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# Techno-economic assessment of hybrid renewable energy system: Case studies in Nordic countries

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**Abstract**— The Nordic countries generate the vast majority of their energy through renewable energy resources. They enjoy extended sunshine in the summer months and moderate to high wind speeds throughout the year, providing good potential in harnessing wind and solar energy. This study focuses on integrating solar and wind energy to supply the electricity demand of a small-scale community in northern Europe. As renewables are inherently intermittent, the hybrid microgrid will be supported by sufficient battery storage units and a backup diesel generator to meet the electricity demand reliably. Techno-economic assessment is utilized to evaluate the cost of energy per generated kWh of electricity based on the lifetime components' costs. The results will be obtained and compared for different northern European cities to evaluate the potential of solar and wind energy under such conditions. Furthermore, the effect of hydrogen generation, storage, and consumption is explored for Turku, Finland as a representative of Nordic climatic conditions. The results indicate the possibility of off-grid microgrids in the Nordic region emphasizing the pivotal role of wind energy. As the wind speed exceeds 7 m/s, a competitive component price of 0.02 \$/kWh is reached. This is while most of Iceland and Denmark's land enjoy wind speeds of more than 8 m/s and even higher on the off-shore Nordic areas. Although the intensity of solar irradiation is limited at high latitudes, the results have revealed the significance of solar energy during summer months to cover the energy demand by solar panels due to the extended days of sunshine. A hydrogen unit was found to be a promising option to curtail the surplus electricity from renewable energy systems.

**Keywords**— *IYCE, HRES, Climate neutrality, Optimization, Hydrogen, Optimization*

## I. INTRODUCTION

A microgrid is a promising energy system to meet energy demand locally that could operate off-grid or in grid-connected modes taking advantage of renewable and distributed energy sources contributing to energy saving, efficiency, security, higher controllability, and so on [1]. Besides, a microgrid curtails energy loss, which originates from voltage variations from power generation to end users [2] or electricity transmission between countries at a long distance such as the high-voltage direct current interconnectors between Nordic countries namely Denmark, Finland, Norway, and Sweden [3]. Hybrid renewable energy systems (HRES) could serve the microgrid integrating various energy resources to increase the efficiency, reliability, and availability of energy due to the inherent intermittency of renewables. Moreover, HRES enjoying the high renewable fraction could serve the health

indicators of society due to emission reduction, which has been studied by Khosravani et al. [4] quantitatively. They introduced the societal cost of electricity based on the Co-benefits Risk Assessment (COBRA) from the U.S. Environmental Protection Agency to integrate corresponding health enhancement due to better air condition into an energy price.

Energy storage systems (ESS) play a pivotal role in balancing off-grid energy systems, especially at the small scale to achieve a high-quality and more reliable energy supply as well as to shave peak demand [5]. Hydrogen has the potential as an energy carrier to not only store surplus electricity for a long period from HRES through the power to hydrogen facilities but also decarbonize heating systems, industries, transportation, and electricity generation thanks to its high energy density [6]. Hydrogen is considered to be an integrated part of future decarbonization, sustainable development, and connection between various sectors [7].

One of the clean energy sources that recently attracted the attention of many scholars is hydrogen produced from renewables (sometimes called green hydrogen). The excess renewable energy is used to generate hydrogen through an electrolyzer. Then, it is stored in a hydrogen tank and used in a fuel cell (FC) as another source of renewable energy to support the HRES and limit the required batteries and emitted pollution [8]. Among two common electrolyzers for hydrogen production, proton exchange membrane (PEM) technology is selected against the alkaline electrolyzer as the PEM electrolyzer has a fast response, which makes it ideal for HRES and oscillating load. Furthermore, the delivered hydrogen from water splitting has a purity of 99% at high pressure which eliminates the compressor for hydrogen storage in a tank [9]. The levelized cost of hydrogen (LCOH) is shown to be 9.1 \$/kg for 400-bar compressed hydrogen versus 8.7 \$/kg of uncompressed one in a study carried out by Ram et al. to generate hydrogen for fuel cells [10].

