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Published in:
Applied Energy

DOI (link to publication from Publisher):
10.1016/j.apenergy.2022.118869

Publication date:
2022

Document Version
Publisher's PDF, also known as Version of record

Applied Energy 315 (2022) 118869

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Towards 100% renewable islands in 2040 via generation expansion planning: The case of São Vicente, Cape Verde

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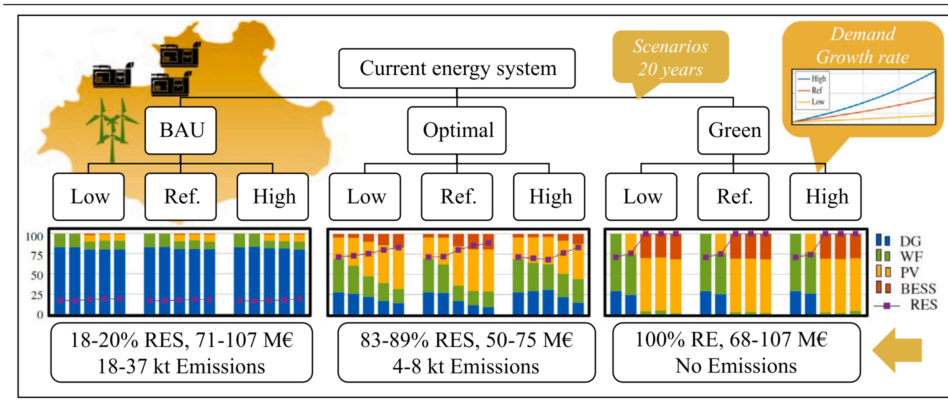
GRAPHICAL ABSTRACT



ARTICLE INFO

Keywords:
Isolated power system
Generation expansion planning
Cape Verde
Optimisation
Power system economics
Energy transition

ABSTRACT

In the energy transition context, islands are identified as particularly challenging regions due to their isolation, and energy dependence; while their excellent renewable resource and rapid growth makes them exceptionally interesting test cases. With the growing number of countries targeting 100% renewable penetration during the next decades, it is important to assess not only how to do so, but also whether we should. This paper focuses on the perspective of a generally overlooked set of regions; island developing nations. Their common challenges and energy policies are exemplified with a comprehensive generation and storage expansion planning (GSEP) for the island of São Vicente, Cape Verde. Formulated as an optimisation problem with hourly resolution, the GSEP minimises investment, maintenance, operation and emissions costs over a 20 year horizon from 2021. The extreme seasonal dependence of wind and solar resources is captured along with the operational dynamics of the generation and storage. Three scenarios are defined, one Business As Usual (BAU) keeping the current operational paradigm, another, Green, aligned with the local government goals, targeting 50 and 100% renewable shares in 2030 and 2040, and, lastly, one finding the Optimal. To reduce uncertainty influence, we consider three load growth levels for each scenario, defined based on expectations from national and international sources, corresponding to 1, 3 and 5%. The robust analysis obtained by combining scenarios and load levels provides a thorough view of Cape Verde's energy system to consider in future energy policy design. Green is the most expensive, BAU represents a 7% cost reduction, while Optimal a 30%, in addition to providing 90% renewable penetration, significant emissions reduction, and enough flexibility to modify the planning course if needed.

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https://doi.org/10.1016/j.apenergy.2022.118869
Received 30 November 2021; Received in revised form 21 February 2022; Accepted 25 February 2022
Available online 7 April 2022

Nomenclature

BAU	Business as usual
BESS	Battery energy storage systems
CVRS	Cape Verde reference system
EW	Equivalent weeks
G	Diesel generator
GEP	Generation expansion planning
Go, WFo	Existing G, WF
GSEP	Generation and storage expansion planning
MILP	Mixed integer linear programming
PV	Solar Photovoltaic
RES	Renewable energy sources
SO	System operator
SOC	State of charge
RD	Ramp down
RU	Ramp up
WF	Wind farm

1. Introduction

The climate crisis requires energy systems to evolve towards economies predominantly powered by renewable energy sources (RES). This transition is also undergone in developing economies, which must be included in the analysis and receive the know-how they need [1]. Particularly, the energy systems of isolated areas, as those of islands, show difficulties for transitioning to RES, as their natural characteristics present specific barriers for the development of RES. However, they also present certain advantages such as tendency to be rich in renewable resources, and presenting excellent testing environments for the energy transition [2]. Moreover, it is recommended to include islands from modest economies to evaluate policy effect on energy plannings aiming to achieve sustainable development [3].

Island developing states present particular challenges in the energy transition such as resulting naturally remote, extreme dependency on imports and low integration in global energy markets. However, some of these challenges can actually boost their energy transition towards more sustainable configurations. For instance, Azores and Madeira are examples of how the high costs associated with fossil fuel imports and emissions motivated the development of local RES [4]. In that sense, other hidden potential can be highlighted, such as the need for and rapid expansion of the electrical grid and the diverse composition of the energy system [5,6]. New technologies such as battery energy storage systems (BESS) can be easily integrated in these systems for three reasons. First, islands tend to have fragile electric systems where BESS are able to play a critical role as stabiliser [7]. In fact, there are several examples where BESS allow various 100% RES share achievements in isolated power grids [8]. Second, they require relatively small BESS sizes to see improvements, which limits the costs to much lower level than for a continental system. Lastly, the costs of BESS have decreased by almost 90% within a decade through the uptake of electric vehicles and small storage solutions [1].

Roadmaps are developed as part of energy planning processes to cover the future development of a system spawning several years, usually from 5 to 20. These are fundamental in different modelling approaches either targeting capturing energy market's games (top-down) or finding the most suitable technology mix (bottom-up). Both can be based on optimisation, which applies a methodology to mathematically minimise the cost of the system, or simulation, which describes a system based on a set of predefined rules. One of the most popular optimisation methods are the so called generation expansion planning (GEP) problems, which aim to find a power system's most economical configuration ensuring an adequate supply of electricity. Originally, they were relatively simple models only considering a few different generation technologies (fossil fuels, hydro and nuclear). However, GEP started including larger technological variety as grids evolved towards RES and energy storage, but also a wider range of operational, and environmental requirements. These are included as constraints or cost-penalties, e.g. the state of charge (SOC) limits of an storage system are usually modelled as tolerance bounds. Conversely, emissions penalties are usually included as part of the objective function to favour RES or carbon capture [9].

In general, generation and storage expansion planning (GSEP) are large-scale optimisation problems representing a broad range of operating conditions, dealing with multistage processes as different reinforcements are undertaken sequentially over time. Such dynamic formulation tends to make the problem intractable unless certain simplifying assumptions are applied. While, long time horizons foster uncertainty arising from the expected evolution of the load, and prices of investment, maintenance and emissions costs [10].

Several examples in recent literature successfully apply GSEP in island systems to assist regulators in decision making processes. For instance, Zafeiratou et al. [11] model Crete's system from 2020 to 2040 to study whether to keep the operational paradigm, shift to a natural gas-focused panorama, interconnect to mainland or pursue a different direction. Their recommendation is a mix between including BESS and small interconnections with mainland. Then, Fitiwi et al. [12] analyse the Irish system from 2020 to 2030, showing how it relies on wind and solar using interconnections to alleviate congestions. Trondheim et al. [13] investigate a GSEP over 10 years for the Faroe Islands. They start from 41% of RES in 2019 towards a milestone of 100% in 2030. They implement an annual rolling-window model in a commercial software (Balmorel), relying on large, predictable hydro and thermal. Lastly, Newbery [14] and Kersey et al. [15] analyse policy effectiveness for RES inclusion in the Caribbean islands and Ireland, using simple simulation and rule-based models.

The archipelago of Cape Verde is a developing state in West Africa with extreme external energy dependency on refined oil imports despite their available solar and wind resources. Aligned with the global energy transition, the local government established goals in 2011 aiming at 50 and 100% RES. However, these dates were shifted, first, in 2013 to 2020 and 2025 [16] and, later, to 2030 and 2050 [17]. These targets show the willingness towards the energy transition, while the deadline changes point towards a lack of proper planning and complexity underestimation. In addition, the country targets full energy access, as the 10% of its population has currently no access to electricity, while up to 30% has very limited access (e.g. they cannot use it for cooking) [18]. It should be noted, how both these challenges and future objectives are common to other island developing nations. Despite this, the international research community has not paid much attention to Cape Verde, unlike to other Macaronesian archipelagos such as the Canary Islands or Madeira. This paper aims to support future decision making process of policy makers and technical leaders in this and other archipelagos worldwide.

To mention the scarcely available work, Ferreira et al. [19] study the main island, Santiago, as part of a GEP spawning 20 years with monthly data considering wind, solar and biomass as energy sources, but no storage. It is concluded that a 100% RES can be obtained with a system based almost solely on solar. Yet, they represent each year with only 12 time periods, thus neglecting day/night cycles as well as all operational dynamics. Segurado et al. [20,21] explore the feasibility and effects of pumped hydro integration in São Vicente island. This allows reaching 84% RES shares. However, the System Operator (SO) of Cape Verde deemed pumped hydro unsuitable for actual implementation on São Vicente due to lack of economical incentives [22]. Conversely, the SO considers BESS more feasible due to the recent developments, cost reduction, replicability potential and capability to deal with stability issues.

This paper presents the following contributions related to developing islands in general and Cape Verde in particular:

- GSEP mix-integer linear programming (MILP) formulation including only two integers and a binary; which effectively contributes towards tractability and solving speed. This allows to capture short term energy dynamics and long term power performance achieved with large resolution (hours) and horizon (20 years) considering 12 equivalent weeks per year.
- Long term techno-economic effects of current governmental policies are studied. Full energy access concerns only developing regions; while RES-shares milestones affect most developed countries as well.
- The system characterisation and data used in this work have their origin in the local government and SO.

