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Research Article

Evaluation of the techno-economic aspects and sustainability of integrated renewable energy systems

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Abstract: With the transformation of the energy sector from big centralized grids and fossil fuel power stations to local interconnected grids based on renewable energy sources, accessibility to dependable energy resource is important for residential and commercial purposes. Due to the fluctuations in wind and solar energy available multiple energy sources as well as appropriate storage is needed to generate affordable electricity and heat for residential and industrial purposes. The benefits of hybrid solar and wind power with battery and hydrogen energy storage-are investigated. The study focuses on a specific location, in Lemgo, Germany under the name of KraftwerkLand, which is a pilot plant with 5 kW_p photovoltaic solar panels, 5 kW wind generator and several energy conversion technologies. In the present work, an analysis with regard to the economic viability and environmental sustainability using RETScreen is performed in KraftwerkLand as a case study. The possibilities to virtually transfer the installation to other locations is shown. Combined renewable energy sources coupled with appropriate energy storage providing local energy grids are an economic environmental friendly and economically viable solution.

Keywords: *Economic assessment, Energy storage, Renewable energy, Sustainability*

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1. INTRODUCTION

1.1. Renewable Energy Systems

The transition of the energy system from fossil fuels to renewable energy poses a big challenge. The hierarchic centralized energy grids established in industrialized countries and the segregation of the energy sectors and forms (electricity, heat and fuels) is replaced by decentralized energy grids with a strong sector coupling, integration of hubs and smart storage systems. In developing countries the energy supply for locations, which are not connected to an energy grid is ensured by local renewable energy resources. The utilization of this off-grid systems replace fossil fuel plants and prevent carbon dioxide emissions. In order to achieve a successful transition these decentralized renewable energy systems have to be sized in an optimal and reliable way. In addition, experience under operating conditions is needed.

Makalesi et al., [1] analyze a mountain house in Sakarya, Turkey mainly powered by renewable energy resources. Power generating systems like wind turbine, PV (photovoltaic), diesel generator and battery are considered in different configurations and a technical and economic analysis is performed and an optimal configuration is found. The most important parameters are wind speed and solar irradiation. Dursun et al., [2] present a techno-economic analysis of hybrid renewable energy systems to supply the electrical load requirements of a nursing home in Istanbul, Turkey. The standalone systems are considered in the analysis comprise different combinations of PV panels, fuel cells, and wind turbines supplemented with hydrogen storage. An optimal configuration of hybrid renewable energy systems is found taking total net present cost and cost of energy into consideration. Jahangir et al., [3] present a hybrid renewable energy system consisting of PV panels, wind turbines, and biogas generator for rural electrification in Fars province, Iran. The system is optimized and a sensitivity analysis is performed. Compared to a coal based power plant, the greenhouse gas emissions are negligible and economically more advantageous. Yang et al., [4] explore a hybrid renewable energy system, including PV, concentrated solar power, wind power, battery, electric heater and bidirectional inverter. A multiple-objective optimization is performed to obtain the optimal combination of power plants and energy storage devices and an appropriate operation strategy of the coupled system. Relying on the distinct characteristics of these technologies very efficient and effective solution can be achieved. Razool et al., [5] propose hybrid wind and photovoltaic generation systems as an effective means of providing power to remote and off-grid areas of developing countries. Wind turbine, photovoltaic, battery bank and converter for the electricity are optimized for the Mander rural community, Iraq. Chaichan et al., [6] optimize a stand-alone and grid-connected hybrid power generation systems for the green island Koh Samui, Thailand. A techno-economic optimization analysis is applied showing that a 100% renewable energy-based microgrid system is possible and a hybrid renewable energy system incorporating solar and wind power is an economical feasible solution. In a different work, Hasan [7] analyzes the cost of solar/wind hybrid power-based hydrogen production for different system configurations at the sites in Basrah, Wasit and Anbar, Iraq. The maximum hydrogen capacity strongly depends on the location, with Basrah having the highest potential. Various wind turbines operated at different hub heights integrated with two different solar panels and electrolyzers having different rated power are considered in the analysis. Algubri et al., [8] assess the feasibility and efficiency of green hydrogen production on an industrial scale using solar and wind energy in Diyala city, Iraq based on the weather data for 2022. An optimization with regard to the equipment size is performed. Here the solar-based green hydrogen production is more advantageous then wind-based methods. Amoussou et al., [9] look into replacing a heavy fuel oil thermal power plant in Limbe, Cameroon, with a hybrid photovoltaic and wind power plant combined with a storage system consisting of lithium batteries and hydrogen associated with fuel cells. The total cost of the project over its lifetime is minimized in this single-objective optimization problem. An optimum is achieved by incorporating all proposed power generating and storage technologies appropriately sized. Al Rawashdeh et al., [10] use a hybrid renewable-energy system to convert a facility (hotel) into a green building in Petra, Jordan. The grid connected hybrid system simulated includes solar photovoltaic, a wind turbine, a diesel generator and a converter. Using all these components a financial attractive significant reduction in green house gas emission may be achieved. Boubie et al., [11] propose an advanced control system to ensure the grid stability when connected to a combined solar and wind power energy generation. It addresses the fluctuations inherent in photovoltaic and wind power sources integrating dynamic modeling with a sophisticated control mechanism.