The energy content of hydrogen is 120 MJ/kg which is three times more than that of diesel, which makes hydrogen a better form of energy carrier and storage than diesel [11]. Hydrogen and battery storage system was shown to have a decarbonization potential and an appropriate flexibility in microgrids [12]. Hydrogen, which is assumed to be one of the main future energy storage possibilities, currently experiences a higher price than electrochemical storage although it is a necessary step to support other industries and electricity generation by a fuel cell [13]. To

take advantage of hydrogen as a clean fuel, fuel cells could be used to generate electricity from hydrogen [14].

Studying in Germany [15], battery storage was not a cost-effective solution for hydrogen generation but a hydrogen backup without a battery. PEM technology was also discussed to have the flexibility to be integrated with renewable energy systems rather than Alkaline electrolyzers. Wind energy plays a major role in hydrogen production to reduce the required capacity in Estonia compared to the PV-driven system due to the wind abundance and lack of solar irradiation [16]. The selling of energy in hydrogen form was shown to be more economical than exporting surplus electricity.

To have further insight into the role of the electrolyzer and fuel cell on the hybrid energy system, Falama et al. [17] demonstrated that fuel cell has a significant impact on increasing the energy price from 0.26 to 0.46 €/kWh without and with fuel cells correspondingly. However, those systems should be coupled with other energy sources to overcome the huge storage banks and the intermittency of solar energy, especially at night. This is while wind energy could be harnessed during the whole day. Exploiting the Monte Carlo method to evaluate LCOH in Poland, Benalcazar and Komorowska [18] explored a large-scale green hydrogen generation by wind and solar energy. They have considered various scenarios and PEM capacities achieving the median of LOCH of 13 €/kg, 4.2 €/kg, and 2 €/kg based on the solar energy and 7.7 €/kg, 2.6 €/kg, and 1.3 €/kg based on the wind energy by 2020 for 1-MW PEM, by 2030 for 6-MW PEM and by 2050 for deployment of 20-MW PEM respectively. This decreasing trend is assumed to be due to the technology development and cost reduction by 2050. Using the same approach, Jang et al. [19] compared various technologies for hydrogen generation resulting in the LCOH of 7.6, 8.55, 10.16, and 7.16 \$/kg alkaline water electrolyzer (AWE), PEM, and SOEC with electric resistance heat or coupled with waste heat accordingly.

Gul et al. [20] studied an anion exchange membrane water electrolyzer to increase renewable fraction by generating hydrogen from excess electricity in a grid-connected system. Assareh et al. [21] explored the effect of renewable energy sources together with heat pumps on grid-connected hybrid cooling, heating, and power generation. The results reveal that the fuel cell could have a major impact on the system's price and that using electricity and hydrogen storage units positively affects the system's reliability.

This study investigates electricity prices based on the lifetime costs of components in optimized HRES including solar energy, a wind turbine, a converter, a diesel generator, and electrochemical batteries under conditions representative of northern European countries. The current work contributes to a better understanding of Nordic climatic conditions and the role of solar and wind energy in HRES. Further exploration will be done on the surplus electricity and energy price in Turku, Finland by integrating an electrolyzer, fuel cell, and hydrogen storage system as a so-called indispensable part of future energy systems into the HRES.

## II. METHODOLOGY

A hybrid renewable energy system necessitates the investigation of various parts and energy resources namely electrochemical battery (BT) and hydrogen storage, solar and wind energy, electrolyzer, converter, fuel cell, diesel generator (DG), solar irradiation, wind speed, and ambient temperature. The available hourly climatic data of 8 northern European areas in Finland, Sweden, Denmark, Norway, Faroe Islands, Greenland, Iceland, and Åland Islands are utilized to investigate the most cost-effective PV/WT/BT/Converter/DG configuration (Fig. 1) regarding the component cost of energy in HOMER, as one of the flexible and broadly used tools for optimization [22]. Furthermore, a hydrogen unit comprising an electrolyzer, hydrogen tank, and fuel cell as can be seen in Fig. 4 is employed in the next section to elaborate on the effect of green hydrogen generation and consumption in HRES.

