A Contrast Study of Climate Influence on the Stand-Alone Microgrid System with a Hybrid Renewable Power Storage System

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Abstract— **In the efforts to combat global warming, diversified social, political and technical strategies have been proposed and partially carried out. The vision to have a 100% renewable energy-based electricity system has been one of the long-term strategies in Germany. It is well known that renewable energy can only be utilized to the full extent when its down-side characteristics of intermittency and variability can be compensated by a practical storage system. Due to its long-term storage capacity in comparison to the battery storage, in recent years, hydrogen storage system has been undergoing a technological development and deployment boom, especially for the microgrid systems. This research evaluates the techno-economic feasibility of a 100% hybrid renewable energy-based system with different scenarios of energy storage systems for an off-grid microgrid system in two distinct climate regions within Germany, namely Hamburg and Munich. The "HOMER Pro" software was used to analyse the economic and environmental impact amongst the case studies. The aim of this theoretical study is to answer the questions: 1) Under different climate conditions which type of energy storage (i.e. battery, hydrogen tank, and hybrid battery-hydrogen tank) can offer the overall flexibility and economic advantages? 2) For a specific climate condition, how is the hybrid storage system deployed to achieve the optimum cost-effective scenario?**

Keywords-hybrid renewable power; hybrid community energy storage; power to hydrogen to power; stand-alone microgrid; climate influence.

I. INTRODUCTION

Until the end of 2020 the observation shows that each of the last four decades has been successively warmer than any decade that preceded it since 1850 [1]. Many changes in the climate system are in direct relation to increasing global warming. It is unequivocal that human-induced climate change is already affecting many weather and climate extremes across the globe, which in turn causes huge damages to our life. Therefore, governments around the world are taking a variety of measures to reduce the greenhouse gas emissions, one of which is increasing the renewable energy (RE) penetration. Further on, since the announcement of the nuclear power phase-out by the end of 2022 triggered by the Fukushima disaster, Germany has revisited the energy transition plan and envisions a 100% renewable energy-based electricity supply system by 2050 [2]. The switch towards renewables in the electricity sector has been successful so far. In 2020, renewable energy sources produced more electricity than all fossil fuels together and now provide 45.3% of German electricity demand, with wind and solar being the top two energy sources in the German electricity mix [3]. Meanwhile, the solar photovoltaics (PV) and wind turbines are currently also the most deployed RE technologies in the global energy system [4].

Wind and PV generation are well-known for their intermittency, which hinders their dispatchability on-demand and leads to instability of power network. In order to tackle this issue, a variety of solutions have been proposed and each of them has its merits and drawbacks [5]. The applicability of these options is often restricted by their geographical and climate characteristics as well as the mindset of local residents. Thus, the synergy of different options could be a more effective way to solve this problem [6-7]. From the resource point of view, the hybrid solar-wind power system would significantly reduce the intermittency impacts and energy production costs compared to single resource (solar or wind alone) system if the complementarity between solar and wind exists [8-10]. While the occurrence of wind has no direct relation to the time of the day, the solar resource has obviously a diurnal cycle. Both can also show strong seasonal variations depending on the geography. The energy storage (ES) technologies have received more attention in recent years, as it is recognized as an essential instrument to overcome the intermittency of wind and solar resources, due to its functionality of shifting the generated electrical energy on different time scales (hourly, daily and seasonally). For example, the research result in [6] indicates the insufficiency of pure aggregation of the wind and solar power to achieve a highly reliable energy system. Therefore, the cost-effective ES technology and strategic combination of other supporting options (load management, flexible generation, etc.) are crucial for a reliable wind-solar system contributing a high fraction to total annual electricity demand. There are various ES technologies available for different time scales and geographical scales. The former is dependent on the renewable resource variability, while the latter is referring to distributed and bulk generation. In this hypothetical study, the scenarios of a distributed electricity generation to supply a local community with a stand-alone microgrid have been