These studies focus on the renewable generation of hydrogen as an energy carrier or on the power supply for weakly developed grids i.e., in emerging and developing countries. Nevertheless this approach is also interesting with regard to the transition to renewable energy in developed countries. Here, especially in rural areas, it is possible to satisfy the demand, due to the availability of the space and the resources needed for the generation of renewable energy. The centralized hierarchical power grids based on big fossil power stations are replaced with smaller, local and decentralized renewable power grids. These intelligent grids will facilitate the coupling of the different energy sectors and the transition from producer and consumer to prosumer. Centerpiece of these local grids in rural areas are hybrid renewable energy systems.

Figure 1. Experimental power plant "KraftwerkLand" near Lemgo, Germany

1.2. Experimental Power Plant "KraftwerkLand"

In order to analyze the performance of hybrid renewable energy systems and collect experimental data a pilot plant was designed and built. The experimental power plant "KraftwerkLand" (rural energy plant) is a multiple rural energy generation and storage system in operation since 2022 (Fig. 1). The generation of renewable energy and its conversion and storage for rural areas are explored. The containerized plant is flexible and mobile and may be located at different spots and integrated in existing energy system. The components are clearly shown in Fig. 2.

Renewable energy is generated by a 4.5 kW wind turbine and a 5 kW_p solar panel. As a short term buffer the electric power is stored in a 10 kWh lithium-ion battery. As long term storage, the electric power is used by a 5 kW AEM (anion exchange membrane) electrolyzer to generate hydrogen, which is transferred to a tube bundle at 35 bar. This hydrogen may be used in a 8 kW_{el} fuel cell for producing electric power, in a biogenic methanation reactor with carbon dioxide to generate methane or alternatively to generate methanol bay a catalytic reaction. to generate methanol. The generated gas may be transferred to the gas grid. The fuels may be used in the mobility sector or for domestic or industrial heating. Different profiles for energy consumers can be implemented. The generated power may also be transferred to the electric grid. The components used are of industrial grade size, similar to those used in actual projects. Thus the results of the field tests are of relevance for industrial projects.

For wide deployment of such hybrid renewable energy systems, they must be economically feasible and environmentally advantageous. The prediction of the system performance in the planning phase is important for an accurate assessment. This can be achieved with an appropriate virtual model. Using this virtual model, different scenarios can be compared. Here the development and the applicability of such a virtual model is analyzed. As a means to chemically store the renewable energy generated, only the hydrogen pathway is considered. The generated heat is not used. Energy is consumed by the laboratory equipment and the office installed.