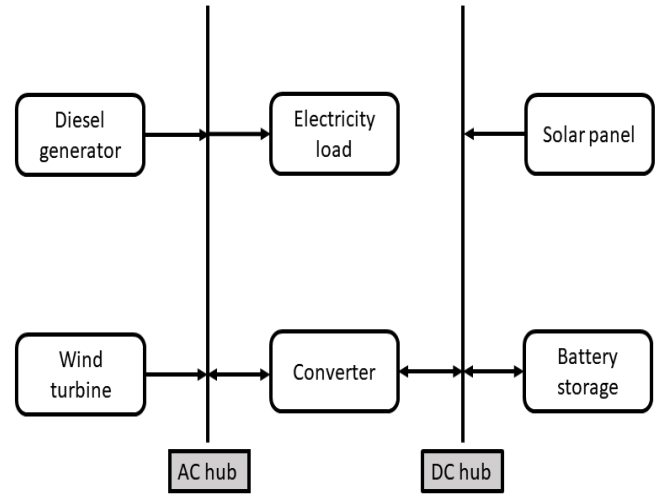


Fig. 1. The HRES schematic comprising WT/PV/DG/BT/Converter.

### A. Climatic conditions

The most significant climatic conditions affecting the considered energy systems are solar irradiation, wind speed, and ambient temperature, influencing the solar panel efficiency and available wind power at the hub height of a wind turbine, which is mentioned in TABLE I.

TABLE I. AVERAGE ANNUAL CLIMATIC CONDITIONS IN 8 NORDIC REGIONS.

Cities	Irradiation (kWh/m <sup>2</sup> /day)	Wind speed (m/s)	Temperature (°C)
Turku	2.8	5.7	5.7
Gothenburg	3	6	7.7
Stavanger	2.8	6.9	7.1
Esbjerg	2.9	8.5	9.1
Tórshavn	2.2	9.9	7.3
Nuuk	2.3	5.5	-2.2
Reykjavík	2.1	7.3	3.6
Mariehamn	2.9	7.7	6.3

### B. Wind and solar energy as well as a storage unit

The available wind energy ( $P_w$ ) in Watt (W) is a function of the  $C_p$ , power coefficient,  $A(m^2)$ , swept area,  $\rho(kg/m^3)$ , air density, and  $U_{hub}(m/s)$ , the wind speed at the hub height. However, there is a limitation ratio of 16/27, which confines the theoretical wind energy harness.

$$P_w = \frac{1}{2} C_p A \rho U_{hub}^3 \quad (1)$$

where the wind speed of  $U_{hub}(m/s)$  at the hub height of  $h_{hub}(m)$  of the wind turbine is a function of the wind speed at the reference point of  $U_{ref}(m/s)$ .

$$U_{hub} = U_{ref} * H(h_{hub}) \quad (2)$$

and

$$H(h_{hub}) = \frac{\ln(h_{hub}/Z_0)}{\ln(h_{ref}/Z_0)} \quad (3)$$

The height of the reference point is  $h_{ref}(m)$  and the length of the surface roughness is  $Z_0(m)$ . The generated energy by solar panels ( $P_{pv}$ ) in Watt correlates with  $P_{rt}(W)$ , a PV output at standard conditions,  $G_T (W/m^2)$ , global irradiation on PV,  $f_d(\%)$ , derating factor,  $\alpha_t(\%/^{\circ}C)$ , the coefficient of the power temperature and  $\theta (^{\circ}C)$  is the temperature of the solar panel.

$$P_{pv} = P_{rt} f_d \left( \frac{G_T}{G_{T,STD}} \right) (1 + \alpha_t (\theta_c - \theta_{STD})) \quad (4)$$

As mentioned earlier, the ambient temperature affects the solar cells' output and their efficiency compared to the standard condition measurement of  $\eta_{mp,STC}(\%)$  where  $T_{c,STC}$  is  $25^{\circ}C$  and the temperature coefficient is  $\alpha_p(\%/^{\circ}C)$ .

$$\eta_{mp} = \eta_{mp,STC} [1 + \alpha_p (T_c - T_{c,STC})] \quad (5)$$

The surplus electricity could be saved in storage batteries at the maximum power ( $P_{cmax}$ ) of three limiting factors namely kinetic battery model (KiBaM), maximum charge rate (MCR), and maximum charge current (MCC) considering the charging efficiency of  $\eta_{ce}(\%)$ .