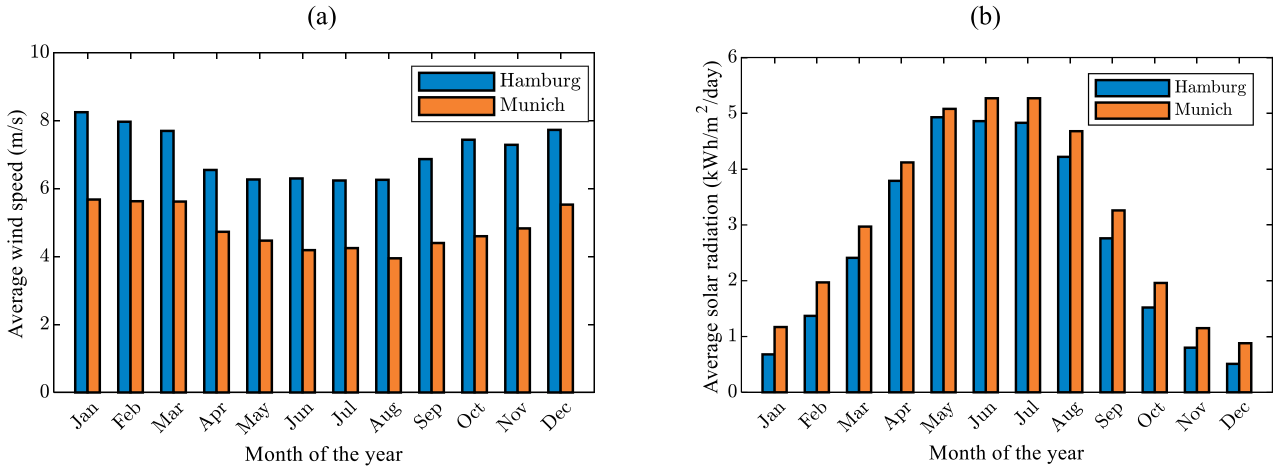

Figure 1. Comparison of wind and solar resource bewteen Hamburg and Munich: (a) Monthly average wind speed (at 50m above the surface over a 30-year period Jan 1984 – Dec 2013); (b) Monthly average solar radiation (global horizontal radiation over 22 years period Jul 1983 – Jun 2005) [11].

investigated. Communities and its related emerging concept of modular community energy storage (CES) have recently been suggested as a key player to support further the penetration of RE technologies [12]. Against this background, several electrochemical ES technologies have been discussed and demonstrated within a microgrid, either stand-alone or connected, to the existing utility grid [12-14]. Among the state-of-the-art technology, the Li-ion battery and the power-to-hydrogen-to-power (P2H2P) system are identified as the practical energy storage options at community scale [12,13,15]. Furthermore, the research results have shown that the hybrid ES system, i.e. Li-ion battery and P2H2P system, could make use of its corresponding strengths and compensate for individual weaknesses: 1) for the P2H2P technology, the energy and power capacities are decoupled, while this is not the case for electrochemical batteries. For example, for a single battery technology system, satisfying both the peak power (kW) demand over a few minutes and supplying sufficient energy (kWh) to the community over a few hours, would lead to an economically unfeasible over-sized battery system. 2) Li-ion batteries with higher round-trip efficiency compared to the P2H2P system are more suitable for both short-term (i.e. minutes) and medium-term (i.e. up to 4 hours) applications such as frequency regulation, demand peak shaving, etc. [16]. In contrast, the low round-trip efficiency of the P2H2P system causes high penalty in the levelized cost of electricity, but it can be a low-cost technology for a long-term energy storage (i.e. days to months) [17].

This hypothetical study aims to examine the different scenarios of the CES for a 100% renewable energy based stand-alone microgrid system under distinct availability of wind and solar resources in two regions of Germany, namely Munich and Hamburg. For each case, the CES scenario of Li-ion battery system alone, P2H2P system alone, and the hybrid form of both is investigated, respectively.

II. METHODOLOGY

A. *Hypothesis and Case Description*

To focus on the climate influence on the ES system configuration, the following assumptions are proposed:

- The selection of the case location is purely fictive and no feasibility condition has been considered.
- The community load profile is independent of the geographical region, which means the regional difference in electricity demand is ignored.

