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Bottom-up energy system models applied to sustainable islands

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ABSTRACT

This paper reviews the existing bottom-up energy system models applied at island level. The aim of the paper is to answer the following research questions: i) which energy system models are mostly used at island level? ii) Are national scale models also used for island applications? If yes, which type of additional constraints or adaptations are implemented? iii) A classification of these constraints will be provided in the paper. iv) Which are the main challenges of energy system models applied at insular level? The mostly used bottom-up energy system models are EnergyPLAN, unit commitment models and HOMER. Almost 37% of the analysed studies present models specifically designed for insular applications. The remaining part utilizes models originally designed for Country (47%) or micro-grid (16%) level applications. The additional constraints required by insular applications have been identified to be: reliability and robustness of the power grid, water desalination, vehicle to grid, demand response and maritime transport. The results have shown that the identified additional constraints are more frequently implemented by models that are specifically designed for insular applications. In particular, unit commitment models are capable to take directly into account reliability and robustness of the power grid constraints while models such as EnergyPLAN, HOMER and H_2RES have to use alternative simplified methods based on the use of indicators to account for them.

1. Introduction

In Europe there are about 2400 islands which are populated by 15 Million inhabitants. These represent 2% of the overall number of Europeans [1]. Most of these islands are characterized by energy systems based on expensive fossil fuels imports. The Clean Energy for EU Islands initiative [2] supports energy transition at island level.

The study of decarbonisation pathways and energy transition in support of policy makers at island level is particularly relevant for the following reasons:

- Islands are one of the most vulnerable areas. Their ecosystems and livelihoods are particularly affected by the impacts of climate change such as the increased recurrence of natural calamities (mostly tropical storms, typhoons, etc.), rise in sea level, climate variability and atypical climatic conditions.
- Energy transition of Islands presents several opportunities. The energy systems of islands are generally based on inefficient fossil fuel technologies. Therefore, the opportunity is both at environmental and economic level. At environmental level, because the introduction of renewable energy generation can improve the overall efficiency, reduce losses and eliminate the energy consumption due to fossil fuels transportation. At economic level, since the price of energy is usually very high due to the transport of fossil fuels and it represents an opportunity for cheaper renewable generation.
- Islands can be seen as frontrunners in the energy transition and, therefore, represent an opportunity to become examples of the decarbonisation process at Country level. The possibility to study and, then, directly implement decarbonisation solutions is an opportunity to quickly test and validate energy system models. A particularly relevant opportunity is given by the possibility to inspect near 100% renewable energy systems. In fact, from a technical point of view the most difficult phase of the energy transition is the final part when moving from 70-80%–100% renewable energy system. This has been demonstrated by different studies. Prina et al. [3] using a multi-objective expansion capacity optimization approach highlighted how the costs to abate the last 20–30% of CO_2 emissions follow an exponential trend. IRENA identified in the industry and transport sectors seven sub-sectors which will be the hardest to be decarbonised. These sectors are the following: iron and steel, chemicals and petrochemicals, cement and lime, aluminium, road

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List of abbreviations

Acronyms

AI	Artificial Intelligence
CHP	Combined Heat and Power
CPP	Critical Peak Pricing
DR	Demand Response
DSM	Demand Side Management
EVs	Electric vehicles
IBDR	Incentive Based Demand Response
LCA	Life-Cycle Analysis
LP	Linear Programming
MILP	Mixed Integer Linear Programming
ML	Machine Learning
MO	Multi-Objective
PBDR	Price Based Demand Response
RE	Renewable Energy
RES	Renewable Energy Sources
RO	Reverse Osmosis
SO	Single-Objective
ToU	Time-of-Use
UC	Unit Commitment
V2G	Vehicle to grid
VRES	Variable Renewable Energy Sources

freight, aviation and shipping. This latter one particularly affects insular case studies and their decarbonisation processes.

