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Abstract: The power sector is experiencing a considerable transformation, shifting primary sources of energy production towards more sustainable alternatives. Despite the benefits, the increasing penetration of renewable raised concerns in terms of intermittency and unpredictability of electricity production, challenging the balance between demand and supply. To this end, the GRIDSOL project proposes Smart Renewable Hubs designed to provide a single and steady output of electricity combining different renewable and storage technologies such as concentrated solar power, photovoltaic, electrical and thermal batteries. This study investigates the technical application and economic feasibility of GRIDSOL for the case of Fuerteventura. Based on different technology configurations, the outcomes show a relevant role of the concentrated solar power plant, replacing diesel plants for electricity generation. In one configuration, GRIDSOL can provide up to 68% of the energy consumption, with a capacity factor of 67% for the concentrated solar power plant and a 24% CO2 emission reduction compared to 2016 levels. The economic assessment, performed over different scenarios, shows that the applicability of GRIDSOL in the Canary system requires support in terms of investments grants on the capital expenditure (58% of the costs) or as feed-in premiums on energy production (54–67 €/MWh) to break-even.

1 Introduction

The European Union (EU), in an effort to reduce fossil fuel use for energy purposes, is aiming at decarbonising its energy system, establishing targets of emission reduction through plans such as 2020 goals [1] or 2030 Energy Strategy [2]. The strategies, aiming at shifting primary sources of energy production towards more sustainable alternatives, poses binding target legislations for each member country in order to meet climate and energy targets established. The bases for the transformation of the energy systems propose, among other measures, an intensive deployment of renewable energy sources (RES), given their increased economic competitiveness against mature conventional power plants. Although beneficial from an environmental perspective, the increasing penetration of renewable has raised major concerns in terms of intermittency, unpredictability and variability of electricity production, raising pressure on the Transmission System Operator (TSO) to balance demand and supply. The condition is particularly relevant for small isolated systems, such as islands, that are more vulnerable in terms of grid stability [3]. Although most of the EU islands present a substantial potential in terms of renewable sources, their supply mostly rely on fossil fuel-based power plants, as renewable-based technologies cannot yet offer a reliable and stable provision of electricity. In this context, the GRIDSOL project proposes Smart Renewable Hubs (SRHs) designed to provide security of supply on tailored-specific locations by means of a single steady output, combining different renewable and storage technologies [4]. Based on solar firm hybrid plants, GRIDSOL SRH proposes the integration of technologies such as Concentrated Solar Power plant (CSP) and gas combined cycle HYSOL [5], linking the synchronous generators with photovoltaic (PV), Battery Energy Storage System (BESS) and Thermal Energy Storage (TES), to provide, through a Dynamic Output Manager of Energy (DOME), a controllable output of electricity. Considering the dispatchable nature of the CSP plant and recent competitive auction results in the United Arab Emirates [6], GRIDSOL represents a valuable alternative for non-interconnected energy systems, based on aged fossil-fuel technologies and characterised by high electricity prices. Furthermore, as recent Spanish regulations for non-mainland systems introduced island-specific electricity prices to ease generation costs [7], GRIDSOL could find its competitive case, having the potential to offer, through a multi-hybridised SRH, security of supply and generation flexibility, while maintaining a high penetration of RES. To this end, this study investigates the technical application and financial feasibility of GRIDSOL through an applied case in the island of Fuerteventura, Canary Islands. First, using the bottom-up energy system model Balmorel, the study tests GRIDSOL's resilience and adaptability within the energy system of Fuerteventura, proposing different configurations of technologies. Thereafter, following the results of the technical analysis, the study investigates on the economic feasibility of the most convenient GRIDSOL configurations, using economic indicators such as Net Present Value (NPV), Internal Rate of Return (IRR), and Levelised Cost of Electricity (LCOE), considering a private economic perspective. The study further discusses on tailored incentive schemes for GRIDSOL, as no support policies have been yet developed for Smart Renewable Hubs. By providing empirical results on the technical applicability and economic feasibility of GRIDSOL for the case of Fuerteventura, the study narrows the knowledge gap on the application of Smart Renewable Hubs in island energy systems. The remainder of the paper is structured as follows. Section 2 presents the methods employed for the technical and economic analysis and Section 3 introduces the case study. Section 4 presents the results of the analysis, which are then discussed in Section 5. Finally, Section 6 concludes the study by drawing practical policy suggestions based on the findings.

