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Design and Optimization of a Fully Renewable-Based Energy Mix

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***Abstract* – The global increase in energy consumption is forcing the energy sector to evaluate the energy transition from fossil-based systems to renewable energy sources. Unfortunately, the impact of non-dispatchable generation affects grid stability and the ability to meet nighttime loads. In addition, a shift from summer to winter is required to increase the penetration of renewables. The introduction of storage technologies and the energy mix could overcome some of the problems associated with the green revolution. The aim of the work is to assess the best combination of generation systems and storage to meet the electricity needs of a 100 MW peak load city in the Latvian region with an annual energy load of 700 GWh. The energy hub considered represents a valuable evolution of a traditional gas-fired power plant coupled with the most cost-effective renewable resource generators: photovoltaic and wind turbines. To exploit the renewable surplus, part of the electricity is converted into hydrogen, which drives a fuel cell and a methanation system linked to the gas turbine. The method used is Trnsys-based numerical modelling coupled with multivariable particle swarm optimization to minimize the levelized cost of electricity under different renewable penetration scenarios. The LCOE is 0.099 EUR/kWh for an 80 % RES production and rises to 0.265 EUR/kWh for a fully renewable system.**

***Keywords* – Energy hub; optimization; renewable energy.**

1. Introduction

The increasing urgency to tackle environmental challenges associated with global warming is reshaping power generation systems by integrating higher shares of renewable energy. This shift is further driven by the decreasing levelized cost of electricity (LCOE), motivating governments to adopt energy mixes that emphasize renewables [1] especially for countries with a special focus on the energy transition [2].

The exploration of hybrid solutions, such as the integration of concentrated solar power and photovoltaic (PV) plants, has been undertaken to enhance cost-effectiveness and performance. Zurita *et al.* [3] have conducted a comprehensive analysis of such hybrid systems, evaluating future cost-reduction scenarios to improve renewable integration. Despite the considerable potential of solar technologies, the lower availability of solar radiation in

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Europe could be offset by a significant wind energy potential. Researchers, including Frank *et al*. [4] have underscored the significance of an optimal blend of wind and solar energy to ensure grid stability. However, as the penetration of renewable energy sources increases (Cole and Frazier [5]), challenges such as variability and the intermittent nature of renewable energy production can disrupt load balancing and grid stability. Addressing these issues requires enhanced grid flexibility and improved power generation modulation capacities. Several studies [6], [7] have highlighted the critical role of energy storage in the integration of renewable energy into the electricity system and the associated economic impacts. The present limitations of PV and wind energy are attributable to electrochemical storage, predominantly through lithium-ion batteries. However, significant advancements in battery production and economies of scale have led to a substantial reduction in costs, as highlighted by Verbruggen [8] and the International Renewable Energy Agency (IRENA) [9].

Hydrogen has gained recognition as a pivotal player in the global effort to decarbonize energy systems [10]. Its versatility allows it to play a significant role across various sectors, including mobility, heating, power generation, and hard-to-abate sectors like heavy industry and long-haul transport. Additionally, there has been recent interest in exploring the potential of hydrogen as a means for seasonal energy storage. Green hydrogen, which is produced via water electrolysis powered by renewable energy sources such as wind and solar, holds particular promise for advancing the energy transition [11]. For instance, green hydrogen produced through alkaline water electrolysis has been proposed for large-scale applications in American regions [12], and the optimization of production with wind and solar has been assessed by Hassan *et al*. [13]. Nevertheless, the expansion of hydrogen production and infrastructure remains a pressing challenge. Currently, the green hydrogen sector is in its early stages of development, with limited case studies and demonstration projects addressing practical issues such as component sizing, regulatory frameworks, and grid integration. Despite the pledges of substantial investments in large-scale projects and the promise of increased electrolyzer manufacturing capacity by 2035, significant barriers persist [14]. These include high production costs and the need for substantial investments in infrastructure to ensure reliable energy supply at competitive prices [15].