Munich (Case A) and Hamburg (Case B) are two major well-known cities in Germany, located in the proximity to the northern edge of the Alps and to the North Sea coast, respectively. Hence, both cities do have their specific climate characteristics, although they are both categorized as oceanic climate, known as “Marine West Coast Climate” [18]. Munich has humid continental features (warm/hot summer and cold winter), while Hamburg is subject to extreme greater than typical marine climate (cool Summer and mild winter). From the perspective of the renewable resources, the two regions have correspondingly displayed a certain degree of discrepancies and similarities. Hamburg has averagely 47% higher monthly wind speed than Munich throughout the whole year as shown in Fig. 1a, while Munich seems to have better solar resource. The monthly solar radiation (kWh/m^2/day) is about 29% stronger than Hamburg as shown in Fig. 1b. For both locations, the solar resource shows stronger seasonal variation (i.e. evident seasonal cycle) than the wind resource and the complementarity of wind and solar resource can be detected. Fig. 1b shows that the solar resource reaches a maximum during summer (June-July), which is up to 6 times and 9.7 times of the winter (Dec-Jan) minimum in Munich and Hamburg, respectively. In contrast, the wind resource peaks in winter (Jan-Feb) and decreases to the minimum in summer (Jun-Aug) by only a factor of less than 1.5 as shown in Fig. 1a.

B. *Load Profile*

The load profile data are the synthesized measurement data of the year 2010 with a time resolution of 1 minute, comprising 74 households located in immediate proximity to each other [19]. The average annual consumption per household is 4.7 MWh. Within the context of this research, the total electricity demand of 74 households is therefore assumed to be the community load profile. It is shown in Fig. 2a that the electricity consumption in typical summer weeks is lower than in winter months, possibly due to the holiday

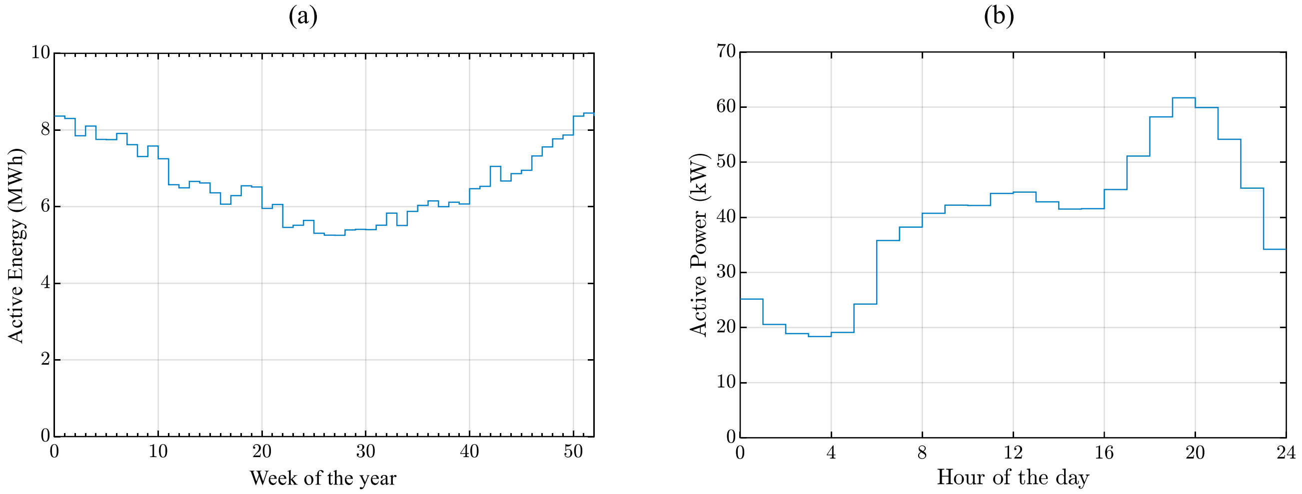

Figure 2. Community load profile: (a) Seasonal profile; (b) Daily profile [19].

period. Around the turn of the year, the consumption reaches its peak value. Compared to the seasonal availability of the renewable resources (Fig. 1), the seasonal demand variation is roughly compatible with the wind resource but inversely correlated to the solar resource. The daily load profile (Fig. 2b) is characterized by a higher demand in the evening and lower demand in the night.