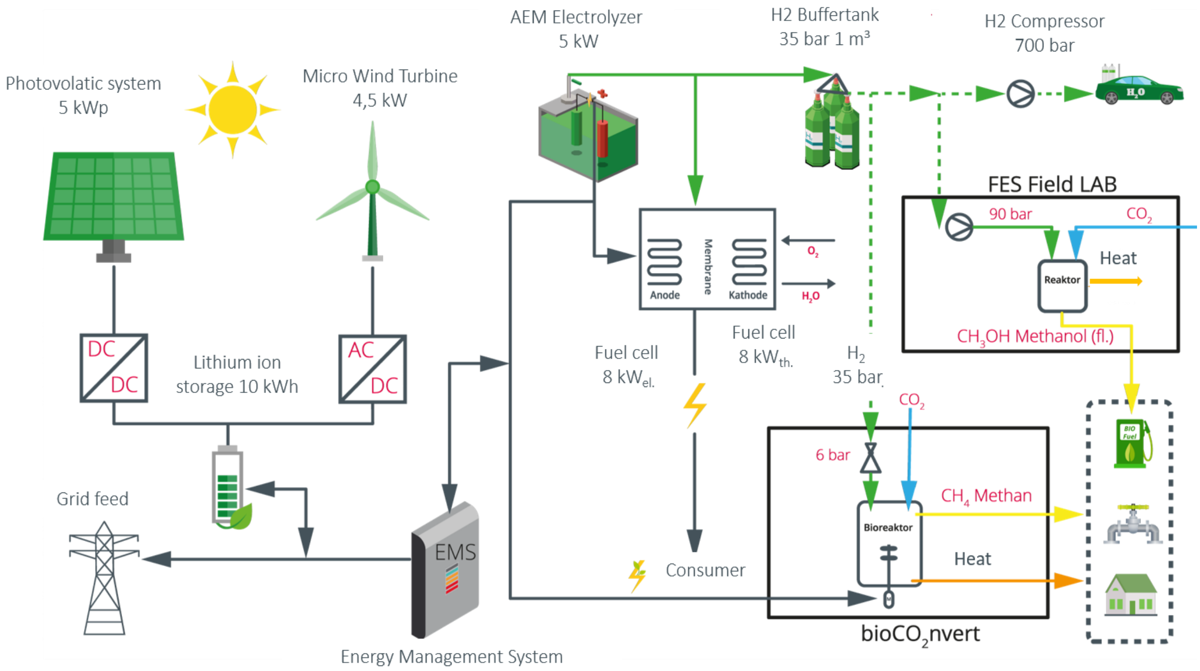

Figure 2. Schematic model of experimental power plant "KraftwerkLand". Installed conversion paths in the Power-to-X pilot plant. Note that the FES-Fieldlab and bioCO₂nvert pathways are not considered in the present work.

2. METHODS

In addition to the measurements in the pilot power plant, a virtual representation using physical models is developed. These models are validated by the measured values. With these models a technical design and optimization may be done, but also an economic and environmental assessment. In this analysis RETScreen is used as a tool. RETScreen is an integrated software platform developed by the Ministry of Natural Resources of Canada. The software allows for the comprehensive identification, assessment and optimization of the technical and financial viability of potential renewable energy projects [12].

2.1. Modelling Approach

The software modules of RETScreen are used as implemented and are described briefly in the following. Worldwide ground-based meteorological data are incorporated directly into the software as well as performance data for a variety of technical equipment. If the data needed is not implemented in the software it may also be provided and input by the user. For the "KraftwerkLand" model used in this study photovoltaic panels, wind turbine, battery, electrolyzer, fuel cells and hydrogen storage are taken into account. This system is connected to the electric grid.

2.1.1. Photovoltaic power

Photovoltaic systems have relatively few system components with a complex interaction and a non-linear behavior. RETScreen uses simplified algorithms to minimize data input requirements and to speed up the calculations, while maintaining an acceptable level of accuracy. The photovoltaic array model takes into account temperature and orientation effects. With the concept of daily utilization, the part of the load that can be met directly by the photovoltaic power is determined. Correlations derived from hourly computer simulations are used to assess how the battery can provide for the rest of the load [12].

As a first step the hourly global and diffuse irradiance on a horizontal surface for all hours of an "average day" having the same daily global radiation as the monthly average are computed for the geographic location chosen based on the weather data available. Then the hourly values of global irradiance on the tilted surface for all hours of the day are computed and summed up to obtain the average daily irradiance in the plane of the photovoltaic array. The array is characterized by its average efficiency which is a function of the average module temperature. The average module temperature is computed depending on the solar module type and the ambient temperature. Corrections are used to take into account the tilt angle and photovoltaic array losses. Energy from the array is either used directly by the load, stored in the battery and the remainder is available to the grid. The inverter is equal to the nominal array power. Appropriate values for battery and inverter efficiency are used [12]. Due to the data available from the solar panel manufacture, the panel performance is modelled with good accuracy, if the irradiation is given and the orientation of the panel is considered. The weather data for the nearby region, i.e. from weather stations, is sufficient, as solar irradiation does not depend as strongly on the immediate location as the wind velocity.