$$P_{cmax} = \frac{\text{Min}(P_{cmax,KiBaM}, P_{cmax,MCR}, P_{cmax,MCC})}{\eta_{ce}} \quad (6)$$

### C. Component cost of energy

To obtain the final electricity price delivered to the end user, all the expenditures should be considered such as the costs of engineering, controlling, infrastructures, taxes, transmission, components, commissioning, capex, operation, replacement, and maintenance, to name but a few. However, the costs related to the components are only considered here for optimization purposes and referred to as the component cost of energy (CCOE), which is per generated kWh of electricity computable

as a ratio of total annualized cost (\$/year) and served electricity (kWh/year).

$$CCOE = \frac{C_{ann,tot}}{E_{served}} \quad (7)$$

### D. Technical specifications of the components

The following components in TABLE II. with their techno-economic specifications are utilized in HRES to obtain the optimized energy system. The diesel generator is selected in a way that could cover the peak demand independently with a 10% higher safety capacity. The project lifetime is assumed to be 15 years with a 3% inflation rate [23], a 4% discount rate [24], and a real discount rate of almost 1% consequently.

TABLE II. TECHNO-ECONOMIC SPECIFICATIONS OF THE COMPONENTS.

Component	Parameter	Value
Diesel generator	Capacity	150 kW
	Capital and Replacement cost	175 \$/kW
	Diesel fuel	2 \$/litre
	O&M	0.1 \$/hour
Hydrogen tank [25]	Initial level	10 %
	Lifetime	25 years
	Capital and Replacement cost	100 \$/kW
	O&M	25 \$/year
Solar panel [26]	Model	Flat plate Polycrystalline
	Rated capacity	0.33 kW
	Lifetime	25 years
	Efficiency	16.9 %
	O&M cost	10 \$/kW
	Capital cost	950 \$/kW
Fuel cell	Replacement cost	900 \$/kW
	Technology	PEM
	Capital [27] and Replacement cost	2 k\$/kW
	O&M	0.03 \$/hour
Converter	Lifetime	10000 hours
	Efficiency	95 %
	Lifetime	15 years
	Capital and Replacement cost	171 \$/kW
Wind turbine [28]	O&M	4 \$/kW/year
	Type	Horizontal
	Hub height	16 m
	Rated capacity	11.5 kW
	O&M	30 \$/year/unit

Component	Parameter	Value
	Lifetime	20 years
	Capital cost	2 k\$/kW
	Replacement cost	1.8 k\$/kW
Electrolyzer [25]	Efficiency	85 %
	Lifetime	15 years
	Capital and Replacement cost	500 \$/kW
	O&M	20 \$/year
Battery storage	Technology	Lithium Iron Phosphate
	Capacity	100 kWh – 2100 Ah
	Voltage	48 V
	Throughput	343 MWh/year
	Capital and Replacement cost	180 \$/kW
	Round trip efficiency	95 %
	50% depth of discharge	5000 cycles

### E. Electricity load

The hourly-based electricity demand is extracted from Finland’s transmission system operator as a representative of Nordic electricity consumption. Fig. 2 illustrates the average electricity consumption of a Finnish individual considering about 45% shares of industries. The load is scaled for 100 persons leading to the average load of 89.3 kW, daily electricity usage of 2.1 MWh with a peak of 136.1 kW. The maximum energy consumption occurs in December and January while the lowest amount of electricity is consumed in June and July with monthly amounts of 749, 820, 556, and 561 kWh respectively.

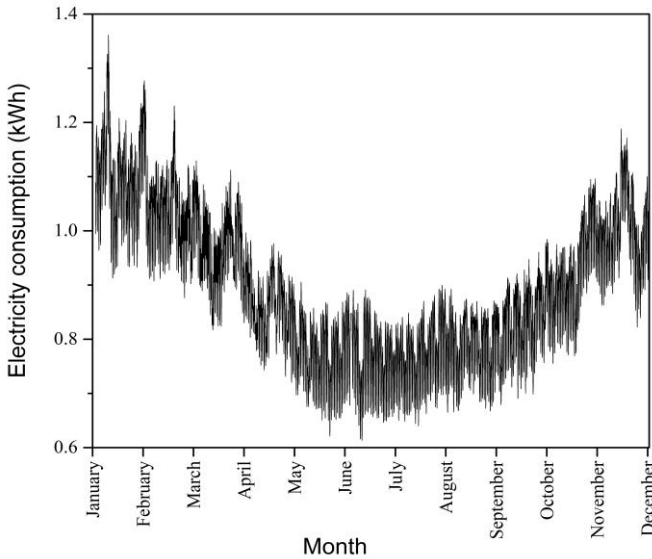


Fig. 2. Hourly electricity demand for a typical Finnish person.