C. Scenario Description

Li-ion Battery and P2H2P systems were considered as energy storage systems for the community. For each case, the following scenarios are considered:

- Scenario 1 (S1): 100% renewable energy-battery system.
- Scenario 2 (S2): 100% renewable energy-P2H2P system.
- Scenario 3 (S3): 100% renewable energy and hybrid battery-P2H2P system.

D. Modelling and Parameters

The proposed system scenarios have been modelled, simulated and evaluated using “HOMER Pro (V 3.14)” [20]. With the given energy resources, load profile, desired system components, as well as other constraints, HOMER can decide which components are best for this system and what size of each component is the most efficient via the cost optimization algorithms. The optimization object function is the lowest net present cost (NPC). HOMER performs energy balance calculation for each time step of the year and then determines whether a configuration is feasible, i.e. to satisfy the demand under provided constraints. For the feasible systems, the cost estimation of installing and operating the system over the lifetime of the project is performed.

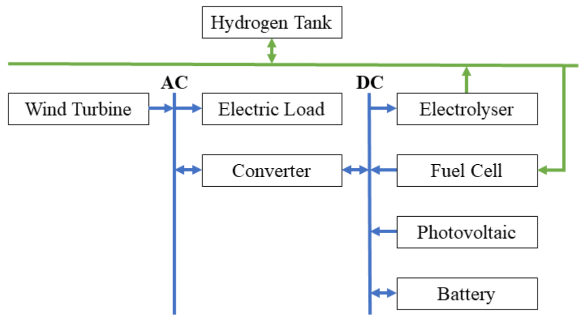

Figure 3. Proposed system configuration.

The proposed system model for all scenarios is illustrated in Fig. 3. The percentage of the solar and the wind energy production in each scenario is not pre-determined, but calculated via the NPC optimization, which uses a derivative-

Table I. Input Parameters used in the optimization [14,11,21-28].

Profile	Variability
Load Type: AC	Day-to-day (%) = 8.668
Peak month: January	Timestep (%) = 13.939
Daily average (kWh/d): 949.85	Time step size: 60 Minutes
Peak (kW): 98.32	Community size: 74 households
Solar PV	Lifetime: 25 Years
Panel Type: Flat Plate PV	Ground reflectance = 20%
Peak month: July	No Tracking system
Efficiency: 20.75%	Capex: €1000/kW (Installed)
Temp.Coefficient: -0.35	Opex: €4.47/kW/yr.
Operating Temp.: 45°C	
Wind Power	Nominal speed: 11 m/s
Size: 300 kW each	Start-up speed: 3 m/s
Peak month: January	Cut-off speed: 20 m/s
Hub height: 55m	Capex: €1325/kW (Installed)
Lifetime: 20 years	Opex: €35.37/kW/yr.
Horizontal axis	
Battery Bank	Minimum SoC: 20%
Type: Lithium-Ion	Capex: €700/kWh (Installed)
Size: 100 kWh each	Opex: €8.93/kWh/yr.
Max. Power: 300 kW	Life time: 15 Years
Roundtrip Efficiency: 90%	
Electrolyser & Fuel Cell (PEM)	Type: PEM Fuel Cell (PEMFC)
Type: PEM electrolyser	Life time: 60,000 hours
Life time: 15 years	Efficiency: 75%
Efficiency: 80%	Capex: €2254/kW(Installed)
Water consumption: 101/Kg H2	Opex: €0.018 op hr
Capex: €2254/kW(Installed)	
Opex: €72 kW/yr	
H^2 Storage Tank	**Economics** [Homer Pro]
Lifetime: 15 years	Project lifetime= 25 years
Capex: €490/KgH^2	Discount rate= 8%
Installed plus peripherals	Inflation rate= 2%
Opex: €4.90/kgH^2/yr	Currency= Euro (€)
Compressed gas (30 bar)	

free algorithm. The same method applies to the battery size. For the P2H2P system, the capacity of each component is specified with a series of options based on the initial estimation.