2.1.2. Wind power

The energy production from the wind turbines is calculated based on the unadjusted energy production, which is the energy that one or more wind turbines will produce at standard conditions of temperature and atmospheric pressure. The calculation is based on the energy production curve of the selected wind turbine and on the average wind speed at hub height for the proposed site. The production curve is specific to the selected wind turbine [12].

Wind speed distribution is calculated as a Weibull probability density function. This distribution is often used in wind energy engineering, as it conforms well to the observed long-term distribution of mean wind speeds for a range of sites. The Weibull probability density function expresses the probability to have a wind speed during the year, with the parameters shape factor and scale factor. The shape factor will typically range from 1 to 3. For a given average wind speed, a lower shape factor indicates a relatively wide distribution of wind speeds around the average while a higher shape factor indicates a relatively narrow distribution of wind speeds around the average. A lower shape factor will normally lead to a higher energy production for a given average wind speed. The scale factor is a measure for the characteristic wind speed of the distribution, which is calculated from the average wind speed value and the gamma function [12].

The energy curve data is the total amount of energy a wind turbine produces over a range of annual average wind speeds. It is specified over the range of 3 m/s to 15 m/s annual average wind speed. The wind turbine power curve data is either taken from the RETScreen database or entered by the user [12].

The model uses the wind turbine power curve and the Weibull probability function described. This unadjusted energy production is the energy produced by the turbines at standard conditions of temperature and atmospheric pressure. The calculation is based on the average wind speed at hub height for the proposed site, which usually differs significantly from the wind speed measured at anemometer height due to wind shear, and is modelled using a power law equation with the wind hear exponent. The wind shear exponent varies with the terrain, i.e. between 0.1 for open water (smooth) or 0.3 for buildings, vegetation, heights (rough). The renewable energy delivered is computed from the unadjusted energy production taking into account atmospheric pressure and temperature conditions at the site and including various losses [12].

As the energy generated by the wind turbine is strongly dependent on the wind speed distribution its correct assessment is essential for an accurate estimation of the wind power. With lower wind turbine heights, the variations of the wind speed due to the influence of the immediate location and surroundings gets bigger and an accurate prediction is only possible with wind data taken at the location at the corresponding height. A prediction based on wind data from weather stations is difficult and often inaccurate.

2.1.3. Economic assessment

The decisive factor for the realization of clean energy projects is the financial feasibility. Based on the technical specification of the equipment needed and the input of various financial parameters the key financial feasibility indicators, such as internal rate of return, simple payback, net present value may be calculated. The approach is based on standard financial terminology; the computations are performed on yearly bases [12].

Revenue is generated by the surplus power fed into the grid. If the generated and stored power does not suffice it has to be procured, generating a cash outflow. The Return on Investment (ROI) is a measure used to evaluate the profitability of an investment. In the context of renewable energy power plants, ROI indicates how long it takes for the savings generated by the energy produced to cover the initial costs of installing the plant. In the plant considered here, in addition to the renewable power generation, which may operate profitable, an additional hydrogen infrastructure for conversion (electrolyzer and fuel cell) and storage (tank bundle and compressor) is implemented, which is very expensive.

2.1.4. Environmental assessment

Based on the technological conditions the greenhouse gas emission reduction potential of a proposed clean energy project is assessed. The greenhouse gas emission of the clean energy project is computed and compared to the greenhouse gas emission of a base case system corresponding to an energy generation based on the state of the art, i.e., with fossil fuels. The methodology implemented in the RETScreen software to calculate these emissions has been developed in collaboration with international organizations and has been validated by a team of experts from government and industry [12].

2.2. Implementation

2.2.1. Photovoltaic system

For the photovoltaic system, the orientation of the modules and the number of modules is recorded. The relevant monthly climate data is taken form the RETScreen data base. All data related to the used solar modules can be imported from the product database in RETScreen, the efficiency of the inverters are supplemented. The annually projected generated electricity is computed and can be used for a comparison with measured data as well as an economic and environmental analysis.

2.2.2. Wind generator

For the wind turbine the characteristic curve of the manufacturer is implemented, the wind data for the nearest weather station available is used. Thus the energy generated by the wind turbine may be predicted. Using this approach, there is a significant deviation of measured and predicted values. The wind is very much dependent on location, thus the wind data used for prediction is adapted: the mean wind velocity is changed to the mean value at the actual location. The vegetation and buildings in the surroundings are significant as they are near the wind turbine and of similar height as the mast of the wind turbine, thus the wind shear exponent is set to 0.4. Using this approach the influence of the immediate vicinity can be taken into account and the predicted and measured values are in much better agreement.