Achieving high penetration of renewable energy sources requires the integration of multiple generators and energy storage systems [16]. In recent years, optimization of the energy mix has become a critical issue for optimal system sizing and a balanced techno-economic approach [17]. Accurate and well-detailed models are crucial, since several components interact with each other, and a large number of dynamic outputs must be predicted [18]; for this reason, codes, such as Homer or Trnsys, characterized by high flexibility in dynamic simulations, are required [19]. Seck *et al*. [20] analyse the French power mix using advanced grid simulations, highlighting the importance of grid balancing and interconnections for efficient renewable integration. Similarly, Balaji and Gurgenci [21] evaluate the optimal power mix for an isolated Australian community with industrial and residential load profiles, considering both electricity costs and environmental impacts. Ishraque *et al*. [22] conducted a comparative analysis of different dispatch strategies for renewable energy systems in various locations across northern Bangladesh. Their findings indicate that the load-following strategy [23] offers the lowest levelized cost of electricity (LCOE) and emissions while maintaining a stable system response. This strategy effectively balances energy supply and demand, making it a viable option for optimizing renewable energy integration in the region. Ramesh and Saini [24] highlight the critical role of storage in grid management, emphasizing that battery operational constraints must be integrated into load-following strategies to extend battery lifespan and reduce operating costs. More recent research by Vaziri Rad *et al*. [25] underscores the value of demand-side management techniques, such as load shifting and deferrable loads, in enhancing system performance compared to traditional dispatching methods.

Building on earlier studies of load-following strategies [26], [27] and adhering to the recommendations outlined by Agajie *et al.* [28], this paper introduces an optimization procedure designed to achieve the lowest Levelized Cost of Energy (LCOE) for a specified renewable energy fraction. The approach identifies the optimal generation mix, including Gas Turbine (GT), Photovoltaic (PV) systems, Wind Turbines (WT), Electrolyzer (EL), Fuel Cells (FC) and a methanation system coupled with hydrogen and methane storages. Using the methodology from [29], it determines the energy contribution from each generation source and the appropriate size of thermal and/or electrochemical storage systems through a comprehensive techno-economic analysis.

The main objective of this research can be summarized as follows:

- The optimization procedure in this study is based on a numerical algorithm that interacts with an accurate model of the complete electrical system, unlike models that deal with component details or management logic;
- A comparison of different renewable energy grids under a load-following strategy is conducted to provide insight into the most effective technologies for increasing the renewable energy penetration in the stand-alone grid;
- An evaluation of the synergy of two storage technologies, namely methane and hydrogen, has been provided to ensure the balance of the power grid.

2. Methods and Model

The paper proposes the design and optimization of a revamped energy hub in Riga (Latvia). The modelling has been assessed with the software Trnsys. Trnsys simulation represents one of the best ways of modelling transient energy systems due to its flexibility. Nevertheless, Trnsys simulates a user-defined system where the design is limited to the user experience. In order to solve this issue, Genopt software has been introduced in the procedure. Genopt, starting from the Trnsys model, optimizes selected variables in the aim of optimizing a specific parameter (i.e., LCOE). The optimized variables obtained from Genopt are then included in the Trnsys model and proposed in the result discussion chapter. This work is based on a versatile power hub model, developed in the Trnsys environment with a time step resolution equal to 7.5 minutes, with generation units, energy storages and a control system, based on a load-following strategy, able to manage a large integration of renewable sources. The layout of the energy hub is depicted in Fig. 1. The proposed hybrid generation infrastructure includes solar PV, wind turbines and methane-fuelled gas turbines. The energy reservoirs include hydrogen systems and synthetic methane production. The electrical actors in the network are interconnected via an AC bus; DC/AC and AC/DC conversion components are also considered where necessary. The primary energy is provided by renewables that drive directly the electric load and the electrolyzer. The hydrogen stream is stored and diverted (according to the tanks levels and electricity demand) to a fuel-cells or to a methanation plant. The methane produced is used to drive a gas turbine (existing power plant in Riga) coupled with a carbon capture process in the flue gas stream to provide CO_2 for the methanation process.