The same input parameters for both cases are shown in Table I. The capital and operating costs (CAPEX and OPEX) of all system components and their specifications were imported from the HOMER Pro library and adjusted to the current near-real cost based on the literature review [11, 14,21-28]. The dispatch strategy of load following and cycle charging are both selected as decision parameters. The feasibility of the system was constrained by the following conditions: 1) satisfying the load requirement for more than 99.9%. 2) capable of dealing with the sudden 10% increase of the load in each time step and 5% increase of the annual peak load. 3) capable of serving the load even if the PV array and wind turbine output suddenly decreases 25% and 50% in each time step, respectively. Additionally, in S1 the battery has a minimum of 12 hours of autonomy and in S2 the hydrogen tank should at least have three days of autonomy as well as the fuel cell should cover the peak load of 98 kW.

III. RESULTS AND DISCUSSION

The tecno-economic comparison of all scenarios for each case in Table II reveals the certain similarities between two cases in spite of their different climate characteristics:

- To ensure the system stability and reliability, S1 with battery alone storage system requires large RE generation capacity, which leaves more than 70% of excess energy, and it has the highest NPC and cost of energy (COE) among all the scenarios.
- Compared to S1, by storing the RE in the form of hydrogen S2 is more effective in cost as well as curtailing the excess energy by around 35%. Due to the long-term storage capability of hydrogen, for the same energy balance of the system, much less solar PV capacity is required. Additionally, P2H2P system has more energy autonomy (~ days) than the battery (~ hours), which is more advantageous for the 100% RE based stand-alone system.
- S3 with hybrid storage system is the most cost-effective (NPC and COE) system of all for the 100% RE-based stand-alone microgrid system. It reduces the excess energy production and has longer autonomy hours, compared to S1. S3 comprises a much smaller capacity of battery and relatively smaller size of the P2H2P system, compared to S1 and S2, respectively. The synergy effect of the two different storage systems, as mentioned in Section I, has been therefore validated. The battery bank in S3 can be used to ensure the power quality for the short-term system stability, while the P2H2P system can be utilized to deal with the long-term energy "shifting" to increase the system reliability.
- Except Case B-S2, all the other scenarios are optimized to a hybrid PV-wind system, regardless of their storage system.

Despite the general similarities between the two cases described above, the differences between the two cases on the system configuration and the cost are pronounced due to their individual renewable resource availability, which shall be discussed in the following by analysing the optimal scenario S3 in depth:

- With one 300 kW wind turbine in both cases, Case A needs additional 158 kW solar PVs to satisfy the electricity demand, while Case B requires only 9 kW PV supply. For example, as shown in Fig. 4, the comparison of the wind turbine (blue curve) and PV (yellow curve) power output at the beginning of July and January between two cases has revealed that the hybrid energy source of wind and solar is indispensable for Case A to improve the system reliability and penetration of RE, while Case B is prone to wind alone system with the aid of P2H2P system in S3 (as well as in S2). However, Case B requires the hybrid energy source as well when the system has only short-term battery storage system (S1).
- Case A demands the size of the hydrogen tank 4 times larger than Case B, and accordingly the relatively larger size of electrolyser and fuel cell. Due to its richer solar resource (Fig. 1b) and insufficient wind resource compared to Case B, the RE system of Case A relies partially on the seasonal shifting of the excess solar energy from summer to winter, which in turn requires larger size of the hydrogen tank. The monthly hydrogen tank level of Case A obviously followed the similar seasonal cycle of the solar resource as shown in Fig. 5a, i.e. the energy was

Table II. Selected simulation results for all scenarios.