## III. RESULTS AND DISCUSSION

### A. WT/PV/BT/Converter/DG in Northern Europe

Taking advantage of solar and wind energy generation and storage, the optimal HRES is examined for the 8 aforementioned Nordic regions to obtain a general overview of Nordic climatic conditions. TABLE III. demonstrates the required wind turbine capacity and electrochemical storage batteries in the most cost-effective HRES. As can be seen, the component cost of energy (CCOE) per generated kWh of electricity ranges between 0.02 and 0.03 \$/kWh although the required wind turbine and storage batteries in the optimal systems vary significantly between 210 – 400 kW and 16 – 27 respectively, mainly due to the available wind energy in those areas as average annual wind speed ranges from 5.5 m/s in Nuuk to 9.9 m/s in Tórshavn referring to TABLE I. More importantly, the available wind energy in Nordic countries is sufficiently competitive to exclude a diesel generator and solar energy from the optimum configurations meeting the electricity demand totally by renewables. The CCOE stabilizes around 0.02 \$/kWh as the wind speed passes the average annual of 7 m/s.

TABLE III. THE OPTIMUM HRES IN 8 DIFFERENT NORDIC AREAS.

Cities	WT (kW)	storage battery (kWh)	CCOE (\$/kWh)
Turku	400	2700	0.03
Gothenburg	360	2400	0.03
Stavanger	280	2000	0.02
Esbjerg	210	1600	0.02
Tórshavn	200	1800	0.02
Nuuk	380	2500	0.03
Reykjavík	310	2500	0.02
Mariehamn	230	1800	0.02

The current CCOE of between 0.02 to 0.03 \$/kWh seems to be competitive compared to fossil fuels and conventional electricity generation. However, it is of great significance to consider other costs such as commissioning, infrastructure, controlling, taxes, engineering, and soft costs, to name but a few to calculate the energy price for end users.

Turku located in the south-west of Finland with a moderate wind speed is selected as a representative of Nordic climatic conditions for further investigation. The optimum system without a wind turbine is also considered to investigate the solar energy potential in Turku. Fig. 3 illustrates the amount of energy production by various components in an optimal HRES containing 1.05-MW solar panels, a 150-kW diesel generator, and 90 batteries when a wind turbine is absent. Interestingly solely solar-based electricity is sufficient to supply demands between April and September due to the extended sunshine in spring and summer time at the CCOE of 0.26 \$/kWh. Excluding even a diesel generator, almost 4.2-MW PV could deliver the electricity load at the 0.4-\$/kWh component price requiring more than 265 storage batteries.

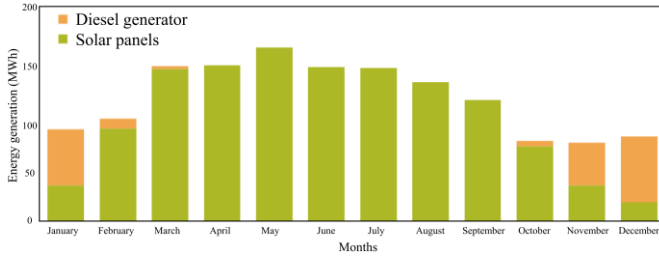


Fig. 3. PV and DG energy generation in an optimum system excluding WT.

#### IV. GREEN HYDROGEN INTEGRATION

Considering the literature review, hydrogen generation and consumption from renewables have become an integrated part of recently published articles on energy systems. However, there is a need for a pack of whole components together such as an electrolyzer, hydrogen tank, and fuel cell [29]. Moreover, it may not be considered as the economic option when grid connection is viable due to the high investment cost of electrolyzer and fuel cell as well as double loss due to the conversion of electricity to hydrogen and then to electricity consequently [30]. The diesel generator typically has an efficiency of near 40% at the optimum point. This value is between 40% to 85% [31] for fuel cells and ranges around 62% to 88% [32] for electrolyzers in most studies leading to a combined efficiency of 25% to 75%.