2 Methods

Two main models have been employed for technical and economic study: the energy system model Balmorel and a custom made cash flow model. An additional tool, the System Advisor Model (SAM), was used to validate the model outcomes in terms of land

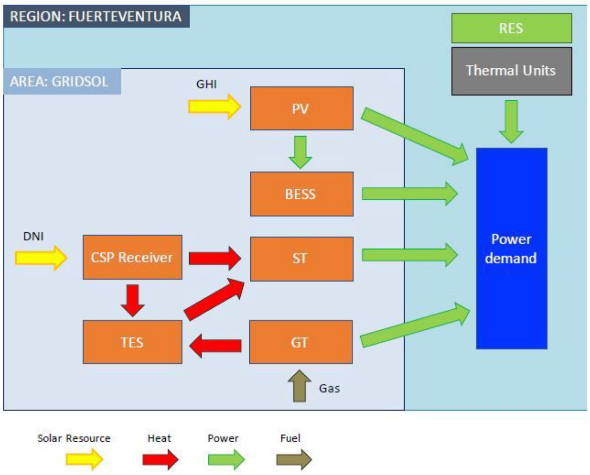

Fig. 1 *Modelling scheme of GRIDSOL components*

availability for the construction of the plants. The three tools are linked together, as the outputs from one model constitute the inputs for another: SAM validates Balmorel and Balmorel provides the capacity of the technology and the annual electricity production, necessary for the costs calculation in the economic assessment of the cash flow model.

2.1 Balmorel

Balmorel is an open source, linear energy system model that optimises investments and operation of power plants, storage devices and transmission lines for the geographical area that can be defined by the user [8]. The model considers a set of neighbouring countries operating in an interconnected electricity market. Each country is composed by one or several regions, among which electricity can be traded and transmitted, with limits imposed by given transmission capacity. In Balmorel, the user can choose the time horizon and time resolution of the analysis depending on the requirements for the specific investigation, with a temporal resolution down to an hourly level. The model allows to simulate scenarios balancing demand and supply of electricity and heat, considering operation, investments, local generation vs. import/export, price elasticity of the demand and other characteristics typical for energy systems [9]. The model relies on a set of exogenous input data that allows to define characteristics of existing capacities for electricity and heat generation technologies, storage devices, transmissions lines and heat and power demand. These characteristics are specified at regional and area level (a country is composed of several regions, and regions are composed by several areas). Additional key assumptions, required for specific analysis on impacts of different policies, are available in regard to fuel prices, CO2 costs, taxes and support schemes. The set of input data, as well as the geographical location of the electricity market under considerations, can be tailored to the need of the user. For the sake of this study, we adapted the Balmorel configuration to the case of Fuerteventura. The details about the case study data are reported in Section 3. In relation to this particular case study, this section reports only the details relevant for the analysis on the power system, excluding heat; for a thorough description of the assumption and modelling behind Balmorel, the reader can consult the manual [10]. The energy system model is set to represent an electricity market with perfect competition in which a set of technologies (i ε I) compete to satisfy the electricity demand (Equation (3)), for every time step (t ε T) in every region (r ε R), at the minimum costs (Equation (1)), while complying with a set of constraints imposed (Equation (2)).