Munich	**Scenarios**	**Scenario 1**	**Scenario 2**	**Scenario 3**
System Component	Solar PV [kW]	289	99	158
	Wind Turbine[kW]	600	600	300
	Battery [kWh]	1,200	X	100
	Fuel Cell [kW]	X	100	80
	Electrolyser [kW]	X	60	60
	Hydrogen Tank [kg]	X	300	400
Autonomy	Battery Autonomy [h]	24.30	X	2.02
	H_2 Tank Autonomy [h]	X	253	337
RE	Excess Energy [kWh/year]	967,063	600,369	223,771
	Excess Energy [%]	72.8	47.3	29.0
Economics	NPC [millions of €]	2.76	2.19	1.63
	Cost of energy [€/kWh]	0.615	0.490	0.364
	CAPEX [millions of €]	1.92	1.40	1.14
	OPEX [€/year]	64,380	61,301	37,998

Hamburg	**Scenarios**	**Scenario 1**	**Scenario 2**	**Scenario 3**
System Component	Solar PV [kW]	158	X	9
	Wind Turbine [kW]	300	300	300
	Battery [kWh]	1300	X	100
	Fuel Cell [kW]	X	100	60
	Electrolyser [kW]	X	60	40
	Hydrogen Tank [kg]	X	120	100
Autonomy	Battery Autonomy [h]	26.30	X	2.02
	H_2 Tank Autonomy [h]	X	101	84.2
RE	Excess Energy [kWh/year]	894,385	589,165	680,645
	Excess Energy [%]	71.4	47.5	57.7
Economics	NPC [millions of €]	2.13	1.35	1.10
	Cost of energy [€/kWh]	0.476	0.301	0.245
	CAPEX [millions of €]	1.47	0.82	0.75
	OPEX [€/year]	51,559	40,920	26,854