Detailed annual simulations have been performed in accordance with realistic ambient conditions, considering seasonal variability and periods of low source availability; furthermore, the LCOE of the system is evaluated for different targets of renewable energy fraction (RF). In the following sections, the models of each technology are reported: main assumptions, technical data, performance outputs under design and off-design operation are presented for power generation units and for storage systems. Subsequently, site meteorological data and the hourly power demand profile are illustrated.

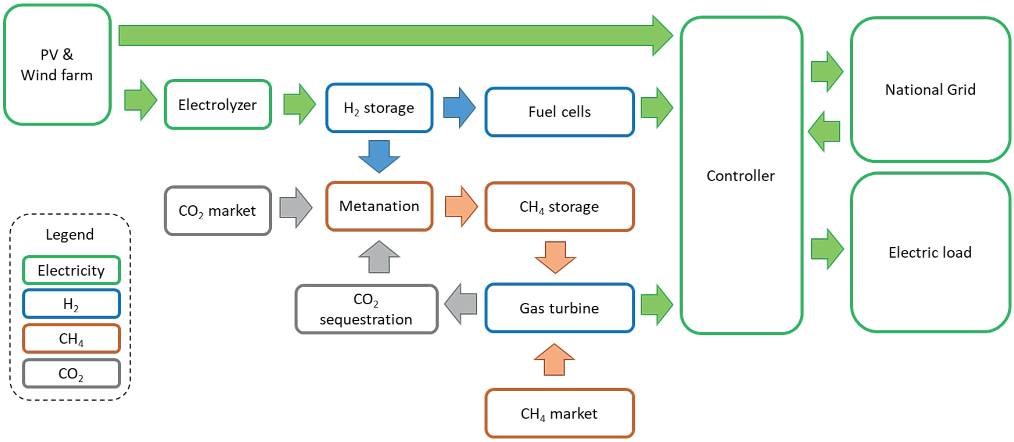
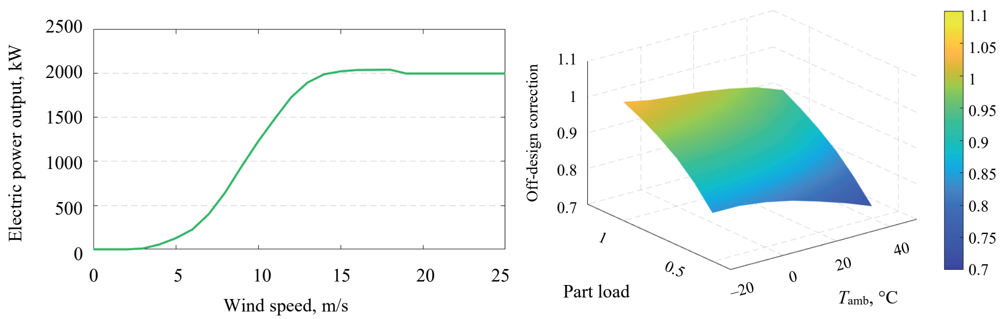


Fig. 1. Energy hub layout.

2.1. Component Performance

The performance of each component has been evaluated under design and off-design operation, further details on the modelling approach have been provided in a previous work [29]. The photovoltaic field emulates the operation of a commercial PV module [30] with an efficiency of 18.3 % and considers the efficiency derating due to panel temperature increase. It is assumed that the wind farm will be composed of 2 MW horizontal axis turbines with a power curve as shown in Fig. 2(a) [31]. Fig. 2(b) proposes the operating map of 47.7 MW gas turbine generator which considers the capacity reduction due to ambient temperature and off-design load performance, based on performance declared by the manufacturer [32].



a) wind turbine power curve

b) Capacity reduction GT

Fig. 2. Off-design performance for wind turbine (a), gas turbine (b) and electrolyzer (c).