$$\min_{e_{i,t,r}} \sum_{t=1}^{T} \sum_{i=1}^{I} \sum_{r=1}^{R} C_i(e_{i,t,r}) \quad (1)$$

$$\text{s.t. } g_i(e_{i,t,r}) \le 0 \quad (2)$$

$$\sum_{t=1}^{T} \sum_{i=1}^{I} e_{i,t,r} = E_{t,r} \quad (3)$$

Equation (1) represents the 'objective function', providing a solution that represents the least-cost combination of operation and investments in technologies, to satisfy the electricity demand ($E_{t,r}$) considering a series of costs (C_i). The costs consider both fuel and emission taxes; investments are also included and consider the annuity of capital costs, assuming a fixed discount rate and an overall economical lifetime into account. Equation (2) represents a set of linear relations imposed to reflect the characteristics of the units generating electricity ($e_{i,t}$), such as capacity constraints. When designing the specific case of Fuerteventura, the thermal units (primarily diesel and gas) already available in the system, are modelled by specifying fuel consumption, fuel efficiency, operational expenditures and emissions, following the structure of the model. However, the addition of GRIDSOL in Balmorel imply some changes as (i) the technology is not available in the dataset and (ii) the case-related technologies interact with each other differently. Fig. 1 provides a modelling scheme of the GRIDSOL's components interaction, which are further described to explain how each technology contribute within the model. The CSP technology comprises three components: the CSP receiver, the power block (steam turbine ST) and the thermal energy storage system (TES). The CSP components, along with solar PV, HYSOL gas turbine and BESS, are located in the GRIDSOL area, which is contained in the Fuerteventura region, following the geographical logic of the Balmorel model. The CSP receiver converts the solar resource (direct normal irradiation DNI) to heat, which is then used either as an input in the steam turbine to generate electricity or is stored in the thermal unit. Heat for the thermal storage is also available from the heat recovery systems of the gas turbine (GT). For this case study, we assume that PV and BESS are not directly connected to the CSP or GT system, but they contribute directly with electricity generation. Also, the modelling of the DOME system is not reported, as the technology is still at an early stage of development.

2.2 Cash flow model

The economic feasibility of the project is evaluated through a Discounted Cash Flow (DCF), considering the net amount of revenues and expenses of the project over a finite period of time. Nominal values of discounted cash flow, changing over time with inflation, are used for the private economic analysis together with considerations on taxes. Three economic indicators are used for the economic assessment: (i) the Net Present Value (NPV) defined as the difference between the present discounted (at an interest rate r) value of cash inflows $\left(\sum_{t=1}^{T}(CF_t/(1+r)^t)\right)$ and cash outflows (investment CF_0) over a period of time (t ε T), reported in Equation (4); (ii) the Internal Rate of Return (IRR) defined as the annual effective compounded return rate of an investment option (i.e. discount rate at which NPV = 0), reported in Equation (5); and (iii) the Levelised Cost of Energy (LCOE) represents the average cost of energy production (q_t) throughout the lifetime of the project, but is also referred as the electricity price at which energy output should be sold to break-even with the costs TC_t. In Equation (6), $TC_t = I_0 + M_t + F_t$ are the total costs in year t, considering the investment costs in year 0 (I_0), the yearly operational expenditures (M_t), and the annual fuel costs (F_t).

$$NPV = -CF_0 + \sum_{t=1}^{T} \frac{CF_t}{(1+r)^t} \quad (4)$$

$$0 = -CF_0 + \sum_{t=1}^{T} \frac{CF_t}{(1+IRR)^t} \quad (5)$$

$$LCOE = \sum_{t=0}^{T} \frac{TC_t}{(1+r)^t} / \sum_{t=0}^{T} \frac{q_t}{(1+r)^t} \quad (6)$$

Table 1 Technical and economical parameters for GRIDSOL

	Solar receiver	ST	TES	GT	PV	BEES
CAPEX [M€/kW]	3.4	1.2	0.96	0.73	1.1	4
O&M fixed [€/kW]	25.88	9.11	7.21	19.55	16.62	2.4
O&M var.[€/kWh]	0.0012	0.0004	0.0003	0.0055	0.0001	0.003
Lifetime [years]	30	30	30	30	30	10
Efficiency [%]	–	0.42	0.95	0.47	–	0.85
Storage [h]	–	–	9	–	–	6

Table 2 *GRIDSOL, preliminary results*

Unit	CSP MW_{th}	TES MWh_{th}	ST MW_e	GT MW_e	PV MW_e	BESS MWh_e
Reference	–	–	0.1	0.2	138	–
Emission	251.2	1769.3	43.9	–	140	11
Subsidies	256	1366	45	–	103.5	–

The project is assessed feasible for an IRR>r and a positive NPV. The opposite works otherwise: a negative NPV or an IRR<r indicate a non profitable project.