We propose reevaluating the country's goals towards 100% RES using an optimal GSEP with focus on São Vicente to ensure replicability in the rest of the archipelago. The GSEP presented in this paper considers technologies that the SO deems feasible and is aligned with the government's milestones regarding RES penetration using three different scenarios. The horizon spans 20 years with hourly resolution in order to capture daily and seasonal cycles. Tractability and consistency of the results are ensured by solving the problem in two ways, as the last year equivalent and as 20 year model using one equivalent week per month, which is equivalent to 40,320 h. Moreover, in order to study the effect of uncertainty, each scenario considers three different levels of forecasted demand based on the expectations from the government and different agencies. The origin of the data is the recently published Cape Verde Reference System, which was developed in collaboration with the local SO and utility company, Electra [23]. It covers the state of the energy system in the island as of 2021, including: types of generation units, hourly demand and RES profiles, etc. Different investment, maintenance and operational costs are obtained from different sources [1,24–31].

The archipelago and especially the island of São Vicente, are presented in more detail in Section 2. The methodology, scenarios, and GSEP model are covered in Section 3, and the results in Section 4. Then, the discussion of the scenarios is in Section 5, and the conclusions in Section 6.

2. The archipelago of Cape Verde

Located in the Atlantic Ocean at approximately 600 km from the westernmost point of continental Africa, Cape Verde is compounded by ten islands; nine of them inhabited by roughly 540,000 people. Their climate is usually regarded as semi-desert, more moderate than that of sub-Saharan Africa due to the oceanic influence. Temperatures are warm all year round, with average daily high temperatures ranging from 24 to 29 °C. Most rainfall concentrates from July until October, while tropical cyclones are relatively common from August until the end of September. The archipelago is a developing state, considered rural due to the general lack of industrialisation, and disperse population [32], with high dependence on fossil fuel imports, despite its exceptional solar and wind resource. This extremely vulnerable position is being addressed by the local government via different regulations targeting increasing rates of RES over time. The original goal of achieving 100% RES penetration in 2020 boosted the energy transition in the country reaching 18% as soon as 2012. However, progress staggered around 20%–25% due the general low reliability of the grid. In fact, as of 2020, RES shares were still 21% [30].

Table 1
Technical data of existing generation units.

ID	Remaining life [years]	Fuel		Rating	
		Type	Emissions [t/MWh]	Max [MW]	Min [MW]
Go	5	Diesel	0.237	30	2
WFo	10	n/a	n/a	7	0

The SO identified several causes for the high blackout risk. For instance, voltage and frequency stability are mayor technical challenges due to the low short circuit power capacity and inertia of the system; although harmonic content is a rising concern [23,33]. Due to the distance between the islands and the depth of the waters surrounding them, it is not economically feasible at the moment to interconnect them. Thus, there are nine independent networks, eight of which operated by Electra. Additionally, the large number and reduced size of the systems prevents achieving economies of scale, but might foster distributed energy systems [22].

The recently published Cape Verde Reference System (CVRS) has been used as the baseline for the present study [23]. It details the topology and components of the networks of both Santiago and São Vicente islands, including load and renewable profiles.

2.1. Energy mix, challenges, and future plans

São Vicente is the second largest island of the archipelago and has a population of around 85,000 inhabitants mainly occupied in the tourism sector. The island embodies perfectly the country's energy mix by relying on fossil fuels complemented with approximately 20% of wind power. The basic technical data of the existing fossil-fuelled generator (Go) and wind farm (WF) as of 2021 are presented in Table 1. Suitable sites for additional wind and solar farms are already identified. However, their installation is pending blackout risk reduction. Aiming to alleviate the aforementioned operational challenges, pumped hydro storage was considered by [20] as a possible inclusion in the system as its highest mountain is a suitable location for this technology. However, it has been deemed unsuitable for actual implementation in São Vicente by the SO due to lack of economical viability [22]. An alternative energy storage method could be a BESS due to the recent developments and cost reductions. Besides being more economically competitive, their operation is simpler, and would allow easy replication on other islands.

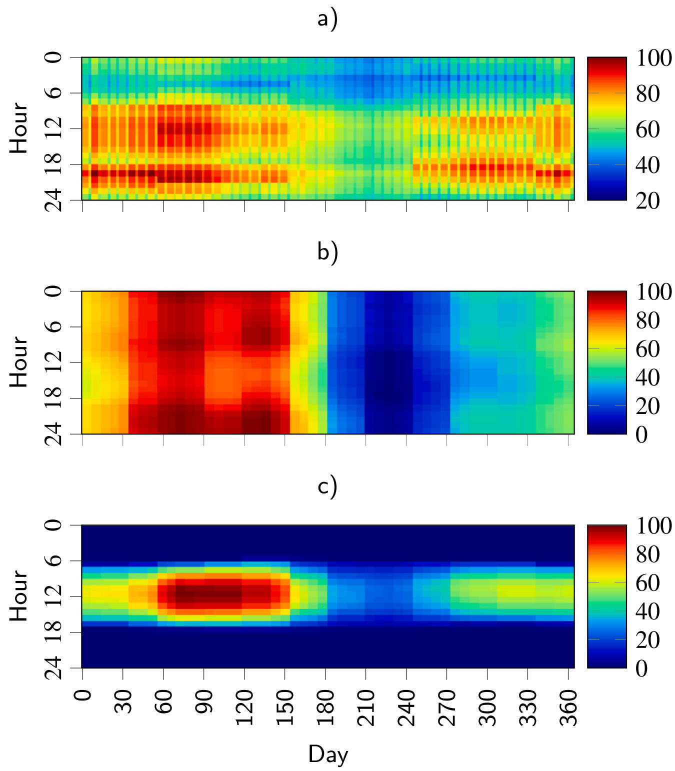

Fig. 1. Reference year profiles: demand (a), wind (b), and solar power (c) [23].

2.2. Forecasted energy demand

After the installation of several RES in different islands in 2010s, the focus of the government has been on increasing energy access, which has grown from 80% in 2011 to 92% in 2020. The current target is to ensure full energy access by 2025 [34]. In addition, tourism, which represents the main industry of the country, was growing at a very fast pace until the COVID-19 crisis. Nevertheless, it is expected to recover from 2022 onward, and continue with the rapid expansion and growth. The economic prosperity coming hand-on-hand with the development of tourism poses additional pressure in the energy system of the archipelago. For instance, water desalination represents the largest consumption in the system [30]. This, combined with the forecast of a nearly exponential growth of their clean water needs for the next decade possess additional challenges [35]. In addition, population is expected to grow at a 3% rate, although the demographics are expected to slow down rapidly beyond the 2030 horizon following the example of other developing countries [36]. Then, direct electricity consumption from tourists will impact the demand, for example with energy intensive devices like air-conditioning systems, which are not available to the vast majority of the local population.

The CVRS includes hourly demand profiles of a typical year, as presented in Fig. 1a, where it should be noted how the demand follows a classic double peak shape with maximums around 12 PM and 7 PM. Autumn and winter present the highest consumption levels, lowering during spring and summer. Regarding uncertainty towards the future system evolution, three different possible growing rates are defined for the energy demand of the country: 1, 3, and 5%, as the low growth (Low), reference (Ref) and high growth (High) scenarios, respectively [17,35]. These are depicted in Fig. 2 using consumption

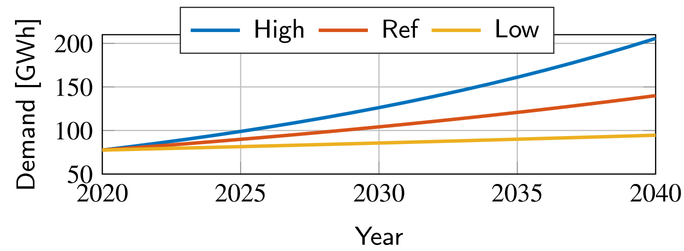

Fig. 2. Demand growth rates.

data from 2020 as the starting value. Lower growth is justified by assuming a slow increase of energy access to the Cape Verdean population, with very limited economic development. In addition, the high growth scenario is justified by a large economic growth, which is reasonable given the touristic and natural potential of the archipelago. Moreover, transport is not currently electrified, and considering that several studies point out the benefits of this approach for islands [37], it could cause a further increase in electricity demand.

2.3. Renewable energy potential

The hourly renewable resource of the island is presented in Fig. 1b and Fig. 1c. Wind power presents a sharp seasonality, with most of the generation capacity concentrated from late December to June and extremely limited availability during the summer months. Similarly, most of the solar resource is available from February to June, with very limited resource during the summer months. This is explained by the cloud coverage during the wet season. On average, there are 11 h of PV production per day. The importance of energy storage in a renewable dominated scenario is evident based on these figures since it is necessary to shift generation capacity from winter towards summer as to accommodate the demand. As for other alternatives, there are no conclusive studies available regarding the potential for other RES like geothermal or tidal energy. Regarding biomass, despite being included in [19] as one of the possible units, the islands present an extremely low land productivity which would force to import biomass from other countries [38]. Since one of the targets is to reduce the external dependency, this study does not consider biomass as part of the analysis.

3. Methodology

In order to compute the GEP, we created a dataset including different generators and storage units with predefined modular size. The algorithm obtains which units to build, how to operate them, and the number of modules of each specific technology as an integer multiplied by basic size up to a maximum of N. This method reduces the computational burden of optimally sizing the units, and allows a gradual expansion of the energy system. The available units to be chosen are: diesel generator (G), WF, solar photovoltaic (PV) and BESS, which are assumed a 20 years lifetime from the moment they are built. Note that this study only discusses the most significant parameters. However, all the information, prices, parameters, etc. regarding the considered units can be accessed by the interested reader in Appendix A.

The complete set of implemented parameters includes purchasing prices, fixed and variable operation and maintenance costs, minimum

Table 2
Overview of the cost of each unit.

Type	Build cost [M€/MW]	Maintenance		r
		Fixed [k€/MWy]	Variable [€/MWh]	
G	1	50	88	1
WF	1.3	37	13	0.994
PV	0.7	15	8.9	0.972
BESS	1.2	31	0	0.972

Table 3
Model configuration summary.

Base load	r_{EMSS}	$\frac{e}{t\ CO_2}$	RU	RD	RES Uncert
0.5	1.18	25	0.25	0.25	0.25

and maximum ratings, ramping limits, minimum stopping limits, maximum starting ratings, minimum and maximum up and down periods, remaining lifetime (only for already existing units), fuel consumption, emissions, marginal cost of production and reserve, start and stop costs. The diesel emissions are considered as 3.15 tons of CO_2 per ton of fuel. Regarding BESS units, the included data is divided in charging and discharging operation, efficiencies, initial, minimum and maximum SOC.

