and LCOE of electricity supplied by industrial grid is also added. The results show that the PtH_2 and $PtCH_4$ concepts could achieve LCOE in identical order of magnitude. However, it must be mentioned here that in case of $PtCH_4$, electricity storage is mainly realized by battery storage and not by the $PtCH_4$ concept. Overall, the LCOE of over 40 ct/kWh are significantly higher than the electricity purchasing prices of industrial grid in Germany before 2022 that is in the range of 17–27 ct/kWh [2], which should have been reduced by the relief of the EEG tariff based on the previous prediction. (Aiming to financing the expansion of PV, wind, biomass and hydroelectric power plant, EEG tariff was introduced in 2000. Until now, it has been levied on end customers via their electricity bills [3]). On the one hand this is due to the only middle quality of the location's wind energy, and on the other hand due to the targeted scenario



Industrial location (RR) with base load power demand and good wind location, no PV



Karlsruhe harbor with medium load power demand and medium wind location, PV has good correlation to power demand

Fig. 9. Wind and solar power full load hours at SI site and KAH harbour

of self-sufficiency i.e. off grid operation Fig. 11. However, the LCOE of $PtCH_4$ is also becoming more competitive with the rising electricity purchasing prices of industrial grid in Germany since 2022 considered, which has been rising into the range of 40 ct/kWh since July 2022 [2].

4.3 Summary of Results

The $PtCH_4$ & CH_4-CHP concept has a lower efficiency and a significant higher complexity of the whole process. This is due to the CO_2 capture and synthesis. The two oxyfuel concepts require a completely new development of the CHP unit for combustion with oxygen. In contrast, the H_2-CHP can be developed based on the conventional

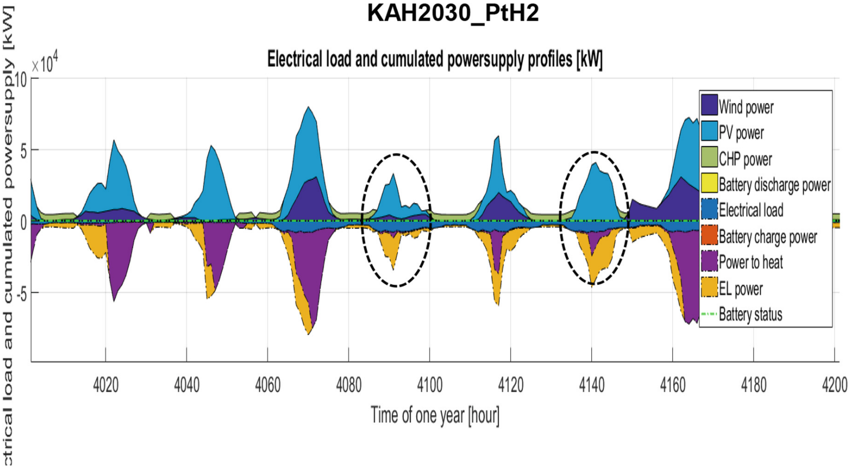


Fig. 10. The selected part power performance of KAH harbour

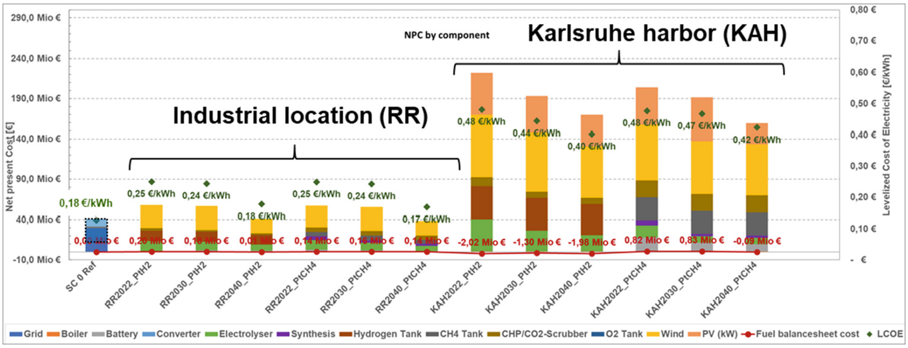


Fig. 11. Comparison of evaluated economic indicators of selected concepts for SI site and KAH harbour for 2022 2030 2040

natural gas CHP. While the PtH_2 & H_2-Oxy-CHP concept shows the thermodynamic potential of higher efficiency, which however would still have to be confirmed for the real engine concept, the $PtCH_4$ & CH_4-Oxy-CHP concept shows a significant lower efficiency. Overall, the PtH_2 & H_2-CHP concept illustrates the most of advantages due to its high efficiency and the simple process, whereby the costs of the hydrogen storage for a long storage period could lead to the $PtCH_4$ & CH_4-CHP concept becoming competitive. In addition, the PtH_2 & H_2-CHP concept is expected to have a very good dynamic of the overall process, while especially for the $PtCH_4$ & CH_4-CHP concept, a dynamic operation would be a technical challenge due to its synthesis and CO_2 capture. Another advantage is that the PtH_2 & H_2-CHP concept can be developed based on the existing natural gas CHP technology. Considering the reasons mentioned so far, the PtH_2 & H_2-CHP concept is recommended as the most promising concept for SI site. For KAH harbour, a self-sufficient i.e. off-grid concept can be realized by incorporating wind and PV energy, nevertheless, it might be not the most promising concept due to its higher LCOE resulted by the high electricity demand and the local medium available wind energy, comparing the electricity purchasing prices of industrial grid before 2022. However, it might become competitive due to the current rising electricity purchasing prices since 2022.

5 Conclusion

Within this work, the Self-sufficient (Off-Grid) microgrids incorporating renewable energy sources, Power-to-X and Combined Heat and Power (CHP) are created and investigated. The Method, operating strategy and toolchain for automated creation of variants, dimensioning, technical-economic evaluation as well as optimization have been in house developed and applied for the selected industrial site and Karlsruhe harbour. Rolls-Royce Solutions GmbH is able to create, evaluate and optimize system solutions according to customer requirements and conditions.

Renewable energy potential of a location has big impact on competitiveness of a renewable Power-to-X & X-CHP microgrid concept. The PtH_2 & H_2-CHP concept achieving competitive LCOE is recommended as the most promising technology variant of the investigated concepts for further development for the selected industrial site. The concepts incorporating wind and PV energy applied for Karlsruhe harbour can achieve self-sufficient (off-grid) operation, however their competitiveness depend on the change of electricity purchasing price of industrial grid. Furthermore, it turns out that the ideal solution for a given site depends strongly on the concrete boundary conditions, thus emphasizing the need for a customer specific system optimization.

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