2.3 System advisor model

System Advisor Model (SAM) is a performance and financial tool designed to model cost and performance of renewable energy projects developed by the National Renewable Energy Laboratory [11]. SAM comprises a set of input data, such as technology characteristics and costs, that can either be manually specified or imported from several libraries available. The tool provides indications on land-related characteristics of a set of technologies under investigation and, for this case study, it has been used to evaluate the maximum capacity for CSP and PV, in relation to land and resources restriction. The outcomes are used to set a limit on the maximum capacity installed for CSP and PV during the simulations in Balmorel.

3 Case study

3.1 Energy framework in Fuerteventura

Following the theoretical approach presented, this section presents the relevant case study data. Fuerteventura belongs to the archipelago of the Canary Island and is electrically disconnected from the mainland. Only one 66 kV submarine cable exists with the neighbouring island of Lanzarote. Due to scarce resources, the island relies heavily on fuel imports. As for 2016, the island generates electricity mostly from diesel-based power plants (89%) while the remaining supply is covered by gas oil (6%), wind (3%) and PV (2%). According to Anuario Energetico de Canarias in 2016 the net capacity of the plants in Fuerteventura amounted to 96 MW for diesel, 63 MW for gas and 26 MW between wind and PV [12]. The annual demand in 2016 was about 680 GWh, with peak consumption usually occurring during summer months. Although non-interconnected, the regulatory framework of electricity market in Fuerteventura is tied to the power prices of Spain. According to the Real Decreto 738/2015 [7], which regulates the power production activity and dispatch in Spanish non-interconnected system, the power pricing scheme differs for each of the islands in the Canarian archipelago. The selling price of electricity thus depends on the average price of the Spanish pool corrected by an hourly coefficient that takes into account the generation costs for each isolated electrical sub-system. Some other conventional plants are not part of the scheme, as they are subject to a special treatment (Régimen retributivo adicional [7]), receiving compensation for fixed and variable operational costs. In 2014, forms of support schemes for renewable installation (PV and Wind) were in place, providing compensation for MW of capacity installed and an additional incentive to reduce the operational costs [13, 14]. The support schemes have not been updated for the years 2017-2019, thus currently leaving no support schemes for renewables in Canary Islands.

3.2 Technical analysis and economic assessment

In addition to the existing capacity in the Fuerteventura's energy system, the analysis proposes a set of technologies in the framework of GRIDSOL. Table 1 thus reports technical and economical parameters for GRIDSOL technology portfolio for the decade 2020-2029; the values are reported consistently with case studies in the literature respectively for CSP system [15–18], GT [19] and PV-BEES [20].

The fuel price and emission factors are set to 11.3 €/GJ and 22.6 €/GJ, 78 kg CO2/GJ and 74 kg CO2/GJ respectively for fuel oil and gasoil. The fuel prices are considered for 2022 and are in line with future developments forecast by the EU [21]. The input data for the economic assessment are hereby summarised. The investment year is assumed to be 2020, while the plant will start operating by 2022. The private discount rate and the corporate tax rate are set to 8% and 4% respectively and an inflation of 2% is assumed. An average degradation rate of 0.4% and an average availability factor of 95% is set for PV and CSP. For each MW installed, the study also considers grid connection costs for substations (14 k€/MW) and interconnection (88 k€/MW). The electricity price, useful to calculate the revenues, is set according to the structure proposed in the framework description, assuming that it will not deviate consistently from the current average of 40.5 €/MWh. Finally three scenarios, representing national energy and renewable support policies, are defined for the analysis: reference, emission and subsidies. The Reference scenario considers a carbon tax of 11.74 €/tCO2, in line with the EU ETS carbon prices [21]. The emission scenario simulates the energy system with a cap on CO2 emission of −20% compared to 2005 levels, according to the EU 2020 climate and energy package [2]. Last, the subsidies scenario consider an average feed-in premium of 105 €/MWh as support for investments in renewable energy projects, according to the 2014 regulation [13].