Energy excess from the renewable generators may be used to produce hydrogen through a PEM electrolyzer with a nominal conversion efficiency of 4.3 kWh/Nm^3 and an off-design correction factor presented in [33]. The hydrogen, stored in tanks with a maximum pressure of 350 bar, can be used directly in a PEM fuel cell to supply electricity to the grid with a nominal efficiency of 0.6, or converted to synthetic methane to feed the gas turbine. The methanation process involves combining H_2 and CO_2 in the presence of a nickel catalyst, to produce synthetic methane (CH_4) and water (H_2O) in the Sabatier reaction with the total efficiency of 85 % [34]. The reaction occurs at an elevated temperature of 400 °C and pressures close to 3 MPa. The synthetic methane was stored as a compressed gas a pressure up to 200 bar according to standard application [35].

2.2. Energy Hub Management

The load-following control strategy is adopted; generation priority is always given to the gas turbine which has a minimum partial load of 50 %. The GT is always on. If the methane storage is not sufficient to guarantee the fuel to the turbine, it must be purchased from the market. The production of the PV and wind turbines is used to meet the demand coupled with the turbine power output, otherwise the excess power is used to produce hydrogen according to the electrolyzer power limit and the state of charge of the hydrogen tank. Depending on the level of methane storage, hydrogen should be converted to methane or used to generate electricity in the fuel cell in case of a power deficit. Sizing components will be assessed under the optimization process.

2.3. Case Study

The following case study is presented to demonstrate the capability of the procedure and evaluate the best improvement of the actual Riga power plant. The hybrid renewable grid is assumed to be located in Riga, Latvia, due to the presence of adequate resource availability and a strong commitment to green energy initiatives. The meteorological data are based on the Meteonorm database, and the main characteristics of solar and wind availability are reported in Table 1. The electric load is derived from [36], with a maximum power requirement of 100MW and a total annual demand of 699.7 GWh.

TABLE 1. AMBIENT PARAMETERS

Riga, Latvia	
DNI	1087 kWh/m^{2}y
GHI	664 kWh/m^{2}y
Wind speed > 3 m/s	3758 h/y

2.4. Economic Evaluation

The objective of the present study is to determine the optimal configuration of generation and storage components to achieve an even higher renewable penetration. The levelized cost of energy (LCOE) is utilized as a comparison term between different configurations and is evaluated for each technology based on the forecast of energy produced and investment and maintenance costs. The economic parameters per unit capacity (kW, m^3 or kg) for each technology have been listed in Table 2, including also the plant lifespan. Where not specified, economic data are from SAM software [37]. SAM software is not adopted as a simulation tool but as a source of economic data. The costs proposed are divided into installation costs and running costs. Running costs include fixed O&M that refers to fixed costs related to the components capacity and variable O&M that refers to costs due to real component operation.

TABLE 2. VALUES USED IN THE SPACE DEVELOPMENT SUB-MODEL FOR BASE SCENARIO

	Installation cost		Ref	Fixed OM, USD/kW	Variable OM, USD/kWh	Lifespan	Ref
Photovoltaic	USD/kW	793	[38]	9		20*	[43]
Wind farm	USD /kW	1000		44		25	
Gas Turbine	USD/kW	1380	[39]		0.009	25 [40]	
Electrolyzer	USD/kW	1500	[41], [42]	2 %/y	0.02	10*	
Compressor	USD/kW	1000		1 %/y		25	
Hydrogen tank	USD/m^3	30 000		1 %/y		25	
Fuel Cell	USD/kW	2000		2 %/y	0.02	10*	
Methanation	USD/m^3	375	[44]	1 %/y		50	
Methane tank	USD/m^3	20	[45]	1 %/y		100	

* Inverter cost is considered twice in CapEx evaluation. The replacement costs of the electrolyzer and the fuel cell are 40 % and 21 % of the installation cost, respectively.