3.1. Prices justification and evolution

The considered economic costs of each unit, presented in Table 2, are based on a survey of different reports [1,24–29] and the yearly accounts of both Electra, the SO, and Cabeólica, the biggest renewable utility in Cape Verde [30,31].

Table 3 presents data related to the problem configuration: the base load is given by the SO along with ramp up (RU) and down (RD) requirements, which are defined as a proportion of the hourly load defined in [23]. We considered a 5% annual discount rate r, accounting for the effects of inflation. This value is common for all scenarios and technologies. However, each individual unit is also affected by another coefficient r_x determining its yearly price evolution, which are also presented in the same table. Note that the price of RES and BESS reduces over time, while the price for Gs is considered frozen. The penalty related to emissions ($\frac{e}{t\ CO_2}$) and its yearly rate are taken from the conservative end of the values recommended by [1]. Note that these coefficients make the operation of fossil fuel units more expensive over time rapidly. Decommissioning costs have not been included due to two factors. First, the lack of consistent data regarding its cost. Second, it will only affect the already existing units as their lifetime expires before the end of the 20 year horizon and not the new units, which are the critical piece of any generation expansion problem.

3.2. Scenario definition

We define three scenarios based on the current situation, the most economically viable and the government goals.

Business as usual (BAU): It portrays the current state and mode of operation of the system, thus representing the baseline. Its main characteristics are: RES are limited to a maximum penetration of 20% and are not allowed to provide reserve. However, BESS is allowed in this system, since the SO is planning its inclusion in the near future.

Optimal: It represents the most economically viable scenario. It has no restrictions regarding RES penetration and it allows reserve provision with a penalty of 25% accounting for the forecast uncertainty.

Green: It implements the same conditions as the Optimal, plus additional requirements regarding RES penetration goals based on current governmental policies. That is, a 50% penetration rate by 2030 and 100% by 2040.

3.3. Generation expansion model

GSEP is applied to make informed decisions considering both long and short term objectives as investments and operation. Such decisions are usually carried as a periodic multistage process, since investment and operational decisions are taken once a year and once per hour respectively. Hence, a model capturing this dynamic is large-scale by default, having computational tractability as its major issue. There are a number of simplifying assumptions such as rolling windows or representative periods allowing to reduce this complexity at the expense of accuracy loss.

GSEP models are classified as static or dynamic based on when are the investment decisions taken. The former considers a single decision point at the beginning of the horizon, while the latter allows several points over the whole period. Static models are simpler as they allow to represent the whole horizon with a single year taken as baseline. Since demand is usually considered as increasing, the last year is taken as reference in order to ensure fulfilling the maximum demand needs. A dynamic approach allows to consider more years. The advantage of static over dynamic models is simplicity. However, they tend to oversize the units and it is not clear when these units should enter into operation. They also result challenging when predicting the actual load considering such a long horizon as small deviations propagate rapidly. One way to overcome intractability is to select characteristic periods representing a longer one (e.g. 1 week to represent 1 month). This way, it is possible to represent reduced versions of a year, providing a better perspective of when are the investments needed over time. However, the results might not be feasible in practice due to the loss of information suffered in the operational side.

Historically, GSEP tend to avoid including intraday constraints such as rampings, maximum on/off times, or other operational restrictions such as reserve. While those were fair assumptions in traditional power systems, they do not hold in RES-based systems [39,40]. In fact, neglecting operational flexibility results in under-investment in flexible generation and storage, ultimately leading to reserve shortage, load shedding and curtailment of renewable generation [41]. Therefore, we include the most representative constraints related to short-term system dynamics, such as power balance, reserve, rampings and minimum and maximum on/off times. The GSEP is formulated deterministically, which enables optimising longer horizons with high resolution. Uncertainty is then considered by performing a sensitivity analysis of the load evolution considering three possible outcomes: low, medium and

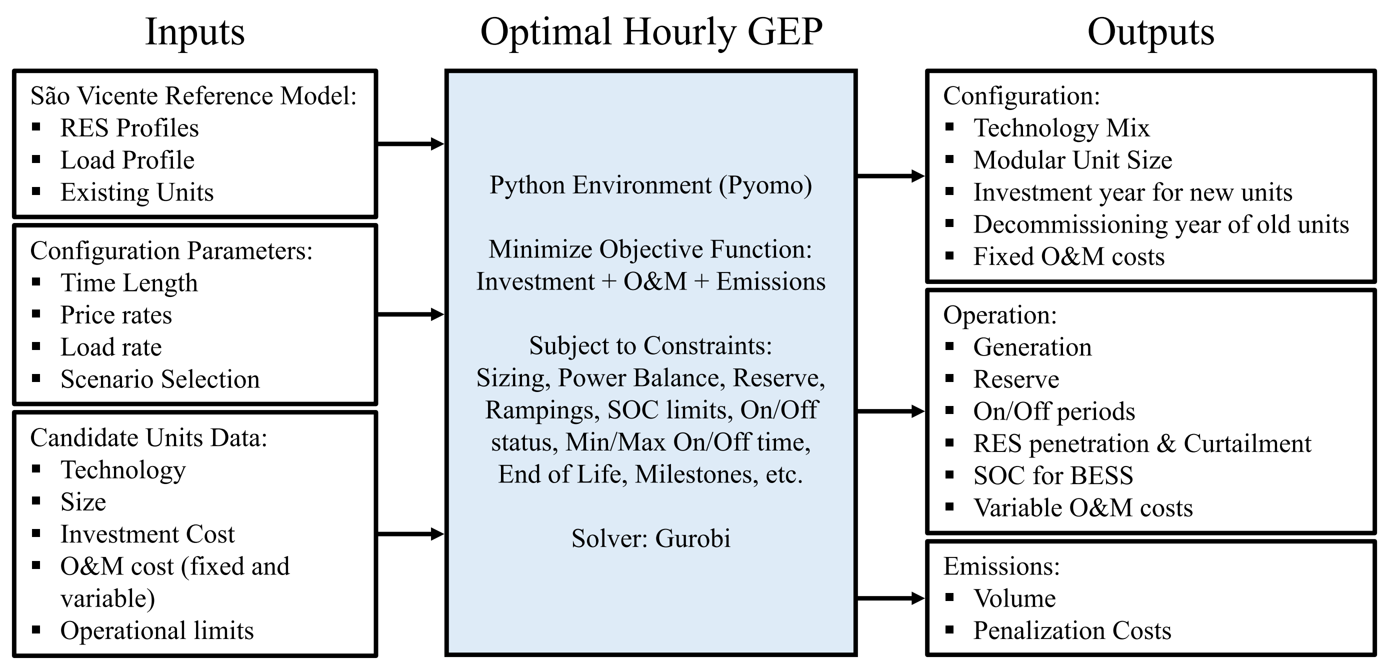

Fig. 3. Graphical representation of the GSEP.

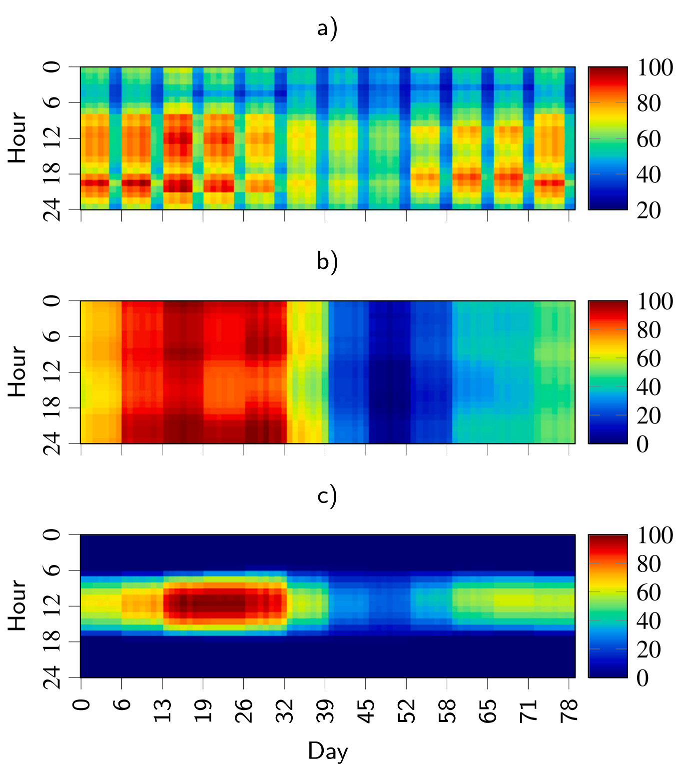

Fig. 4. Equivalent Week profiles: demand (a), wind (b), and solar power (c).

high increases. All the constraints and representative information about the GSEP model are summarised in Fig. 3, while the full mathematical description is available in Appendix B.

Model complexity for a single year is computationally manageable. In fact, the full static model considered 10,000 h in order to introduce knowledge of the beginning of the following year. This is a common practice known to improve a model's ability to capture seasonality and periodicity. Yet, note that the considered results correspond to the first 8,760 h. In addition, we also formulated the problem using one equivalent week per month and year; that is 84 days/year or 40,320 h in 20 years. The equivalent weeks (EW) were obtained from the original dataset using the method by Growe et al. [42] and are presented in Fig. 4. This method allows, first, to compute the dynamic GSEP for the 20 years horizon and, second, to also consider the model as static to evaluate modelling sensitivity. In the EW we used 2,318 time periods for the optimisation, 2,016 for the results.

Lastly, it is worth mentioning that network-related constraints are not modelled, hence, the GSEP is formulated as a single-node model. The advantage of a multi-node model is to capture congestions in the lines or even to study the effects of topology changes. This of course adds a variable degree of further complexity depending whether a DC or an optimal power flow are implemented. Nevertheless, we discarded this due to the fact that the grid in Cape Verde is currently in expansion and this process is expected to continue during the foreseeable future following criterias related to energy access and political will, rather than techno-economical feasibility. Thus, falling out of scope.