2.3 Analysis

The climate data is used as an input into the model to predict the amount of energy generated by wind and solar power. Using the load profile of the consumers and the capacity of the electrolyzer the amount of energy consumed and stored is determined. The amount of energy stored as hydrogen is no limiting factor as sufficient tank capacity is available. The computed data of the generated energy is compared to the measured data at “KraftwerkLand”, which was registered in the course of the year 2023.

The influence of the climate data is assessed by virtually moving the “KraftwerkLand” from Lemgo to other locations and performing an analysis for these additional plant. The geographic locations taken into account are shown in Fig. 3.

Figure 3. Three different geographic location chosen for analysis: Lemgo in Germany, Bergen in Norway, Palma de Mallorca in Spain.

The corresponding weather data for the potential of generating renewable energy are shown in Table 1. In the cold months, the renewable energy may be generated mainly by wind, in the hot months it is mostly solar energy. Here the chosen locations differ strongly with regard to the solar energy available. Lemgo has 1700 sunshine hours with a solar radiation of 1079 kWh/m^2 over the year. The wind is relatively strong for an inland location, in the cold months the average velocity is slightly bigger than in the warm months. The average wind speed for the nearby weather station in Bad Lippspringe is 4.9 m/s. Bergen is one of the least sunny cities in the world. Due to the coastal location there is more wind available, which is stronger in the cold months. Palma has significantly more sunshine hours and solar radiation as the other locations. In the summer months, the wind speed is lower than in the rest of the year.

3. RESULTS

3.1. Validation

Over the year 2023 the performance of the “KraftwerkLand” located at Lemgo was analyzed: The energies generated by the solar panels and the wind turbine as well as the amount of energy stored and the energy transferred to and from the grid are recorded. The measured data is compared to the computed values by the virtual model. The predicted and measured values for solar power are in very good agreement. The predicted and measured values for wind power differ strongly. As a basis for the prediction the Weibull distribution of the wind velocity from the weather station in Bad Lippspringe near Lemgo is used and adjusted to the mean wind velocity at the location using data at 50 m height. The Weibull distribution is then adjusted to the wind turbines height 10 m. The wind power predicted in this way and the recorded wind power differ strongly. The wind distribution is strongly influenced by the surroundings, which is not ideal for small wind turbines: There are nearby buildings and vegetation (see Fig. 1). This influence has to be taken into account by adjusting the shear factor in the logarithmic boundary layer distribution of the wind. Using this adjustment the wind power can be predicted with sufficient accuracy. Thus, it is essential for the prediction of the wind power to make an adjustment for the actual location and influence of the surroundings or to use measured wind data at the location.

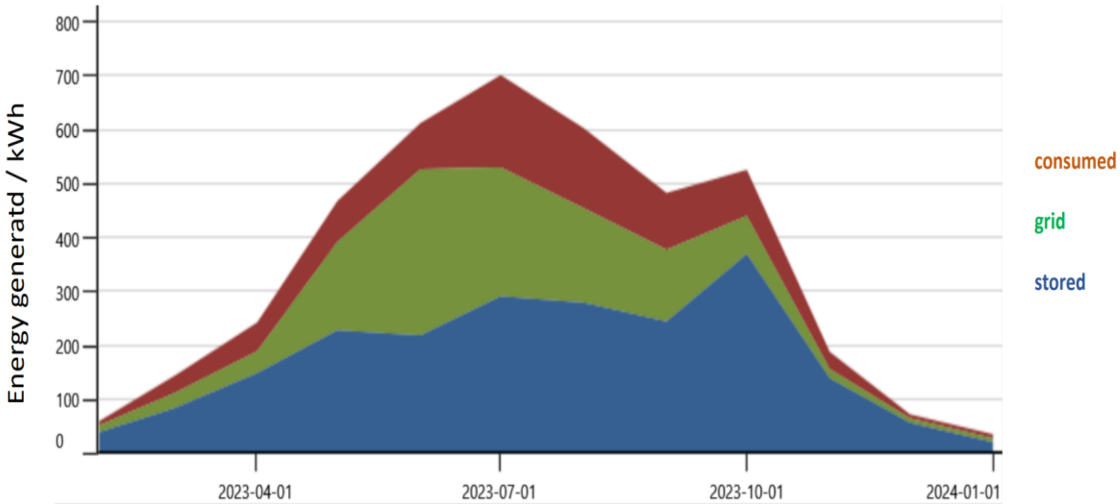

Figure 4. Energy generated in the course of the year 2023 in Lemgo, Germany. Amount of energy consumed, stored and grid feed-in.