The LCOE calculation for each technology is calculated using Eq. (1), the canonical LCOE formula that includes the installation cost multiplied by the capital recovery factor ($C_{\text{plant,PV}} \cdot CRF_{\text{PV}}$) to evaluate the installation cost on an annual basis and added to the O&M; the photovoltaic (PV) plant serves as a representative example. The capital recovery factor, as outlined in Eq. (2), is derived under the assumption of an interest rate of 4 %, in accordance with the designated technology lifespan, as detailed in Table 2 and represents the amount of installation cost that refers to a single year of operation under the predicted lifespan. The LCOE of the comprehensive hybrid grid (Eq. (3)) is determined as the average of the LCOE for each technology, with the weighting based on the annual energy production (Y_{prodn}), according to the procedure proposed in [46] and includes the import and export of electric energy and the purchase of CH_4 and CO_2 from the market.

$$LCOE_{\text{PV}}\left(\text{USD/kWh}_{\text{e}}\right) = \frac{CRF_{\text{PV}} \cdot C_{\text{plant,PV}} + OM_{\text{f,PV}}}{Yprod_{\text{PV}}} + OM_{v,\text{PV}} \tag{1}$$

$$CRF_{\text{PV}} = \frac{i\left(1+i\right)^{Ny}}{\left(1+i\right)^{Ny} - 1} \tag{2}$$

$$LCOE = \frac{\sum_1^n LCOE_n \cdot Yprod_n}{\sum_1^n Yprod_n} = \sum_1^n LCOE_n \cdot Yprod\%_n \tag{3}$$

2.5. Optimization Procedure

The optimization of the energy hub was carried out by the software GenOpt [47], which executes multiple annual Trnsys simulations to select the best configuration that minimizes the objective function on an annual basis (Eq. (4)). Starting from 100 seeds and 100 generations, the optimization compares the annual LCE results to select the best component sizing combination. The selected combination of particle swarm and the Hooke and Jeeves algorithms has been demonstrated to improve the global optimum identification. The search space is reported in Table 3 in the form of minimum value, maximum value and grid spacing.

TABLE 3. OPTIMIZATION ALGORITHM SEARCH SPACE

Components	Unit	Min	Max	Step
Electrolyzer capacity	MW	20	600	2
FuelCell capacity	MW	4	50	1
H_2 storage capacity	t	200	40 000	50
Methane tank capacity	t	1	20	0.5
PV capacity	MW	100	800	5
WT capacity	MW	20	2000	2

The optimization procedure was based on the global LCOE (Eq. (3)) minimization. The problem was modified by adding constraints as penalty terms in the objective function (Eq. (5)), forcing the software to reject undesired solutions. First, a minimum renewable penetration (RF) ranging from 50 % to 100 % was imposed ($\mu = \min(RF)$). Furthermore, the grid balance was managed with the parameter θ, which restricted any excess or deficit to less than 1 %.

$$f_{\min} = LCOE + Penalty \tag{4}$$

$$Penalty = Pen\left(RF < \mu\right) + Pen\left(\text{excess prod} > \theta\right) + Pen(\text{deficit} > \theta) \tag{5}$$

During the optimization process, a total of more than 10^6 combinations were evaluated. Due to the substantial nonlinearity of the optimization function, the impact of each variable on the final electricity cost is challenging to predict with precision. The comprehensive optimal results are outlined in Table 4.

TABLE 4. OPTIMIZATION RESULTS

		Renewable fraction					
Components	**Unit**	**0.50**	**0.60**	**0.70**	**0.80**	**0.90**	**0.975**
Electrolyzer capacity	MW	68	84.8	106.6	134.2	175.4	368
GT capacity	MW	47.7					
FuelCell capacity	MW	8.7	10	11.5	12.8	14.5	25
H_2 storage capacity	t	1100	2200	4400	8000	14 000	24 000
Methane tank capacity	t	8.2	8.3	8.5	9.2	10	12
PV capacity	MW	216	234	243	261	297	540
WT capacity	MW	124	190	290	410	580	1300
PV+WT capacity	MW	340	424	533	671	877	1840
LCOE	USD/kWh	0.0758	0.0775	0.0842	0.0991	0.1503	0.2651

3. Results and Discussion

The main goal of the work was to determine the best configuration, for a selected location, able to achieve a determined renewable fraction. Fig. 3 shows the renewable energy sources capacity adopted in the system with respect to the renewable fraction achieved. As reported the photovoltaic system shows a quite constant trend (except for the 100 % RF) while the wind farm capacity exhibits a trend proportional to the RF up to 85 % when the capacity increases drastically. The trend highlights the importance of selecting the most profitable renewable fraction to achieve with the current market-available technologies. Achieving a high-level renewable fraction forces the optimization tool to oversize the components.