Summarising, the GSEP is formulated as single-node, deterministic and both static for the last year using one EW per month, and dynamic using only the reference weeks approach. Then, uncertainty is tackled with a sensitivity analysis and a comparison among scenarios, models and load levels in order to recommend a final configuration/strategy. A sensitivity analysis of GSEP modelling is presented in Appendix C.

4. Results

This section presents the outcome for the GSEP of São Vicente under BAU, Optimal and Green scenarios for the three load levels over a 20 year horizon. The focus is put on the evolution of the energy mix, the cost distribution and the overall emissions.

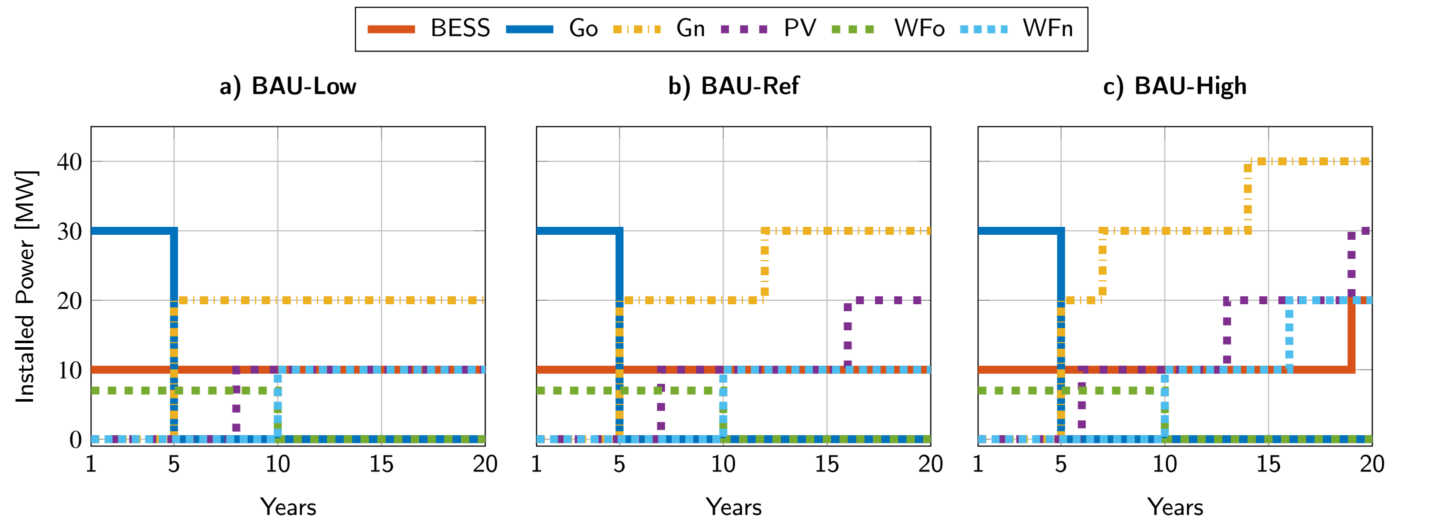

Fig. 5. BAU: Energy mix configuration.

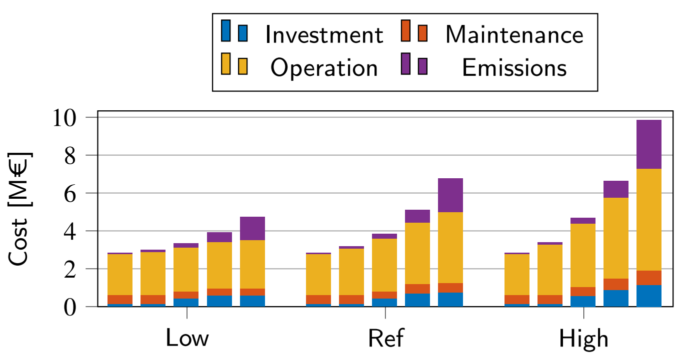

Fig. 6. BAU: Cost distribution years 1, 5, 10, 15, and 20.

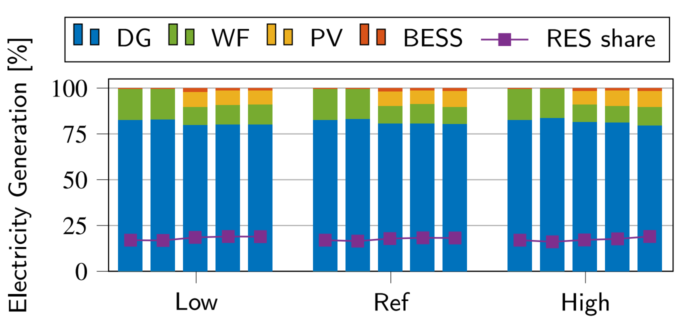

Fig. 7. BAU: Energy Mix years 1, 5, 10, 15, and 20.

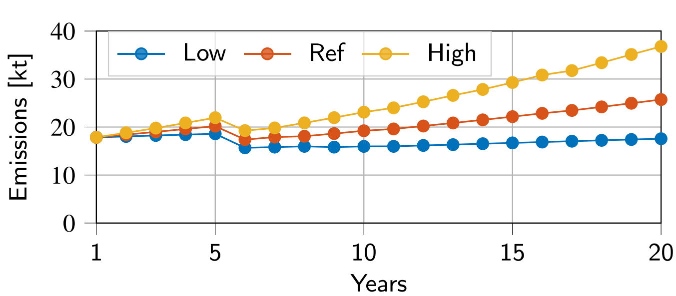

Fig. 8. BAU: Emissions in kt of CO_2.

4.1. BAU

The energy mix evolution over the whole horizon is presented in Fig. 5, where the end-of-life decommissioning date of Go and WFo in years 5 and 10, respectively, should be noted. Besides, given the RES-shares limitation and the reserve provision prevention, the amount of renewables installed is limited. In Ref, fossil-fuels are first reduced from 30 to 20 MW in year 5, but then restored in year 13 back to 30 MW. WFo is replaced with 10 MW, and 20 MW of PV are inserted in two steps. Regarding Low, the only difference is the lack of a second expansion. Conversely, High motivates a third expansion of the fossil-fuelled units up to 30 MW, and a faster renewable development, reaching 40 and 20 MW for PV and WF, respectively.

Given the relatively low installed power in the BAU scenario, we can expect low and homogeneous expenses in the investment category. This is depicted in Fig. 6 along with the rest of the economic categories. The cost distribution among cases is similar and related to the load level, which also drives operational and emissions costs growth. All in all, Investment, Maintenance, Operation, and Emissions represent 12, 8, 54 and 26% respectively for all the scenarios.

Fig. 7 presents the electricity generation distribution, which results almost identical among the different cases. The restrictions of the BAU scenario limit RES shares to 20%, making fossil-fuels the primary energy source representing little over 80% of the overall production every year. It is important to note how the BESS is mostly used for reserves until PVs are included in the system. Then, BESS also start contributing to load shifting. This explains their limited representation over the first few years. Regarding system emissions, these are strongly correlated with the electricity mix. Then, in Fig. 8 the different cases present similar shapes with different growth rates as the emission value is only dependent on the increasing load level. The most interesting result from this scenario might be the ominous forecasting of a 50% emissions increase in 20 years if the operational paradigms are left unchanged.

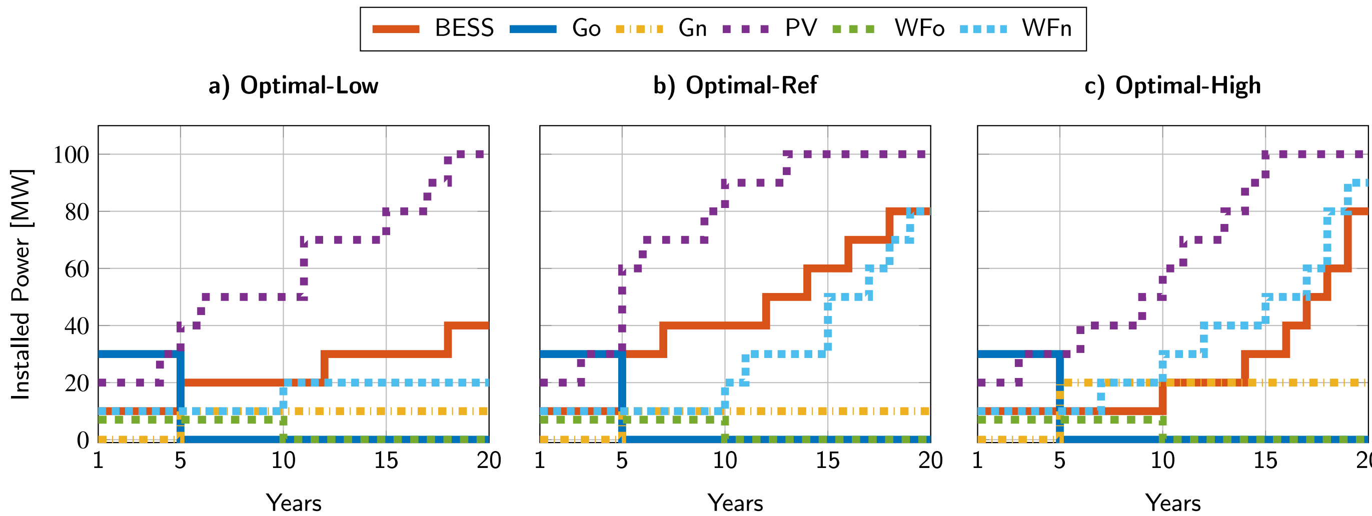

Fig. 9. Optimal: Energy Mix Configuration.

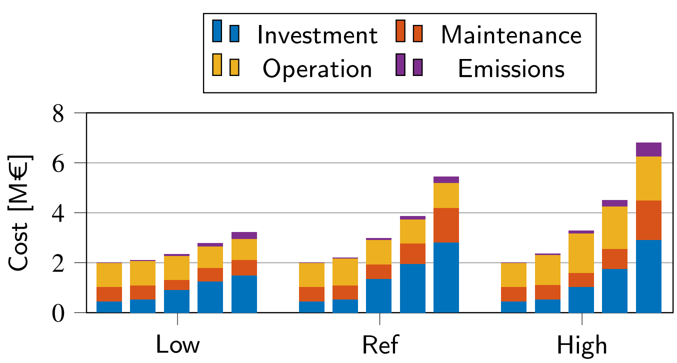

Fig. 10. Optimal: Cost distribution years 1, 5, 10, 15, and 20.