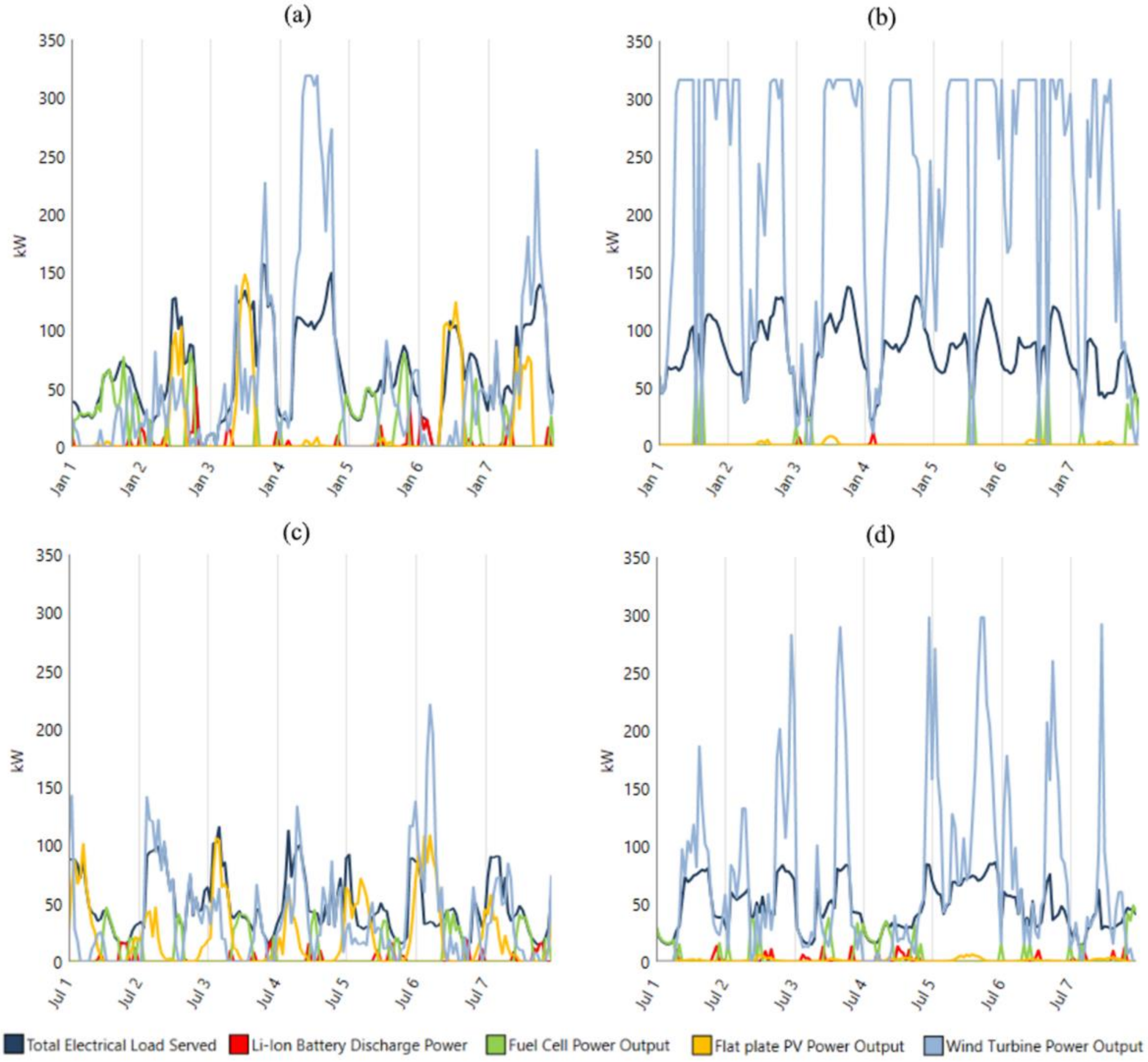

Figure 4. The system components' power output of S3: (a) Munich, January; (b) Hamburg, January; (c) Munich, July; (d) Hamburg, July.

stored in the form of hydrogen in the seasons of abundant solar resource, while the hydrogen as fuel was largely consumed during the winter months with low supply of solar energy. In contrast, the hydrogen tank level in the wind resource dominant RE system of Case B behaves erratic due to the high variability of the wind resource. An example of worst-case scenario in Case A can be identified as 05 Jan – 06 Jan shown in Fig. 4a. During this period with the unavailability of the renewable resources, the fuel cell generates electricity alone to satisfy the load. The average hydrogen tank level in January varies between 34-49 kg (Fig. 5a), which is around 21-32 hours system autonomy (0.039 kg H2 per kWh), although the full capacity of the hydrogen tank provides maximum 337 hours of autonomy as shown in Table II. Hamburg, in spite of a much smaller size of hydrogen tank compared to Munich, has averagely 38 hours of autonomy in January and a maximum of 84 hours system autonomy.

- Case B has about 33% lower NPC cost in comparison to Case A, owing to its more abundant wind resource (Fig. 1a) throughout the year. Thus, as discussed above, more expenditure on PV and hydrogen tank leads to the higher NPC cost in Case A as shown in Fig. 6. Case A has to pay around 18 and 4 times of the cost for the PVs and the hydrogen tank as Case B, respectively.
- Case B possesses at least 3 times of excess energy as Case A (Table II) due to its plentiful wind resource. By increasing the production and storage capacities (i.e. electrolyser and H_2 tank), the excess energy can be further curtailed via utilizing the stored hydrogen in other forms of energy, such as heating, cooking and e-mobility. In Case A, more hydrogen can be stored in summer to improve the system autonomy in the worst-case scenarios.

IV. CONCLUSION

In this research, a 100% hybrid RE based stand-alone microgrid system for a community in two different regions of Germany with individual climate characteristics was proposed and modelled via HOMER Pro software. Three different scenarios of CES, namely a battery based, a hydrogen based and a hybrid battery-hydrogen based storage system were evaluated and compared between two cases.