The energy systems of islands are dissimilar from the stable and interconnected energy systems at Country level. Scenarios generation and energy system modelling presents some differences when applied at island or Country level. Energy system modelling at island level usually needs some additional requirements to consider the main characteristics of insular areas. These features are the following:

- Intrinsic morphological structure. Islands are characterized by inherent isolation. For this reason, they are highly dependent on their natural surroundings, including conditions affecting possible renewable energy (RE) utilization. The intrinsic morphological structure of the island affects the type of renewable energy sources (RES) which can be installed. The potential installation of RE is contained and limited by the available natural resources, by landscape constraints, public opposition and the need to preserve tourism. The limited availability of suitable locations to install RES produces a highly variable hourly profile of generation. The variability is not smoothed by spatially distributed generations [4] as happens at Country level.
- Islands are usually characterized by tourism and consequent seasonal change of population. This produces strong changes in the quantity and shape of the profile of energy demand. The consequence is the need for oversizing infrastructure. A typical infrastructure that has to be oversized is the power system and especially the back-up generators and the distribution grid that needs to be sized on demand peaks. Nevertheless, oversizing infrastructure is needed in all fields, energy and miscellaneous. Water demand and waste handling demand are two examples.
- Water demand. If there is not availability of high-quality water within the own resources of an island, there is the need to overcome this limitation. This can be done through two different processes: water import from another area or desalination of sea water, both fuel and energy consuming activities. However, the integration of a desalination plant can support higher penetration of renewable energy sources as demonstrated by several studies: Padrón et al. [5] for the Canary Archipelago, Novosel et al. [6] for the Jordanian energy system and Mentis et al. [7] for the islands of South Aegean Sea. As already mentioned, water demand can increase seasonally with tourism and thus oversizing can be necessary.
- Management of wastes. Tourism also increases waste and the waste management especially during touristic seasons. This generates a serious problem due to limited area, high costs and scale of recycling processes.
- The price of electricity is higher in insular power systems than in the mainland. This is mainly due to some factors: the high fuel transportation costs and the higher need for spinning primary reserve and secondary reserve. Spinning reserve is very important at island level due to the limited number of spinning machines. At Country level spinning reserve is usually neglected due to the high number of rotating machines available in the electricity generation field. Islands usually presents weaker electricity grid structures and are more sensitive to power quality issues such as frequency and voltage deviations especially if the penetration level of RES is high due to the volatile nature of these sources. Secondary reserve is also relevant in insular power systems. In fact, a generator on an island cannot have significant capacity due to system security reasons. Therefore, higher reserve capacity than in the mainland networks should be included.
- Economies of scale are contained by the limited size of the island. As a consequence, the costs of the technologies to install are higher on average than in the mainland. This produces higher costs for energy.
- Marine transport usually largely affects the overall CO_2 emissions of the energy system. This is especially true for small islands. The extreme decarbonisation process therefore has to deal with it.

Several reviews on the topic of energy transition and decarbonisation of the energy system of insular areas already exist. Kuang et al. [8] presented a review on the current status and future potential of energy resources at island level. They also analysed the technologies to improve the penetration of renewables taking into account measures such as different type of energy storage systems and demand-side management. Erdinc et al. [9] analysed the insular power system focusing on the operational requirements needed to integrate high shares of renewables, the challenges and opportunities of the energy transition. In Ref. [10], Eras-Almeida and Egido-Aguilera analysed business models and policies that are typical for insular energy systems. Also, Rious and Perez [11] studied the topic of decarbonisation of islands' energy systems dealing specifically with storage energy systems and mostly discussing the potential supporting schemes that could support their deployment in insular contexts. Michalena and Hills [12] also focus on islands but narrowing the spectrum specifically to Pacific islands and on the following topics: (i) RE governance, (ii) link the level of RE governance preparedness to actual RE penetration, and (iii) identify key areas in which RE penetration could be strengthen throughout the Pacific region. Groppi et al. [13] recently analysed the topic focusing on the role of storage technologies and DSM solutions. Tsagkari and Jusmet [14] reviewed a policy issues for the promotion of renewable energy in islands non-interconnected with the mainland.

Even though the topic of decarbonisation of islands is dealt with by an important number of researches, there is still a gap in terms of modelling techniques and software that are mostly used to analyse insular energy systems. To the authors knowledge, the most complete research from this point of view is provided by Liu et al. in Ref. [15]. They identified and classified the performance of different modelling techniques useful to study the energy systems for isolated areas. They concentrated on forecasting techniques for both energy demand and RES generation, energy planning models, subsidies mechanisms and uncertainty analysis. About energy planning models, they conclude that the most used models at insular level are H_2RES and HOMER. Starting from this latter approach, the aim of this paper is to further collect and compare different energy system models applied at insular level. The final scope of the paper is to answer the following research questions which have not been addressed by the previously mentioned review articles on island energy system modelling:

i) Which bottom-up energy system models are mostly used at the island level?
ii) Are models used at national scale also adopted for island applications?
iii) Which type of additional constraints or adaptations are implemented to apply energy system models designed for country applications to insular case studies? The additional constraints are necessary due to the intrinsic characteristics of energy systems at island level. A classification of these constraints is provided in the paper.
iv) Which are the main challenges of energy system models applied at insular level?