4 Results

4.1 Energy system analysis

The SAM model was used at first to evaluate the potential maximum capacity for both PV and CSP, given land-related constraints. The results of the model highlighted a limit of 45 MW_e (e = electric) for the steam turbine, 256 MW_{th} (th = thermal) for the solar tower receiver (including mirrors) and 140 MW_e for the PV. Once implemented in Balmorel, the model provided the preliminary results presented in Table 2, for simulations performed on the energy system for 2022, the year in which GRIDSOL is expected to be fully working.

The outcomes present two extreme situations: for the first scenario, no CSP capacity is considered, as the carbon tax alone doesn't provide enough support for investments in CSP. On the contrary, the results from the second and third scenario show that CSP is exploited completely, together with TES, ST and PV.

Table 3 *Results: technologies capacity for subsidy scenario*

		Case A	Case B	Case C	Case D
			Capacity		
CSP	MW_{th}	256	256	256	256
TES	MWh_t	1362	1367	1362	1367
ST	MW_e	45	45	45	45
GT	MW_e	–	–	8.8	10.1
PV	MW_e	–	103.5	–	103.5
GRIDSOL	MW_e	45	148.5	54	159
			Capacity Factor		
CSP	%	58	58	67	67
GT	%	–	–	75	65
PV	%	–	22	–	22
GRIDSOL	%	58	33	68	38

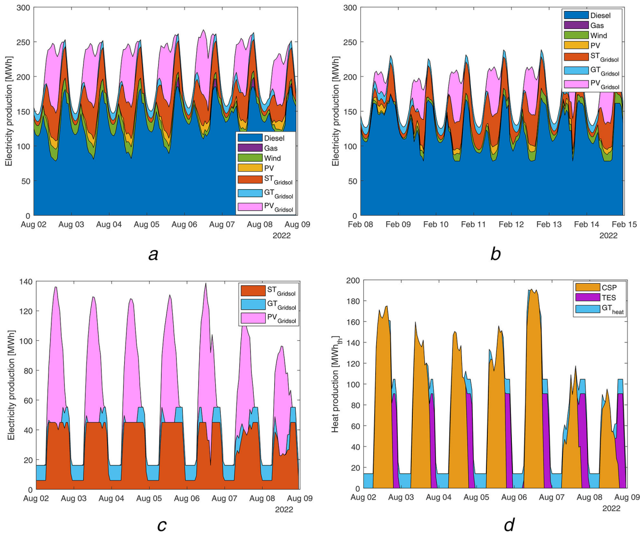

Fig. 2 *Hourly electricity dispatch of technologies*
(a) Weekly total electricity generation (Summer) ***(b)*** Weekly total electricity generation (Winter) ***(c)*** Weekly electricity generation from CSP ***(d)*** Weekly heat generation from CSP

Emission constraints and high fuel prices don't allow the penetration of GT, but favour the thermal storage. Although promising for the CSP, the results violate the basic concept of GRIDSOL: a gas turbine should always be available to provide back-up generation for extreme cases. To this end, we performed new simulations based on the subsidy scenario for four different configuration of technologies, imposing a minimum back-up electricity generation for the gas turbine (i.e. 25% of CSP) for two configurations and proposing a subsidy level of 105 €/MWh, the minimum level of support required to exploit the CSP potential in terms of maximum installed power. The four combinations of technologies are tested to investigate the economic impact resulting from the interaction of the technologies: (A) CSP, (B) CSP + PV, (C) CSP + GT, (D) CSP + GT + PV. Table 3 reports the results for the new configurations. The results show that the optimal value of subsidy allows to exploit the CSP full potential according to land restrictions.