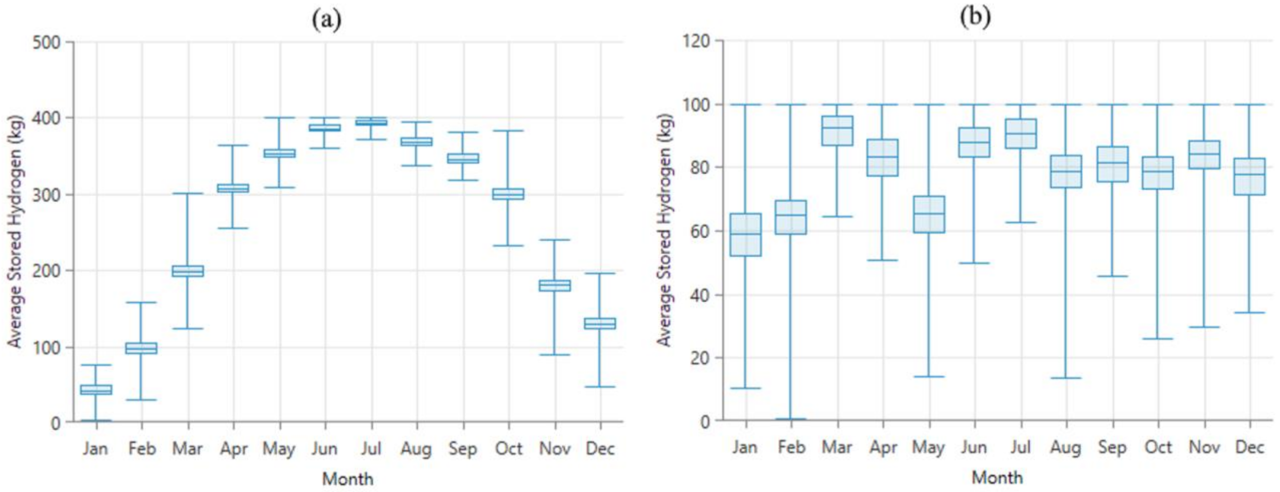

Figure 5. Monthly hydrogen tank level: (a) Munich; (b) Hamburg.

Of all the scenarios and regardless of the individual case, the hybrid solar-wind RE system with a hybrid battery-hydrogen based CES (S3) was demonstrated as the most promising approach towards a 100% RE based off-grid community microgrid system, which not only has the lowest NPC and COE along the project lifetime of 25 years but also improves the system resilience. Moreover, the hybrid storage system curtails the excess energy compared to the battery alone storage system. Additionally, storing the energy in the form of hydrogen can also make full use of excess energy by converting it into other forms of energy or increase the system autonomy.

The different climate characteristics of two cases have a marked impact on the proposed S3 system because of the individual availability of the renewable resource: for the region (Case B) with abundant wind resource throughout the year, the optimal hybrid energy storage system is more wind energy dominant and requires smaller size of P2H2P system. In contrast, the complementarity of solar and wind resource is more advantageous for the region (Case A) with stronger solar radiation and insufficient wind resource. From the economic perspective, Case B-S3 is more cost-effective than Case A-S3, as the lower availability of wind resource requires Case A to expend more on PV and hydrogen storage tank, so that the solar energy can be shifted seasonally.

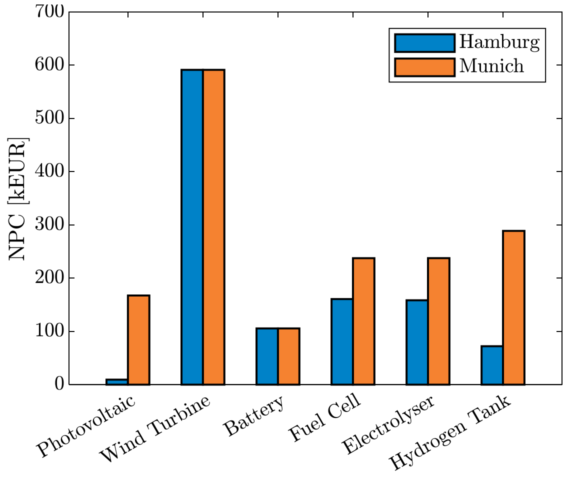

Figure 6. Comparison of the total net present cost of each component in S3.

The insight suggested in this hypothetical research is based on certain assumptions both empirically and numerically. The stable power supply in the reality therefore needs a case-specific designed energy management system. The further exploration of the possibilities of utilizing the excess energy, especially in the form of the stored hydrogen, to supply non-electric energy demand of the community, such as heat and e-fuel, could be future research.

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