Thus, the scope of the paper is not to review and compare different models. For an overview of the existing models, refer to the work of Ringkjøb et al. [16] in which they reviewed 75 modelling tools used for analyzing energy and electricity systems or to the Openmod initiative [17] which presents an extensive list of open bottom-up energy system models. The scope of this paper is to answer the above mentioned research questions on the bottom-up energy system models applied at insular level which have not been addressed by other studies yet. It is

Table 1
Bottom-up energy system models applied at island level: case studies and used models. (abbreviations: Ref. = Reference, Pub. Year = Publication year, Inhab. = Inhabitants).

Authors	Ref.	Pub. year	Island case study						Model name
			Name of the Island	Country	Surface [km^2]	Inhab.	Population density [inhab./km^2]	Interconnection with the Mainland	
Meschede et al.	[53]	2019	La Gomera island	Spain	370	21,136	57	not interconnected	EnergyPLAN
Dorotić et al.	[54]	2019	Island of Korčula	Croatia	279	15,522	56	interconnected	EnergyPLAN
Marczinkowski et al.	[55]	2018	Samsø	Denmark	114	4233	37	interconnected	EnergyPLAN
Marczinkowski et al.	[56]	2019	Islands Samsø and Orkney	Denmark	990	22,100	22	interconnected	EnergyPLAN
Østergaard et al.	[57]	2019	Samsø	Denmark	114	4233	37	interconnected	EnergyPLAN, energyPRO
Cabrera et al.	[58]	2018	Gran Canaria	Spain	1560.1	850,000	545	not interconnected	EnergyPLAN
Haydt et al.	[18]	2011	Flores island (Azores)	Portugal	143	3907	27	not interconnected	EnergyPLAN
Yue et al.	[59]	2016	Wang-An Island	Taiwan	13.7	5188	379	interconnected	EnergyPLAN
Medić et al.	[60]	2013	Hvar Island	Croatia	299	11,077	37	interconnected	EnergyPLAN
Alves et al.	[61]	2019	Pico and Faial islands, Azores	Portugal	620	30,000	48	not interconnected	EnergyPLAN
Alves et al.	[62]	2020	Pico and Faial islands, Azores	Portugal	620	30,000	48	not interconnected	EnergyPLAN
Child et al.	[63]	2017	Åland Islands	Finland	1580	28,666	18	not interconnected	EnergyPLAN
Groppi et al.	[64]	2019	Favignana	Italy	19.8	3400	172	not interconnected	EnergyPLAN
Groppi et al.	[65]	2021	Favignana	Italy	19.8	3400	172	not interconnected	EnergyPLAN
Cabrera et al.	[66]	2021	Lanzarote	Spain	845.9	152,289	180	not interconnected	EnergyPLAN
Thomas et al.	[67]	2016	Agios Efstratios Island	Greece	44	300	7	not interconnected	HOMER
Sadrul Islam et al.	[68]	2012	St. Martin Island	Bangladesh	87	72,892	838	not interconnected	HOMER
Hall et al.	[69]	2017	Prince Edward Island	Canada	5660	142,907	25	interconnected	HOMER
Pfeifer et al.	[70]	2017	Vis	Croatia	90	3617	40	interconnected	HOMER
R.Henderson et al.	[71]	2009	Star Island	United States	0.15	–	–	not interconnected	HOMER
Groppi et al.	[72]	2018	Favignana	Italy	19.8	3400	172	not interconnected	HOMER
Uwineza et al.	[73]	2021	Popov Island	Russia	12.4	1316	106	not interconnected	HOMER
Krajačić et al.	[74]	2009	Mljet Island	Croatia	98	1088	11	interconnected	H_2RES
Antoine et al.	[75]	2008	Malta	Malta	316	494,000	1563	not interconnected	H_2RES
Duić et al.	[76]	2004	Porto Santo	Portugal	42	5483	131	not interconnected	H_2RES
Segurado et al.	[38]	2011	S. Vicente	Cape Verde	226	81,014	358	not interconnected	H_2RES
Maïzi et al.	[77]	2018	Reunion Island	France	2512	850,727	339	not interconnected	TIMES
Selosse et al.	[45]	2018	Reunion Island	France	2512	850,727	339	not interconnected	TIMES
Selosse et al.	[78]	2018	Reunion Island	France	2512	850,727	339	not interconnected	TIMES
Timmons et al.	[50]	2019	Mauritius	Mauritius	2040	1,265,475	620	not interconnected	OSeMOSYS
Taliotis et al.	[51]	2020	Cypus	Cypus	9251	1,189,265	128	not interconnected	OSeMOSYS
Karl Critz et al.	[79]	2013	Oahu (Hawaii)	United States	1600	1,000,000	625	not interconnected	UC - WILMAR
Dominkovic et al.	[80]	2018	Aruba insland	Aruba	180	112,309	624	not interconnected	UC - PLEXOS
Taibi et al.	[81]	2018	Barbados	Barbados	430	284,800	662	not interconnected	UC - PLEXOS
Loisel et al.	[82]	2018	Yeu Island	France	23.32	5000	214	interconnected	UC
Hansen et al.	[83]	2012	Crete	Greece	8450	632,674	75	not interconnected	UC
Sigrist et al.	[84]	2016	La Palma	Spain	743	83,971	113	not interconnected	UC
Pezic et al.	[85]	2013	El Hierro	Spain	268.7	10,162	38	not interconnected	UC
Psarros et al.	[86]	2018	Lesbos	Greece	1633	86,436	53	not interconnected	UC-ED
Wang et al.	[87]	2020	Astypalaia Island	Greece	97	1238	13	not interconnected	UC
Raveendran et al.	[88]	2020	Menorca	Spain	695	91,000	131	not interconnected	UC
Corsini et al.	[89]	2009	Ventotene island	Italy	1.75	768	439	not interconnected	TRNSYS
Barone et al.	[90]	2021	El Hierro	Spain	268.7	10,162	38	not interconnected	TRNSYS