The capacity factor for the CSP (grouping CSP, ST and TES) is relatively high, pointing to an intensive use of the combination of technologies. Also, the integration of GT with the CSP plant leads to higher capacity factors: the heat recovered from the gas turbine and further stored in TES increases the capacity factor from 58% to 67%. Fig. 2 (*a,b*) shows the hourly electricity dispatch for a summer and winter week highlighting the contribution of configuration (D). The dispatch shows that GRIDSOL CSP (ST) and PV act as a peaker power plants, while the rest of the system is dominated by diesel, which represents the bulk of the base load.

The presence of solar PV shifts the GT and CSP output to later hours, probably since the PV partially covers the role of the CSP during daylight, thus allowing a higher energy volume to be stored in TES. Summer and winter scenarios show similar behaviour for the technologies, with a lower contribution of the PV during winter, compensated by the diesel power plant. Fig. 2 (*c,d*) provide an insight on the heat and electricity hourly generation from the single GRIDSOL during a summer week. The results highlight the great production from PV during daily hours, and the intercorrelation between GT and ST by night. Fig. 2 (*d*) further confirms that the steam turbine runs during the night due to the integration provided by the gas turbine heat recovery system (See GT_{heat}).

4.2 Feasibility analysis

Table 4 presents the outcomes of the economic assessment for the four configurations. The results show negative NPVs and IRRs lower than the discount rate, indicating a non profitability for the project, for the year and the simulations considered. In regard to the LCOEs, they appears to be quite high, compared to the average price of Fuerteventura's electricity market, around 40 €/MWh.

5 Discussion

The results provided open the bases for discussion, in terms of GRIDSOL impact on the energy system and economic feasibility of the project. In terms of the energy system, the penetration of GRIDSOL technology portfolio is evaluated on the timing dispatch of the day-ahead market. The hourly resolution of power production highlights the prominent role of the CSP. For configuration D, the total GRIDSOL system reaches 68% of Fuerteventura total consumption with capacity factor up to 67%. This is achieved combining GT and TES and the other technologies, allowing not only to decrease the generation burden

Table 4 *Indicators for private economic analysis*

Indicator	Unit	Case A	Case B	Case C	Case D
NPV	M€	−172.9	−217.9	−217.8	−262.8
IRR	%	0.2	1.7	−4.1	−0.2
LCOE	€/MWh	127.9	101.4	119.5	101.4

Table 5 *CO_2 energy-related emission reduction for 2022 (compared to 2016 levels)*