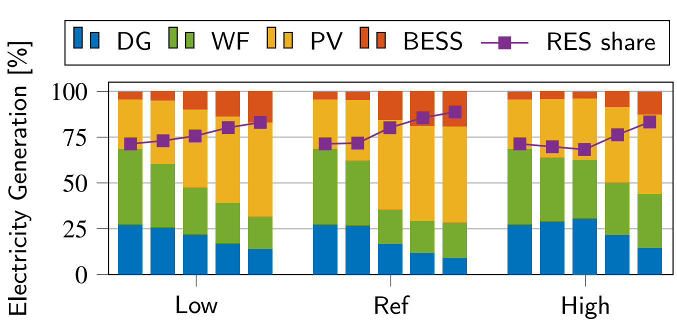

Fig. 11. Optimal: Energy Mix years 1, 5, 10, 15, and 20.

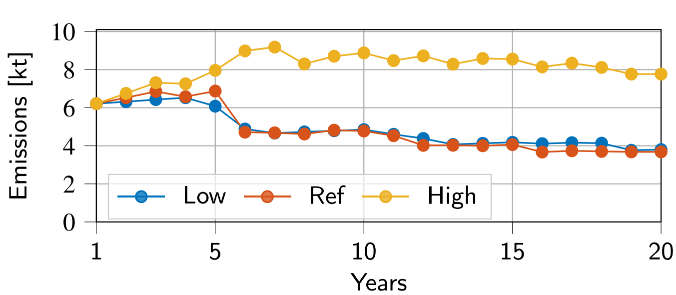

Fig. 12. Optimal: Emissions in kt of CO_2.

4.2. Optimal

Fossil-fuelled units are replaced with 10 MW in the Ref and Low cases and with 20 MW for the high case, as shown in Fig. 9. Solar is the most uniform energy source, starting with 20 MW and expanding to 100 over the horizon with different rates depending on the case. Regarding wind, a 10 MW expansion is done on the first year and after the decommissioning of WFo. Subsequently, wind reaches 80 and 90 MW in Ref and High, respectively. Lastly, BESS start with 10 MW rising up to 40 MW in the Low case and 80 MW in the other two, although presenting faster growth in Ref.

As presented in Fig. 10, the total cost is proportional to the load level, but is differently distributed between cases. In relative terms, Ref presents the highest investment and maintenance costs and the lowest operational and emissions costs with 51, 26, 18 and 5% respectively. Low and High cases present identical distribution for operation and emissions with 26 and 8%, and similar investment and maintenance costs with 47%–43%, and 19%–23%, respectively. Such distribution is explained by the electricity generation distribution, presented in Fig. 11. There, Ref achieves the best RES share level with 89%, compared to 83% in the other two cases, which in practice lowers operational and emissions costs.

Regarding technological distribution, WFs dominate at the beginning of the study, while solar takes over from year 5 or 7 depending on the load level. In Ref, PV dominates the mix and is supported by the rest of the units, while in the other two cases the distribution is more homogeneous. Lastly, diesel shares are similar in Low and High, around 16%; falling to 11% in Ref. Consequently, Ref is the system with lowest emissions as depicted in Fig. 12. Low load levels do not justify investments in large RES and BESS units, which maintains the need for fossil-fuels as bulk generator. As for High, the maximum installation size of 100 MW per technology limits the emission reduction as it forbids the BESS expansion, which would deal with the large seasonal variation. Hence, fossil-fuelled units are again required as base generator.

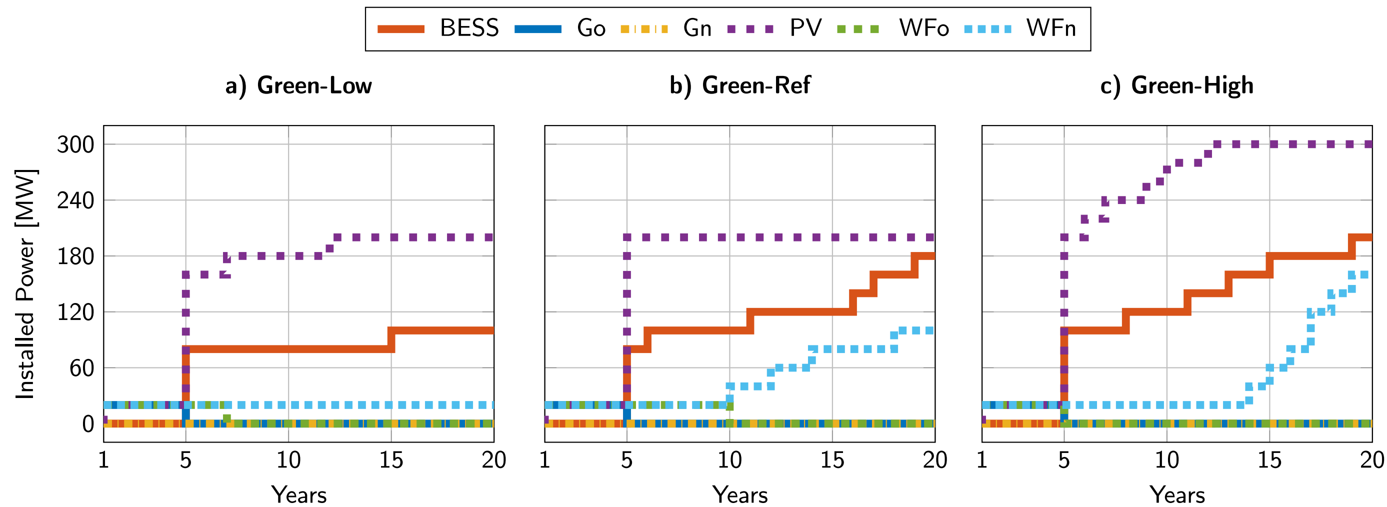

Fig. 13. Green: Energy Mix Configuration.

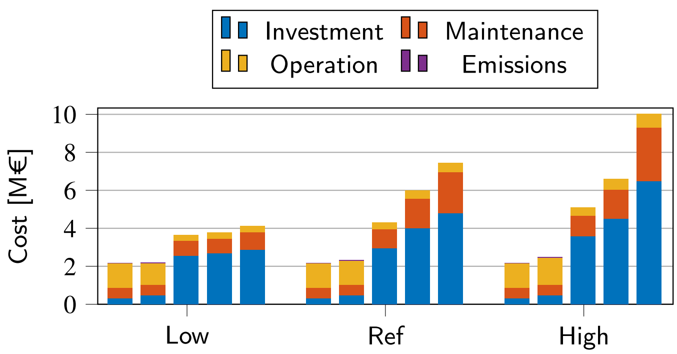

Fig. 14. Green: Cost distribution years 1, 5, 10, 15, and 20.

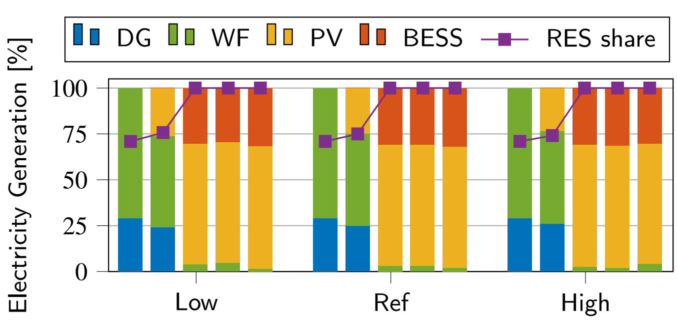

Fig. 15. Green: Energy Mix years 1, 5, 10, 15, and 20.

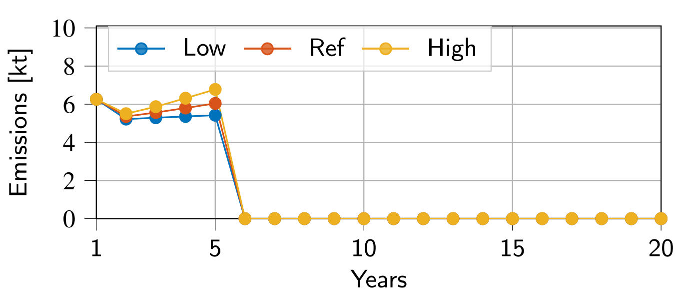

Fig. 16. Green: Emissions in kt of CO_2.

4.3. Green

While the different units were sized in steps of 10 MW up to 10 modules, this scenario required first using 20 MW modules, and second allowing 15 units for the High scenario. Otherwise the problem results unfeasible. This is due to the requirement of reaching 100% RES by year 20, which also avoids the replacement of the fossil-fuelled unit decommissioned after its end-of-life. Hence, as shown in Fig. 13, the system finalises the renewable transition in 2026 (year 5). Solar starts as a relatively small installation with 20 MW in year 2, but ends up reaching the maximum allowed in all the cases. That is, 200 MW for Low and Ref, and 300 MW for High. Regarding WFs, the existing unit stays until its end-of-life in Ref, while being substituted with 20 MW in both Low and High. The final size corresponds to 100 and 160 MW for Ref and High, respectively. Lastly, BESS effectively substitute the fossil-fuel units, gradually reaching 100, 180 and 200 MW in Low, Ref, and High, respectively.

Low and High cases present a cost difference of roughly 50% decrease and 25% increase respectively compared to Ref, as shown in Fig. 14. There, it is clear that distributions are nearly identical for the three cases. Investment, Maintenance, and Operation represent 68, 25, and 7%, respectively.

The evolution and distribution of electricity generation is again virtually identical for all cases as presented in Fig. 15. Fossil-fuelled units produce 25% of the electrical needs until year 5. During this period, WFs dominate the renewable generation, whose overall shares are around 75%. However, this changes radically from year 6, where RES shares reach 100% until the end of the horizon. From this point, solar represents 90% of the electrical penetration, while wind is limited to the remaining 10%. The role of the storage is also common for the three scenarios, and is focused on providing reserve and shifting generation from the rich renewable energy period to the poor one. Subsequently, emissions grow related to the load level until year 5 when they plummet. After the decommissioning of the existing diesel unit, the island of São Vicente becomes 100% renewable, thus emissions free (see Fig. 16).