3.2. Lemgo

Energy is generated by wind and solar power. Due to the seasonal variations of the renewable energy available, the most energy is generated in the summer months. The amount of energy consumed, stored and transferred to the grid is shown in Fig. 4. Here the amount of energy stored (as hydrogen) is building up in the warm months and is then consumed in the cold months. Peaks in energy production which are not consumed and cannot be stored as the maximum capacity of the electrolyzer is reached are transferred to the grid. In some instances the renewable energy generated does not suffice for the peaks in the energy demand, thus in addition to the battery storage energy is also imported from the grid. For the computations the electricity in the grid is generated mainly by fossil fuels.

3.3. Bergen

The total amount of energy generated does not vary strongly. The most part of renewable energy is generated by wind. The lower wind speeds in the warm months are compensated by solar power. Due to the higher amount of wind energy the energy generated is bigger than in Lemgo. The electricity in the grid is mainly renewable.

3.4. Palma

The most energy is generated by solar power. A sizeable amount of wind energy is only available in the winter months, so that the drop in solar energy is partly compensated. Due to the higher amount of solar radiation the energy generated is bigger than in Lemgo.

Table 1. Geographic locations and renewable energy generated by pilot plant.

Location	Solar Power	Wind Power	Total Power
Lemgo	4029 kWh	2818 kWh	6847 kWh
Bergen	3427 kWh	4955 kWh	8382 kWh
Palma	1042 kWh	6774 kWh	7816 kWh

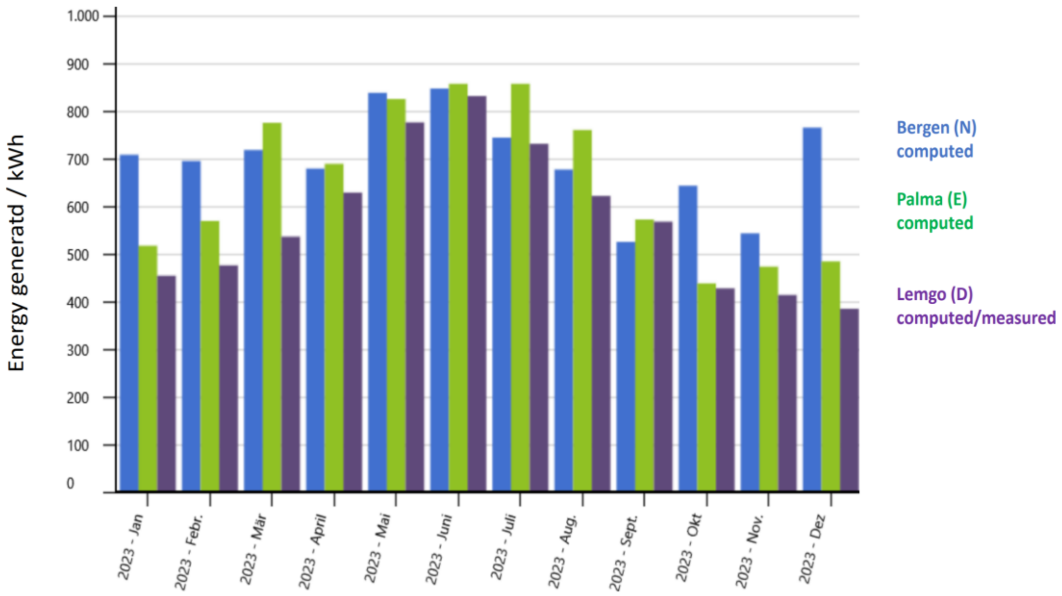

Figure 5. Comparison of energy generated for three different locations: Bergen, Norway, Palma de Mallorca, Spain and Lemgo, Germany.