also important to underline that the presented models are not compared on what they are generally capable to do, but on how they have been applied in the reviewed articles. Thus, they are not compared based on their full capabilities, for instance in terms of sectors that could be analysed, but only based on the specific implementations of the reviewed articles, e.g. Haydt et al. [18] analyse only the power sector in their article even though EnergyPLAN could potentially analyse all sectors.

The paper is structured as follows. The chapter 2 “Energy system models at insular level” collects the literature review on bottom-up energy system models that are applied at island level. It compares the different approaches with the final aim of finding which existing methods are available for energy planning studies with this focus at insular level. Then, the chapter 3 “Features of island energy system models” analyses the characteristics of bottom-up energy system models and the additional constraints which are needed when dealing with insular applications. The aim of the chapter 4 “Classification of existing literature review” is the comparison of the reviewed studies on the characteristics and additional constraints found in the previous chapter. Scope of this latter chapter is also to highlight the weaknesses of this research topic and its main challenges. Finally, the last section provides conclusive remarks.

2. Energy system models at insular level

Table 1 shows the collected literature review on energy system models applied at island scale. The table reports information on the publication, on the case study and on the model used for the analysis. It is possible to see how the most used models at island scale can be divided in the following categories:

- One of the most used tools to perform energy planning and support energy decision makers is EnergyPLAN [19]. Developed by Aalborg University [20], EnergyPLAN software is a deterministic simulation model, it is suited to describe future scenarios with high degrees of VRES, it simulates one-year period with an hourly time-step and it integrates the three primary sectors of the energy system. The model is designed to be applied at Country (Macedonia [21], Ireland [22], Portugal [23], Denmark [24], Croatia [25], Finland [26], Jordan [27]) or regional level (Tamil Nadu in India [28], South Tyrol in Italy [29]) but it has also been applied at European level [30] and to towns and municipalities (the city of Osijek in Croatia [31] and the municipality of Bressanone-Brixen in Italy [32]) other than at island level.
- HOMER [33], originally developed by NREL [34], is now distributed by HOMER Energy. It is another popular tool mostly used at micro-grids level [35]. It is mainly applied to villages power systems, island power systems, grid-connected campuses and military bases.
- Another widespread tool is the H_2RES model [36]. It has been developed within the RenewIslands methodology [37] which is composed by four different phases: i) mapping the island’s needs, ii) mapping the island’s resources, iii) devising scenarios with technologies that can use available resources to cover the needs and iv) modelling the scenarios. The model H_2RES has been specifically designed for islands and isolated regions. The literature review shows that although it has been applied in many case studies in the past it is not anymore largely used. The last paper adopting this model has been published in 2011 [38].