Therefore, hydrogen production, storage, and consumption are coupled with HRES as one of the possible strategies to manage excess electricity generation in Turku climatic conditions. The diesel generator is replaced by a fuel cell as illustrated in Fig. 4 leading to a renewable fraction of 100% for all cases and the optimum system is studied for the various numbers of wind turbines to see how fuel cells could support the HRES.

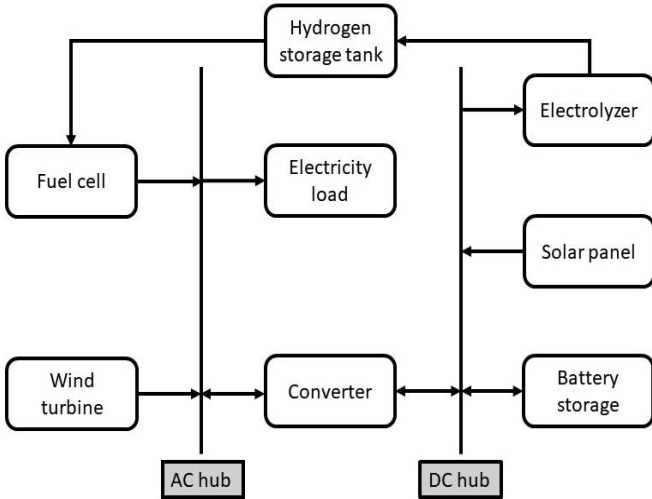


Fig. 4. HRES schematic with hydrogen generation and consumption unit.

The electrolyzer of 1 kW, hydrogen tank of 1 kg, and fuel cell of 1 kW have been selected with the illustrated results for optimal HRES with various number of wind turbines in TABLE IV. The optimum system without hydrogen units generates annual excess electricity of 1590 MWh.

TABLE IV. THE OPTIMIZED PV/WT/FC/ELECTROLYZER/STORAGES HRES IN TURKU. THE FUEL CELL AND ELECTROLYZER HAVE A 1 kW CAPACITY AND THE HYDROGEN TANK HAS A CAPACITY OF 1 KG.

WT (kW)	PV (kW)	Battery (kWh)	Component cost (\$/kWh)	Surplus energy (MWh/year)
400	0	2700	0.028	1588
300	0	3800	0.029	986
200	0	5400	0.033	382
150	44	6200	0.034	130
100	980	7100	0.105	890

The results indicate that a fuel cell can reduce the excess electricity compared to the system with a diesel generator although it is only around 110 kWh per year for the most optimum case. The surplus electricity decreases until the lowest annual amount of 130 MWh with 15 wind turbines and a component cost of 0.034 \$/kWh, 21% higher than that of the most optimum HRES with a component cost of 0.028 \$/kWh. The surplus energy and costs rise as the wind turbines diminish due to the tremendous need for a large capacity of solar panels and storage batteries to meet demand.

#### V. CONCLUSION

The component cost of energy (CCOE) for optimal hybrid renewable energy systems (HRES) comprising a diesel generator, solar and wind energy, and an electrochemical energy storage unit has been studied in 8 northern European cities. In addition, Turku has been selected (as the representative of Nordic climatic conditions) to examine the integration of hydrogen generation by an electrolyzer, storage, and consumption using a fuel cell. The main findings are summarized as follows:

- The CCOE ranges between almost 0.02 and 0.03 \$/kWh in studied cases. As the wind speed surpasses 7 m/s, the energy price is at about 0.02 \$/kWh.
- The optimum system excludes a diesel generator and solar panels due to Nordic areas' satisfactory available wind energy.
- The electricity demands could be supplied solely by solar energy and battery storage units between April and September thanks to the sufficient sunshine in Turku at the component price of 0.26 \$/kWh.
- Green hydrogen originating from renewables is considered to be an integrated part of the future energy systems. The substitution of a diesel generator with a hydrogen unit and fuel cell leads to achieving a renewable fraction of 100% and reducing the surplus of electricity.

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