	Case A	Case B	Case C	Case D
% CO2 reduct.	4%	17%	10%	24%

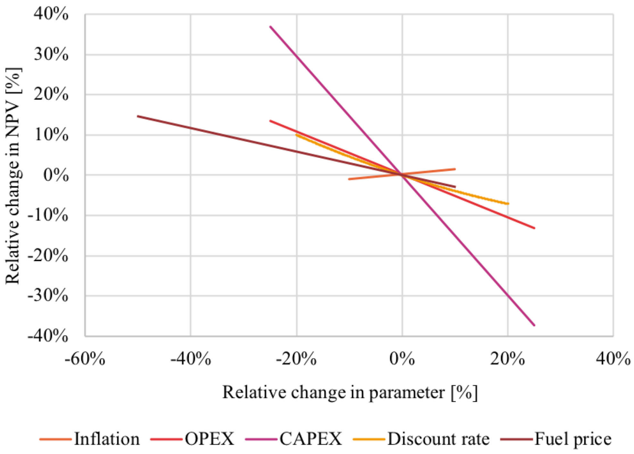

Fig. 3 *Sensitivity analysis on relevant parameters*

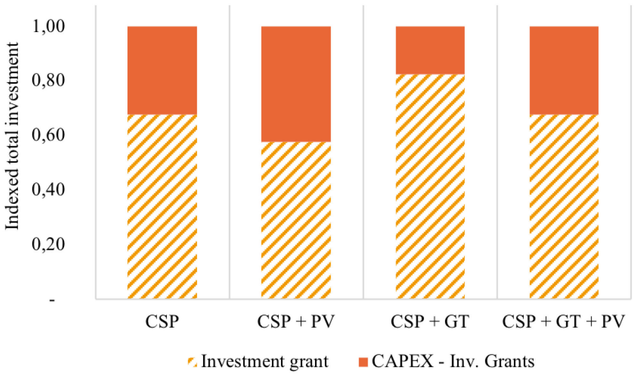

Fig. 4 *Investment grants vs. CAPEX*

from diesel plants during night but also to phase out existing gas turbines operating on demand peaks. This effect is further enforced in scenarios that account for a relevant integration of PV, which acts as a daily peaker in the hourly generation. The combination of CSP and PV is particularly useful during summer, when the demand peaks and the light resources are abundant. The integration of the GRIDSOL technologies thus leads to a relief for the energy system in terms of reducing the need of diesel plants and CO2 emissions. Table 5 shows the CO2 energy-related emission reduction for 2022, compared to 2016 levels, highlighting that the introduction of GRIDSOL can lead up to 24% reduction for the case with CSP, GT and PV (Case D).

To this end, the study investigates on the parameters that affect the most the negative feasibility of the project, in terms of economic assessment. Fig. 3, presented for case D, shows that the NPV is most sensitive to changes in fuel prices, discount rates and OPEX.

Focusing on the CAPEX, the analysis shows an even higher relation, with the NPV drastically increasing (+20%) with lower capital costs (-10%). The results thus suggest that support policies should particularly focus on the initial investment costs or on the operation of the plants, providing subsidies in terms of e.g. feed-in premium. Fig. 4 provides an indication on the level of support required for the CAPEX, expressed as a ratio of the total investments. It results that even the cheapest configuration would still require 58% of the CAPEX in form of support (around 219 M €). Alternatively, the project could benefit using feed-in premium tariffs to reach the break even point. For this case, the support required would be 83 €/MWh, 55 €/MWh, 73 €/MWh and 54 €/MWh, respectively for case A, B, C and D.

The level of subsidies would further decrease if a private discount rate of 6% is assumed for the analysis. In this case, the feed-in premium would decrease to 58 €/MWh, 35 €/MWh, 55 €/MWh and 38 €/MWh. A higher price, e.g. driven by higher CO2 prices, could drastically reduce the required subsidy over the lifetime of the plant. A combination of feed-in premiums and investment grants would yet be preferable to face an eventual realisation of less optimistic discount rates. From a regulation perspective, the regulated market environment of the Canary Islands could facilitate the integration of GRIDSOL as dispatch of renewables is prioritised over conventional power generation. Meaning that, in economic terms, the daily market would allow CSP and PV to secure the revenues, enhancing the value of investing in GRIDSOL. This favourable condition may be used as a further motivation for policy makers in the Canary Islands to introduce renewable support, making a future investment in GRIDSOL not only merely attractive but also worthwhile on a long-term perspective.

6 Conclusions

This study has investigated the technical and private economic feasibility of a Smart Renewable Hubs, GRIDSOL, for the case of Fuerteventura. The technical analysis shows that GRIDSOL technologies can offset part of the diesel-based plants to provide electricity for the island, contributing to CO2 emission reduction up to 24% compared to 2016 levels. The interlinking between thermal energy storage, PV, CSP and GT can provide a stable and consistent output of energy throughout the year. The economic assessment shows, at the current situation, a non profitability for the project. Sensitivity analyses performed over parameters and support policies shows that feed-in premiums up to 54-67 €/MWh and CAPEX support up to 58% of the investments costs can facilitate the realisation of the project and lead to break even. More stringent policies capping CO2 emission levels, RES-specific support schemes and further development of the technology to bring down costs, will pave the way for the development of Smart Renewable Hubs like GRIDSOL, contributing to a more sustainable and yet resilient energy system in the Canary Islands.

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