5. Discussion

This section focuses on analysing in depth the results of the 20 year analysis and its sensitivities. In addition, the interested reader can find a similar discussion regarding the single year static model in Appendix C.

The final configurations for each scenario and load growth level are presented in Table 4. In BAU, there are minor differences between the cases. The influence of the RES-share limitation is remarkable, causing diesel installation to drive renewable installation instead of getting displaced over time. In Optimal, there are small differences between Ref and High of only 10 additional MW in G and WF. Here, Low requires 75% and 50% less WFs and BESS than Ref. These variations are due to the aforementioned operational differences that lead Ref to present a higher RES penetration. Lastly, in Green, power needs grow exponentially following the demand for generators, but not for storage. Low represents 20% and 45% reduction in wind and storage compared to the reference. Concerning High, there is a 60, 50 and 10% increase in terms of WFs, PVs and BESS, respectively.

Disregarding modelling approaches, the results show clear tendencies. For instance, if the operational paradigm is kept unchanged, the island of São Vicente faces a very expensive future, both in economic and pollution terms. Given the developing character of the country and considering tourism as their main industry, it is clearly the worst option. The scenario aligned with the government goals, Green, results far-fetched with current technology since it would imply an extreme generation over-installation along with very large and expensive BESS, which should be replaced periodically due to degradation. Nevertheless, since the government has already adapted these milestones in the past according to technical limitations, they can be considered as helpful motivators towards a green transition. Lastly, the most economical scenario is the Optimal, where São Vicente reaches high RES shares of around 90% with fewer installed capacity, thus increasing the system efficiency. Therefore, the authors recommend to follow the configuration proposed in the reference case of the optimal scenario, as it is flexible enough to allow pivoting towards greener or more energy intensive plans.

A recently published study for the Faroe Islands, Denmark went beyond the now classical RES, wind and solar; exploring other sources such as wave and tidal [13]. In the case of Cape Verde, there is one study evaluating the wave energy potential which highlights the resource available, particularly for the northern islands, such as São Vicente [43]. Unfortunately, the study identifies the wave resource to match that of the wind. Therefore, it would not help to mitigate the extreme energy seasonality of the archipelago. Furthermore, offshore installations in the archipelago are potentially complex given the large oceanic depth already preventing the interconnection of the islands. Also, wave energy does not present commercial readiness to a comparable level with wind and solar deeming it more expensive.

On a different direction, given the volcanic origin of the archipelago, geothermal is expected. There are no studies about São Vicente, but the latest evaluations conducted in Fogo, and Santo Antão point towards the availability of such resource in small amounts [44]. Whether this potential could be enough to substitute fossil fuels as base-load in a generation mix similar to the optimal remains unknown [22]. Then, biomass was seen as a carbon neutral alternative to diesel by Ferreira et al. [19], the latest study regarding GSEP in Santiago. Besides the doubts regarding the carbon-neutrality of biomass-based electrical generation, there is nearly no biomass production potential in the islands, which would maintain imports dependency. Thus, we recommend a energy potential study of the islands, whose results could modify the energy mixes proposed in this study. Also, the development of new energy storage technologies such as molten-salt or gravity-based could keep the energy mix, while modifying the installed technology.

Table 4
Energy mix summary for the Dynamic model [MW/MWh].

Scenario	Case	G	WF	PV	BESS
BAU	Low	20	10	10	10/40
	Ref	30	10	20	10/40
	High	40	20	30	20/80
Opt	Low	10	20	100	40/160
	Ref	10	80	100	80/320
	High	20	90	100	80/320
Green	Low	0	20	200	100/400
	Ref	0	100	200	180/720
	High	0	160	300	200/800

A limitation of this study worth mentioning is the non-consideration of the transmission system expansion. While it might not be necessary in terms of capacity for the reference load levels in both BAU and Optimal scenarios, it is unavoidable in the Green scenario given the required over-installation. However, the transmission system expansion was not undertaken to keep tractability of the problem. In addition, it does not result critically important given the energy access goals set by the government, which will cause a number of grid expansions and reinforcement yet to be decided difficult to capture in any analysis. Nevertheless, a complementary study shows the most suitable locations for new generation and storage installations according to power system resiliency [33].

6. Conclusions

Islands, particularly those in developing states, are in high need for inclusion and support in the transition to RES-based energy systems. This paper proposes an optimal GSEP with hourly resolution and spanning 20 years, using São Vicente island in Cape Verde as study case. The formulation minimises the addition of investment, maintenance, operation and emissions costs for three different scenarios: BAU, Optimal and Green. The first represents the current operational paradigm of the system expected to continue in the near future; a cap on RES shares of 20% and the impossibility for RES to provide reserve. The second does not present any particular restriction and the last imposes a minimum of 50 and 100% RES-shares penetration in 2030 and 2040, as according to the government goals.

The modelling approach is detailed, described, and validated in Appendices B and C. The results of the sensitivity analysis point towards the suitability of the EW method to capture both power and energy dynamics. Then, uncertainty is addressed with three load evolution levels: Low, Ref and High, corresponding to 1, 3 and 5% yearly demand growth rates, respectively. The lack of major variations across cases justifies the robustness of the proposed method. Moreover, RES-related stability issues are tackled based on generous reserve requirements following the trend in large power systems like the European. For instance, WF in the Iberian system are mandatorily requested to keep a 1.5% of their available power ready for fast ramping [45]. In the proposed GSEP, RES uncertainty is heavily penalised, increasing the security level and favouring dispatchable resources.

There are two major findings in this study, the cost-based ranking of the scenarios and their quantitative differences. Green is the most expensive due to the over-installation, caused by the extreme seasonality of the available renewable resources and the high price of energy storage. BAU is not much cheaper, roughly 7%, but presents large emissions levels which approximately double over the horizon.

Lastly, the Optimal scenario presents a cost reduction of 30 and 25% compared with the other two. It limits the over-installation needed by running fossil-fuelled generators during the energy poor period of the year, reaching about 90% RES-share. In this sense, Optimal presents a double benefit as not only ranks as economically superior, but presents an impressive renewable penetration level. In addition, it is flexible enough to accommodate other generation or storage technologies that might reach commercial stage during the studied horizon.

Nomenclature

Sets and Indices:	
$\mathcal{A}$	Generators
$\mathcal{A}^p \subseteq \mathcal{A}^r$	PV power plants
$\mathcal{A}^r \subseteq \mathcal{A}$	Renewable generators
$\mathcal{A}^s \subseteq \mathcal{A}$	Synchronously coupled generators
$\mathcal{A}^t \subseteq \mathcal{A}^s$	Thermal generators
$\mathcal{A}^w \subseteq \mathcal{A}^r$	Wind farms
$\mathcal{B}$	Built units in the first year
c/d	Charge/discharge operational state
$h \in H$	Operational time periods (hours)
$H^b \subseteq H$	All hours in the year but the first
$H^e \subseteq H$	First hour of each year
$j \in J$	Investment time periods (years)
$\mathcal{L}$	Demand
$\mathcal{NB}$	Non-built units in the first year
$\mathcal{S}$	BESS units
$\mathcal{U} \in \mathcal{A} \cup \mathcal{S}$	Unit
y	Year corresponding to hour h
α, β	Milestone years
Ξ	Set of all variables
Parameters:	
$\underline{DR}, \underline{UR}$	Downward/upward reserve [% of base load]
$\overline{DR}, \overline{UR}$	Maximum ramp-down/up limit [MW]
E	Emissions cost [€/ton CO_2]
FC	Consumption of fuel [tons of fuel/MW]
FE	Fuel emissions [tons CO_2/tons of fuel]
G	Growth rate profile
H^{dw}	Number of periods t until decommission
$\underline{H^{up0}}, \underline{H^{dw0}}$	Minimum on/off time from initial h
$\overline{H^{up0}}, \overline{H^{dw0}}$	Maximum on/off time from initial h
$\overline{H^{up}}, \underline{H^{up}}$	Maximum/minimum on time [periods h]
$\underline{H^{dw}}$	Minimum off time [periods h]
I	Investment cost [€]
$\widetilde{L}$	Demand profile [p.u.]
$\overline{L}$	Demand peak [MW]
M^f	Fixed maintenance cost [€]
M^v	Variable maintenance cost [€/MWh]
$\overline{N_j^m}$	Maximum number of modules per unit
N^h	Hours in a year
N^j	Total number of years
O^o	Operational cost [€/MWh]
O^{rd}, O^{ru}	Downward/Upward regulation cost [€/MWh]
O^{sh}	Shut-down cost [€]
O^{st}	Start-up cost [€]
$\overline{P}, \underline{P}$	Maximum/minimum power limit [MW]
$\overline{P^{sh}}$	Maximum power before shut-down [MW]
$\overline{P^{st}}$	Maximum start-up power [MW]
$\overline{R}$	Maximum share of RES [p.u.]
$\widetilde{R}$	Profile of maximum RES share [p.u.]
R^s	RES uncertainty [p.u.]
$T^y\ y \in \{\alpha, \beta\}$	RES share milestone [p.u.]
$\overline{V}, \underline{V}$	Maximum/minimum SOC [MWh]
V^b	Initial SOC [MWh]
X	Discount rate
ΔE	E growth rate
ΔI	I growth rate
ΔL	Demand growth rate
η	Efficiency [p.u.]
τ	Year for decommissioning
Variables:	
e	Emissions cost [€]
g	Fuel consumption [tons of fuel]
i	Investment cost [€]
m	Maintenance cost [€]
n^m	Number of modules (integer)
o	Operational cost [€]
o^{sh}	Shut-down cost [€]
o^{st}	Start-up cost [€]
p	Power output [MW]
$\overline{p}$	Max available power [MW]
r^{dw}	Downward reserve [MW]
r^{up}	Upward reserve [MW]
v	SOC [MWh]
w	CO_2 emissions [tons of CO_2]
σ	Binary. 1 if online, and 0 otherwise
σ^{aux}	Integer auxiliary variable

CRediT authorship contribution statement

Daniel Vázquez Pombo: Conceptualization, Methodology, Software, Validation, Formal analysis, Resources, Data Curation, Writing – original draft, Visualization. **Jon Martinez-Rico:** Conceptualization, Methodology, Validation, Writing – original draft, Visualization, Supervision. **Hannah M. Marczinkowski:** Supervision, Writing – original draft.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors would like to thank the Ministry of Industry, Commerce and Energy of Cape Verde, and the teams from Electra and Cabeólica for their collaboration and support.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.11583/DTU.14778243.