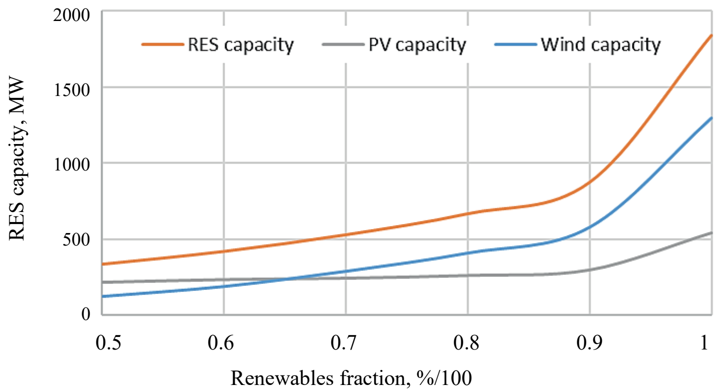
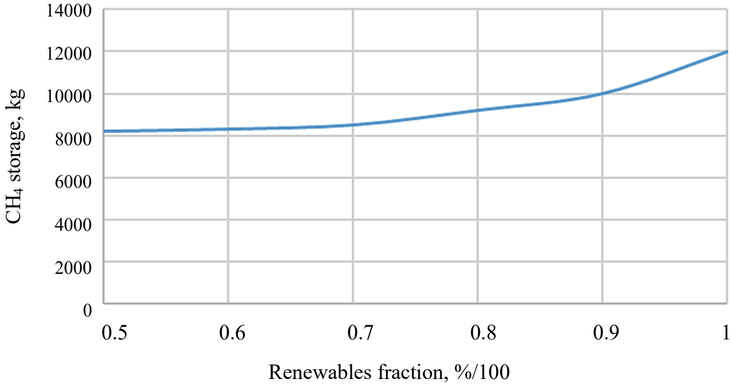
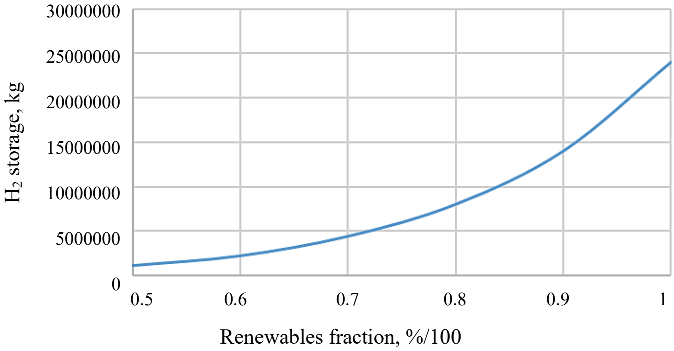


Fig. 3. Optimized renewable energy system capacity.

A completely different behaviour is exhibited by the storage systems as reported in Fig. 4(a) and Fig. 4(b): the methane storage capacity is an order of magnitude lower with respect to the hydrogen one and the trend is quite constant. The hydrogen tank capacity rises more than proportionally with respect to the renewable fraction achieved. The capacity of the methane storage is due to the requirements of the gas turbine and a base capacity is requested also for a low renewable fraction while the capacity of the hydrogen one is affected by the requirements from the gas turbine and fuel cells. Considering the results from the optimization, the fuel cell solution represents the best solution with respect to the methanation chain due to the additional costs of the system. Consequently, the capacity of the electrolyzer (Fig. 5) is directly correlated to the capacity of the renewable's installation and the capacity of the storages. As reported for the renewable capacity, an optimum level of renewable fraction could be selected to avoid large capacity components without a real improvement in the operation.