3.5. Comparison

The amount of energy generated at the three locations in the course of the year 2023 is shown in Fig. 5. In Table 1, the energy generated by solar and wind power for the three locations is compared. Using the same equipment, the energy generated at the different locations may vary strongly. There are also strong differences with regard to the variation in the energy generated over the course of the year. In locations with strong solar radiation, i.e. Palma, the most renewable energy is available in the warm months, in locations with strong wind, i.e. Bergen, the most energy is available in the cold months. The location in Lemgo may not be ideal with regard to the amount of renewable energy generated, compared to the more sunny and windy locations. Nevertheless, for the local energy demand there seems to be no feasible alternative as the local generated renewable energy.

For wind power the highest amount of energy generated is typically in December, the lowest amount is typically in June. For solar power, the situation is vice versa, i.e., the highest in June and the lowest in December. Thus for a maximum yield of renewable energy the amount of solar and wind power generated and thus the site of the equipment has to be adjusted to the local conditions at the actual location. The size of solar panel and wind turbine used in this study is not optimal for the locations considered. As the amount of energy generated at the different locations is of similar order of magnitude, an optimum design would yield more energy but also of similar order of magnitude.

Table 2. Geographic locations and annual savings and revenue

Location	Annual Revenue
Lemgo	1957 €
Bergen	1747 €
Palma	2957 €

The annual revenue resulting from the net electricity fed into the grid for the different locations is shown in table 2. It correlates with the amount of energy generated. The hydrogen storage is the most expensive part of the investment, amounting to 50,000 € – 100,000 € per installed Kilowatt storage system. As the revenue is less than 1 % of the investment, these power plants do not represent a lucrative business case, nevertheless their implementation may be economically feasible, if the cost of installation is not taken into account. The benefit lies in the utilization of renewable energies and the reduction of greenhouse gas emissions. The return on investment may be more significant as the system is optimized for the consumer profile and the weather data at the location and when in the future the equipment costs (i.e. especially for electrolyzer and fuel cells) will decline.

Table 3. Geographic locations and greenhouse gas (GHG) emission reduction in CO_2 equivalent.

Location	GHG Emission Reduction
Lemgo	2.8 t CO_2
Bergen	0.05 t CO_2
Palma	2.6 t CO_2

The reduction in greenhouse gas emissions as carbon dioxide (CO_2) equivalent for the three locations is shown in Table 3. It depends on the renewable energy generated and the share of renewable energy in the local grid. With the biggest share of fossil fuels, the greenhouse gas emissions is biggest in Lemgo, and with green electricity in Bergen, the reduction there is negligible. Considering the price of EU emissions allowance (i.e. 50 €/t - 100 €/t CO_2) would not significantly increase the profitability. The reduction of greenhouse gas emissions is a goal in itself.

4. DISCUSSION

The optimum design depends on the amount of renewable energy available as well as on the energy demand. As the results show, the performance is strongly influenced by the weather data and in the case of the wind power by the surface roughness of the surrounding landscape. The prediction of energy data is reliable for solar power. The prediction of wind power is more demanding as it is strongly influenced by the direct surroundings of the location, which cannot be represented by the weather data base. Here an adjustment with regard to the shape and the roughness of the surrounding terrain is necessary.

Nowadays the realization of renewable energy systems is not yet interesting as a financial investment. The benefit lies in the avoidance or reduction of greenhouse gas emissions. Thus the implementation is most interesting for the transition of grids based on central fossil fuel power plants to decentralized renewable energy grids and for off-grid applications.

5. CONCLUSION

The experimental power plant “KraftwerkLand” near Lemgo, Germany was put into operation and performance data gathered during the first year of operation 2023. The operation of a hybrid renewable energy system as a cornerstone of a developing intelligent decentralized renewable energy grid is analyzed. The use of hydrogen as an energy carrier for seasonal energy storage is not economically feasible yet.

A model for the renewable energy power and storage plant has been developed. The model is validated against measured data. This model can be used to compute the generated electrical energy. Based on these results, the environmental impact and financial feasibility may be assessed. As a further step an optimization with regard to the appropriate sizing of PV-panels, wind turbines and storage equipment may be performed. Wind power is more sensitive to the surroundings of the location than solar power. This has to be considered in the preliminary design phase. Renewable energy systems have to be adjusted to the consumer profile as well as the renewable energy available on site. These factors strongly influence an optimum dimensioning of the equipment.

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