Appendix B. Mathematical formulation

The MILP formulation of the optimisation problem described in Section 3 is presented here. It minimises the incidence of integer variables employing one for the sizing, a binary for on/off state and another auxiliary to linearise their product. It keeps tractability despite simultaneously sizing generation and storage employing high resolution and long horizons as hours and 20 years using 12 equivalent weeks per year. RES-related stability issues are covered with massive reserve requirements and uncertainty related penalties following the example of upcoming European regulations. For instance, wind farms in the Iberian market are mandatorily requested to keep a 1.5% of their available power ready for fast symmetric ramping [46].

Index h represents the hours, j the years, and y the year corresponding to h. Note that, BESS perform both c/d states while generators only present the later. The objective function is defined in Eqs. (1)–(5) and is conformed by investment (i), maintenance (m), operational (o) and emissions (e) costs. These are further defined in Eqs. (6)–(12).

$$\min_{\Xi} \quad i + o + m + e \tag{1}$$

$$i = \sum_{j}^{J} \mathcal{I}_{j,u}(1+X)^{-j}, \quad \forall j, \forall u \in \mathcal{U} \tag{2}$$

$$o = \sum_{h}^{H} o_{h,u} + o^{st}_{h,u} + o^{sh}_{h,u}, \quad \forall h, \forall u \in \mathcal{U} \tag{3}$$

$$m = \sum_{j}^{J} m_{j,u}, \quad \forall j, \forall u \in \mathcal{U} \tag{4}$$

$$e = \sum_{h}^{H} \sum_{u}^{\mathcal{A}^t} w_{y,u} E \Delta E, \quad \forall h, \forall u \in \mathcal{A}^t \tag{5}$$

$$i_{j,u} \geq I_u\, \Delta I_u n^m_{j,u}, \quad j = 1, \forall u \in \mathcal{U} \tag{6}$$

$$i_{j,u} \geq i_{j-1,u} + I_u\, \Delta I_u \left(n^m_{j,u} - n^m_{j-1,u}\right), \quad \forall j > 1, \forall u \in \mathcal{U} \tag{7}$$

$$o_{h,u} \geq O^o_u (p^d_{h,u} + p^c_{h,u}) + O^{ur}_u r^{up}_{h,u} + O^{dr}_u r^{dw}_{h,u}, \quad \forall h, \forall u \in \mathcal{U} \tag{8}$$

$$o^{st}_{h,u} \geq O^{st}_u \left(\sigma_{h,u} - \sigma_{h-1,u}\right), \quad \forall h > 1, \forall u \in \mathcal{U} \tag{9}$$

$$o^{sh}_{h,u} \geq O^{sh}_u \left(\sigma_{h-1,u} - \sigma_{h,u}\right), \quad \forall h > 1, \forall u \in \mathcal{U} \tag{10}$$

$$m_{j,u} \geq M^f_u n^m_{j,u} + \sum_{(j-1)N^h+k}^{jN^h} p_{k,u} M^v_u, \quad \forall j, \forall k = 1 : N^h N^j, \forall u \in \mathcal{U} \tag{11}$$

$$i_{h,u}, m_{h,u}, o_{h,u}, o^{st}_{h,u}, o^{sh}_{h,u} \geq 0, \quad \forall h, \forall u \in \mathcal{U} \tag{12}$$

Integer variables are defined in (13)–(18), including an auxiliary variable linearising the product of $\sigma_{h,u}$ and $n^m_{j,u}$.

$$\sigma_{h,u}, \sigma^{aux}_{h,u} \in \{0, 1\}, \quad \forall h, \forall u \in \mathcal{U} \tag{13}$$

$$n^m_{j,u} \in \left[0, \overline{N^m_u}\right] \in \mathbb{Z}, \quad \forall h, \forall u \in \mathcal{U} \tag{14}$$

$$\sigma^{aux}_{h,u} \leq \overline{N^m_u}\, \sigma_{h,u}, \quad \forall h, \forall u \in \mathcal{U} \tag{15}$$

$$\sigma^{aux}_{h,u} \leq n^m_{y,u}, \quad \forall h, \forall u \in \mathcal{U} \tag{16}$$

$$\sigma^{aux}_{h,u} \geq n^m_{y,u} - \overline{N^m_u} \left(1 - \sigma_{h,u}\right), \quad \forall h, \forall u \in \mathcal{U} \tag{17}$$

$$\sigma^{aux}_{h,u} \geq 0, \quad \forall h, \forall u \in \mathcal{U} \tag{18}$$

Commissioning rules are covered in (19)–(23). On/off states and existence are linked with (24), and operational bounds are defined in (25)–(28).

$$n^m_{j,u} = 1, \quad j = 1, \forall u \in \mathcal{B} \tag{19}$$

$$n^m_{j,u} \geq n^m_{j+1,u}, \quad \forall j < J, \forall u \in \mathcal{B} \tag{20}$$

$$n^m_{j,u} = 0, \quad \forall j \geq \tau_u, \forall u \in \mathcal{U} \tag{21}$$

$$n^m_{j,u} \leq n^m_{j+1,u}, \quad \forall j < J, \forall u \in \mathcal{NB} \tag{22}$$

$$n^m_{j,u} = 0, \quad j = 1, \forall u \in \mathcal{NB} \tag{23}$$

$$\sigma_{h,u} \leq n^m_{y,j}, \quad \forall h, \forall u \in \mathcal{U} \tag{24}$$

$$\underline{P^{c/d}_u} < p_{h,u} < \overline{P^{c/d}_u}\, \overline{N^m_u}, \quad \forall h, \forall u \in \mathcal{U} \tag{25}$$

$$\underline{P^{c/d}_u} < \overline{p^{c/d}_{h,u}} < \overline{P^{c/d}_u N^m_u}, \quad \forall h, \forall u \in \mathcal{U} \tag{26}$$

$$0 < r^{up}_{h,u} < \left(\overline{P^d_u} + \overline{P^c_u}\right) \overline{N^m_u}, \quad \forall h, \forall u \in \mathcal{U} \tag{27}$$

$$0 < r^{dw}_{h,u} < \left(\overline{P^d_u} + \overline{P^c_u}\right) \overline{N^m_u}, \quad \forall h, \forall u \in \mathcal{U} \tag{28}$$

On/off states are imposed with (29)–(35) minimising the appearance of $\sigma^{aux}_{h,u}$; reducing the solving time. Then, operation and reserve are coupled with (36)–(41), while ramps and other dynamics are covered in (42)–(44).

$$p^{c/d}_{h,u} \geq \underline{P^{c/d}_u}\, \sigma^{aux}_{h,u}, \quad \forall h, \forall u \in \mathcal{U} \tag{29}$$

$$\overline{p_{h,u}} \leq \overline{P_u}\, \sigma_{h,u}\, \overline{N^m_u}, \quad \forall h, \forall u \in \mathcal{A}^s \tag{30}$$

$$\overline{p_{h,u}} \leq \overline{P_u}\, n^m_{j,u}, \quad \forall h, \forall u \in \mathcal{A}^s \tag{31}$$

$$\overline{p_{h,u}} \leq \overline{P_u}\, \sigma_{h,u}\, \overline{N^m_u}\, \widetilde{R_h}, \quad \forall h, \forall u \in \mathcal{A}^r \tag{32}$$

$$\overline{p_{h,u}} \leq \overline{P_u}\, \widetilde{R_h}\, n^m_{j,u}, \quad \forall h, \forall u \in \mathcal{A}^r \tag{33}$$

$$\overline{p^{c/d}_{h,u}} \leq \overline{P^{c/d}_u}\, \sigma_{h,u}\, \overline{N^m_u}, \quad \forall h, \forall u \in \mathcal{S} \tag{34}$$

$$\overline{p^{c/d}_{h,u}} \leq \overline{P^{c/d}_u}\, n^m_{j,u}, \quad \forall h, \forall u \in \mathcal{S} \tag{35}$$

$$p_{h,u} + r^{up}_{h,u} \leq \overline{p_{h,u}}, \quad \forall h, \forall u \in \mathcal{A} \tag{36}$$

$$p_{h,u} - r^{dw}_{h,u} \geq 0, \quad \forall h, \forall u \in \mathcal{A} \tag{37}$$

$$p^d_{h,u} + r^{up}_{h,u} - p^c_{h,u} \leq \overline{p^d_{h,u}}, \quad \forall h, \forall u \in \mathcal{S} \tag{38}$$

$$p^c_{h,u} + r^{dw}_{h,u} - p^d_{h,u} \leq \overline{p^c_{h,u}}, \quad \forall h, \forall u \in \mathcal{S} \tag{39}$$

$$r^{up}_{h,u} \leq \overline{p^d_{h,u}} + \overline{p^c_{h,u}}, \quad \forall h, \forall u \in \mathcal{S} \tag{40}$$

$$r^{dw}_{h,u} \leq \overline{p^d_{h,u}} + \overline{p^c_{h,u}}, \quad \forall h, \forall u \in \mathcal{S} \tag{41}$$

$$\overline{p^{c/d}_{h,u}} \leq \overline{p^{c/d}_{h-1,u}} + \overline{UR^{c/d}_u}\, \sigma^{aux}_{h-1,u} + \overline{P^{c/d,st}_u} \left(\sigma^{aux}_{h,u} - \sigma^{aux}_{h-1,u}\right) + \overline{P^{c/d}_u} \left(n^m_{y,u} - \sigma^{aux}_{h,u}\right), \quad \forall h > 1, \forall u \in \mathcal{U} \tag{42}$$

$$\overline{p^{c/d}_{h,u}} \leq \overline{P^{c/d}_u}\, \sigma^{aux}_{h+1,u} + \overline{P^{c/d,sh}_u} \left(\sigma^{aux}_{h,u} - \sigma^{aux}_{h+1,u}\right), \quad \forall h < H, \forall u \in \mathcal{U} \tag{43}$$

$$p^{c/d}_{h-1,u} - p^{c/d}_{h,u} \leq \overline{DR^{c/d}_u}\, \sigma^{aux}_{h,u} + \overline{P^{c/d,sh}_u} \left(\sigma^{aux}_{h-1,u} - \sigma^{aux}_{h,u}\right) + \overline{P^{c/d}_u} \left(n^m_{y,u} - \sigma^{aux}_{h-1,u}\right), \quad \forall h > 1, \forall u \in \mathcal{U} \tag{44}$$