(a) Methane storage capacity



(b) Hydrogen storage capacity

Fig. 4. Optimized storages capacity.

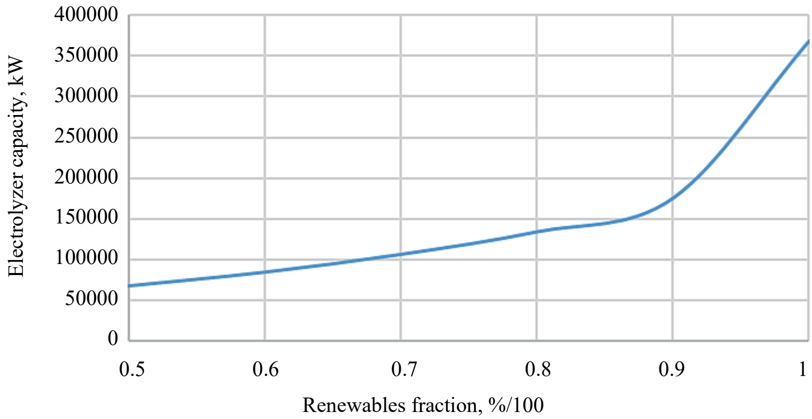
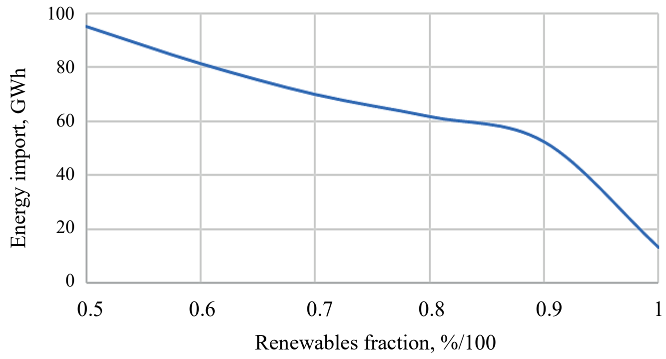
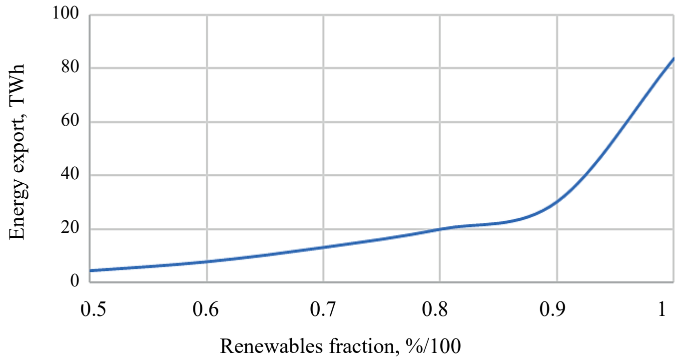


Fig. 5. Optimized renewable energy system capacity.

Moving to the energy balances, reported in Table 5, some considerations require a detailed discussion. The amounts of electricity import and export are proposed in Fig. 6(a) and Fig. 6(b), the annual import is proportionally correlated to the annual load and the renewable fraction achieved while the export is affected by the renewable generators installed. The oversizing of generators, required to achieve a high renewable fraction, is highlighted by the export amount at 100 % of RF that is double the annual electric load.



(a)



(b)

Fig. 6. Optimized renewable energy system capacity.

The most important parameter to evaluate the feasibility of the 100 % renewables solution is the economic Levelized Cost of Electricity, reported in Fig. 7. The chart shows the capability, starting from a traditional generation park, to achieve a high RF (up to 80 %) without an excessive cost burden. Only in the case of fully renewable generation, which, however, continues to use a GT gas-fired with synthetic methane, does the cost increase exponentially. Considering the amount of energy import for a 50 % renewable fraction and a high amount of export for a high level renewable fraction the LCOE variation due to import and export could be relevant. The proposed study considers the market prices in the year 2023. By this way, a parametric analysis of energy market price (electricity and methane) will affect the LCOE evaluation yielding a different optimized solution for low renewable fraction. Furthermore, for a high renewable fraction, as proposed by the authors in [48], the energy hub components are forced to fulfil the renewable fraction despite the cost.

TABLE 5. ENERGY BALANCE IN OPTIMIZED CONFIGURATION

		Renewable fraction					
Energy	**Unit**	**0.50**	**0.60**	**0.70**	**0.80**	**0.90**	**0.975**
Electricity production (GT+Rene+FC)	GWh	792.8	931.5	1123.1	1346.6	1666.0	3237.6
ElectFromRene (PV+ Wind)	GWh	403.2	548.3	743.0	968.1	1287.0	2865.1
ElectFromGT	GWh	341.1	331.6	324.5	319.4	314.8	295.8
ToLoadFromRene	GWh	257.3	288.8	312.7	328.6	343.7	415.2
ReneSurplus (Product-Eload))	GWh	145.9	259.5	430.4	639.6	943.3	2449.9
ElecLoad	GWh	699.6	699.6	699.6	699.6	699.6	699.6
FCprod	GWh	48.6	51.6	55.6	59.1	64.1	76.6
ToElectrolyzer	GWh	74.3	116.2	162.8	208.7	261.6	462.4
ExportFromRene	GWh	94.3	172.8	302.2	467.9	720.2	2024.9
ExportFromGT	GWh	19.7	24.3	28.5	32.1	37.0	63.9
Export	GWh	114.0	197.1	330.7	500.0	757.1	2088.8
Import	GWh	95.1	81.4	70.0	61.8	52.4	13.3

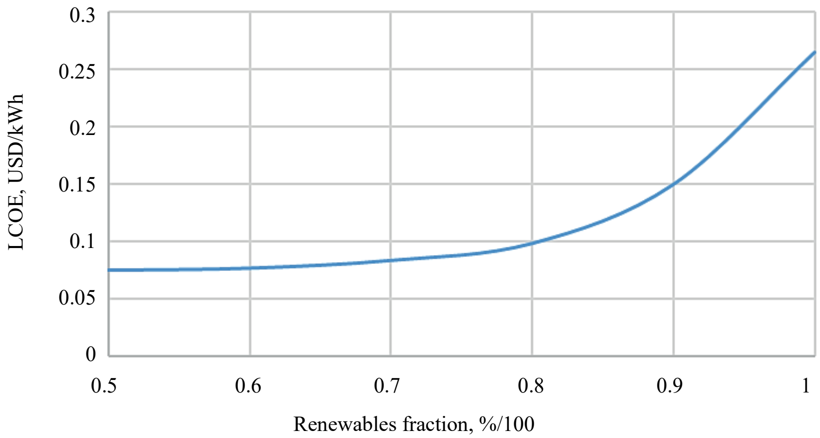


Fig. 7. Optimized renewable energy system capacity.

4. CONCLUSIONS

The paper proposes a techno-economic optimization for designing a renewable energy hub by minimizing the LCOE starting from a traditional power generation plant; the optimization method selects the best combination of power generation mix and storages to satisfy the energy demand at all times with different renewable fraction levels. The main results are summarized as follows:

- High renewable penetration is compatible with the electricity market price. The optimization shows a trend between 0.075 USD/kWh and 0.265 USD/kWh.
- The optimized configuration shows that up to an RF of 80 %, the LCOE rise is limited to 0.10 USD.

- For a completely renewable system (100 % RF), the LCOE increases to 0.265 USD/kWh due to the system oversizing and the large amount of energy that must be exported to the national grid.
- A RF 80 % appears to be the most convenient renewable penetration for the case study.

Nevertheless, considering the results as a privileged starting point for new analyses, some aspects require better investigation. In particular, the model could be adapted to evaluate different economic scenarios considering consistent energy market fluctuations and dependency on the renewable penetration. Furthermore, the model is still open to accepting new layout solutions such as power-to-X and X-to-energy with the aim of improving flexibility and reducing the LCOE for high renewable fraction scenarios.

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