On/off periods are expressed as (45)–(52). Then, power and reserve are balanced with (53)–(55). RES-shares limits and milestones are imposed with (56)–(57).

$$\sum_{k=1}^{\underline{H^{up0}_u}} \left(1 - \sigma_{k,u}\right) = 0, \quad \forall u \in \mathcal{U} \tag{45}$$

$$\sum_{n=k}^{k+\underline{H^{up}_u}-1} \sigma_{n,u} \geq \underline{H^{up}_u} \left(\sigma_{k,u} - \sigma_{k-1,u}\right), \quad \forall u \in \mathcal{U}, \forall k = \underline{H^{up0}_u} + 1 \dots H - \underline{H^{up}_u} + 1 \tag{46}$$

$$\sum_{n=k}^{H} \left(\sigma_{n,u} - \left(\sigma_{k,u} - \sigma_{k-1,u}\right)\right) \geq 0, \quad \forall u \in \mathcal{U}, \forall k = H - \underline{H^{up}_u} + 2 \dots H \tag{47}$$

$$\sum_{k=1}^{\underline{H^{dw0}_u}} \sigma_{k,u} = 0, \quad \forall u \in \mathcal{U} \tag{48}$$

$$\sum_{n=k}^{k+\underline{H^{dw}_u}-1} \left(1 - \sigma_{n,u}\right) \geq \underline{H^{dw}_u} \left(\sigma_{k-1,u} - \sigma_{k,u}\right), \quad \forall u \in \mathcal{U}, \forall k = \underline{H^{dw0}_u} + 1 \dots H - \underline{H^{dw}_u} + 1 \tag{49}$$

$$\sum_{n=k}^{H} \left(1 - \sigma_{n,u} - \left(\sigma_{k-1,u} - \sigma_{k,u}\right)\right) \geq 0, \quad \forall u \in \mathcal{U}, \forall k = H - \underline{H^{dw}_u} + 2 \dots H \tag{50}$$

$$\sum_{n=k}^{k+\overline{H_u^{up}}-1} \sigma_{n,u} \leq \overline{H_u^{up}} \left(\sigma_{k,u} - \sigma_{k-1,u}\right), \quad \forall u \in \mathcal{U}, \forall k = 0 \dots H \tag{51}$$

$$\sum_{n=k}^{k+\overline{H_u^{up}}-1} \sigma_{n,u} \leq \overline{H_u^{up}} - \overline{H_u^{dw}}, \quad \forall u \in \mathcal{U}, \quad \forall k \in \{0, H, 2H, \dots, \overline{H_u^{up}} - H, \overline{H_u^{up}}\} \tag{52}$$

$$\sum_{u\in\mathcal{A}} p_{h,u} + \sum_{u\in\mathcal{S}} p^d_{h,u} - \sum_{u\in\mathcal{S}} p^c_{h,u} - \sum_{u\in D} \widetilde{L_h}\, \overline{P_u}\, G_{y,u} = 0, \quad \forall h \tag{53}$$

$$\sum_{u\in\mathcal{A}^s\cup\mathcal{S}} r^{up}_{h,u} + \sum_{u\in\mathcal{A}^r} r^{up}_{h,u} \left(1 - R^s\right) \geq URL\widetilde{L_h}\ \overline{L}\Delta L, \quad \forall h \tag{54}$$

$$\sum_{u\in\mathcal{A}^s\cup\mathcal{S}} r^{dw}_{h,u} + \sum_{u\in\mathcal{A}^r} r^{dw}_{h,u} \left(1 - R^s\right) \geq DR\widetilde{L_h}\overline{L}\Delta L, \quad \forall h \tag{55}$$

$$\sum_{u\in\mathcal{A}^r} p_{h,u} \leq \frac{\overline{R}}{1-\overline{R}} \sum_{u\in\mathcal{A}^s} p_{h,u}, \quad \forall h \tag{56}$$

$$\sum_{u\in\mathcal{A}^r\cup\mathcal{S}} p_{h,u} \geq \sum_{u\in\mathcal{U}} p_{h,u} T^y, \quad h^\alpha \leq h \leq h^\beta \tag{57}$$

$$\sum_{u\in\mathcal{A}^r\cup\mathcal{S}} p_{h,u} \geq \sum_{u\in\mathcal{U}} p_{h,u} T^\beta, \quad h \geq h^\beta \tag{58}$$

Finally, SOC dynamics are defined with (59)–(64), while fuel usage and emissions are covered in (65)–(66).

$$0 \leq v_{h,u} \leq \overline{V_u}\, \overline{N_u^m}, \quad \forall h, \forall u \in \mathcal{S} \tag{59}$$

$$\underline{V_u} n^m_{y,u} \leq v_{h,u} \leq \overline{V_u} n^m_{y,u}, \quad \forall h, \forall u \in \mathcal{S} \tag{60}$$

$$v_{h,u} = V^b_u n^m_{y,u}, \quad h = 0, \forall u \in \mathcal{S} \tag{61}$$

$$v_{h,u} \geq V^b_u n^m_{y,u}, \quad h = H, \forall u \in \mathcal{S} \tag{62}$$

$$v_{k,u} = v_{k-1,u} + \eta^c_u p^c_{k,u} - \frac{1}{\eta^d_u} p^d_{k,u}, \quad \forall k \in H^b, \forall u \in \mathcal{S} \tag{63}$$

$$v_{k,u} = v_{k-1,u} + \eta^c_u p^c_{k,u} - \frac{1}{\eta^d_u} p^d_{k,u} + V^i_u \left(n^m_{y,u} - n^m_{y-1,u}\right), \quad \forall k \in H^e, \forall u \in \mathcal{S} \tag{64}$$

$$g_{j,u} = \sum_{N^h(j-1)+k}^{N^h j} p_{k,u} FC_u, \quad \forall j, \forall k = 1 : N^h N^j, \forall u \in \mathcal{A}^t \tag{65}$$

$$w_{j,u} = g_{j,u} FE_u, \quad \forall j, \forall u \in \mathcal{A}^t \tag{66}$$

Appendix C. Sensitivity analysis

The implications of the different assumptions taken in the formulation are discussed here. Neglecting network constraints is a common practice in GEP problems as it greatly simplifies solving time. Often, the focus is placed on finding the energy mix as grid expansions are conducted based on multiple reasons and not only optimal techno-economic optimisation. Then, distances are much shorter in islands than in the continent. Hence, transmission lines represent a comparatively lower cost fraction than generation and storage. Particularly, developing nations such as Cape Verde are undergoing a fast paced grid expansion in order to comply with energy access goals independently of the GEP. Then, clustering of generation units is also reported as recommended practice due to the benefits of increasing tractability against the minor operational dynamics observed for desagregated generation. Also note that only the already existing diesel units are clustered, thus its effects are neglected. Lastly, most high resolution GEP available in the scientific literature use only a few days to represent the last year equivalent leading to under-investment in dispatchable units. [10,41]

Table 5
Energy mix comparison for the Static model [MW/MWh].

		G	WF	PV	BESS
BAU	Year	30	10	0	10/40
	EW	30	10	0	10/40
Opt	Year	20	30	50	20/80
	EW	20	20	40	20/80
Green	Year	0	200	200	180/720
	EW	0	120	200	160/640

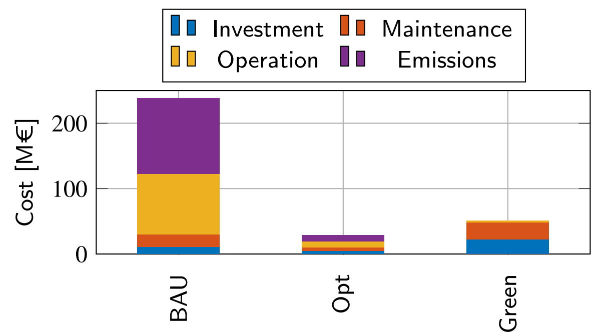

Fig. 17. Resulting cost distribution in the Static model.

The robustness of the equivalent periods methodology is validated by comparing both static formulations (complete and EW) in the Ref case to explore how modelling differences affect the results for the last year equivalent. The comparison focuses on the resulting energy mix, summarised in Table 5, and the cost distribution among investment, maintenance, operation and emissions, depicted in Fig. 17. The latter corresponds to the last year with the investment presented as an annual instalment.

BAU is unaffected by the modelling approach, while Optimal requires additional RES units. Then, Green presents the largest difference pointing towards limitations in capturing energy dynamics of a system including large storage with reference periods. Nonetheless, the cost distribution is virtually identical for all scenarios, suggesting that the importance of each category is balanced and well kept. In BAU, investment represents nearly half of the overall cost, followed by emissions, operation and maintenance, which represent 26, 21 and 4% respectively. Besides replacing the existing units after their end of life, a small BESS is added. Consequently, the balance of the annual cost is tilted towards emission penalties and operation. The Optimal scenario presents higher investment costs reaching 75% of the total, while halving maintenance and operation costs compared to BAU, keeping emissions cost in the same range. However, its annual cost distribution is balanced among the four categories. Lastly, in Green, investments represent 94% of the overall costs due to the over-installation required to deal with the extreme seasonality of the island. The remaining expenses are divided as 5 and 1% among maintenance and operation.

Note how when compared with the 20 year long calculation, BAU returns a nearly identical configuration, while the other two scenarios differ significantly. This is due to the increasing importance of storage in Optimal and Green; since energy dynamics are difficult to capture in both methods. The modelling either fails to fully capture short-term variations or long-term trends. Yet again, the cost distribution is nicely captured highlighting its suitability as GSEP.

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