- Other models that are applied at island level are multi-period time-horizon models such as TIMES [39], developed by International Energy Agency [40] and OSeMOSYS [41], developed by KTH Royal Institute of Technology in Stockholm [42]. TIMES model is designed for application at country level (Nordic countries [43] and Ireland [44]) but it has also been applied at island level, as shown in Table 1, for the case study of Reunion island [45]. Similarly OSeMOSYS has been applied at continental (South America [46] and Africa [47]) and country level (Brazil [48], Bolivia [49]), but it has also some applications at insular level (Mauritius [50] and Cyprus [51]).
- Unit commitment (UC) models are largely used mathematical optimization methods which are applied in energy system modelling to scheduling and expansion capacity problems. The scheduling and coordination of generation units can be a difficult task due to the number of generators, the different energy generation cost and the constraints about how energy can be produced and exchanged. Typically, these models are applied at the power sector [52]. In literature several UC models exist specifically designed for the national/regional level, but, as shown in Table 1, also UC models have been designed for the particular case of insular applications.

From this initial classification is possible to conclude that the most used bottom-up energy system models applied at island level are: i) models designed to be applied at country level which are adapted to be used for insular applications, EnergyPLAN, TIMES and OSeMOSYS are valid examples, ii) models specifically designed for insular and micro-grid applications such as HOMER and H_2RES model, and iii) UC models designed both for country level applications and for insular applications. Fig. 1 shows the number of studies reviewed in this article by model type.

EnergyPLAN, HOMER, H_2RES are used for both interconnected and not interconnected island, while UC models are mostly applied to not interconnected islands. The reason could be that in not interconnected cases the necessity to model the reliability and robustness of the power grid is higher because of the lack of support from the mainland. Therefore, models that better account grid stability issues such as UC models are required. About size and density population of the case study, there is not a clear trend. The considered models are applied for both islands with small and large surfaces and for both islands with a low or high density of population.

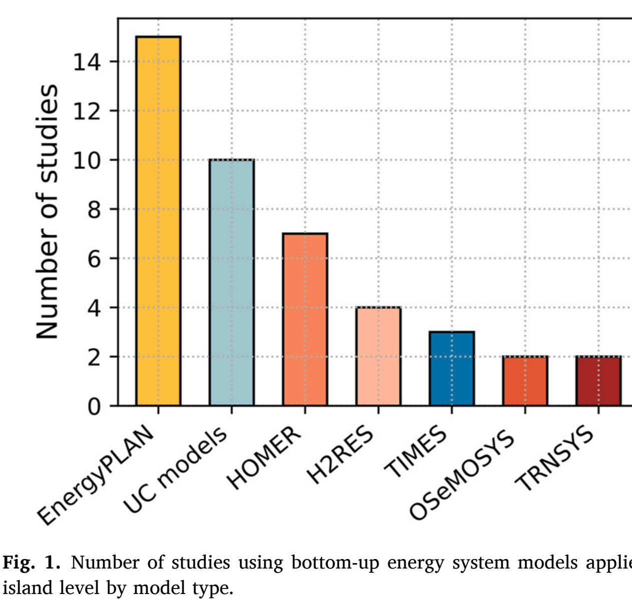

Fig. 1. Number of studies using bottom-up energy system models applied at island level by model type.

3. Features of island energy system models

Energy system models can be classified in bottom-up and top-down approaches [91]. Top-down approach, used by economists and public administrations, concentrates on macro-economic impacts of a certain energy policy. A simplified representation of the energy system is usually implemented in this type of models. The final aim of this category of models is the assessment of the impacts of energy and climate policies on socio-economic sectors as public welfare, social growth, employment etc. Bottom-up approach concentrates on the energy system analyzing in detail the components and the technologies which characterize it. These models are used to evaluate different future alternatives of the energy system by comparing the impact of different technologies. The aim is the identification of the best energy transitions or energy mixes to lower GHG emissions and meet the energy targets. While these models achieve a higher detail in the description of the energy system, they do not take into account macro-economic impacts.

This paper focuses on bottom-up energy system models at insular level. Before going into detail of insular applications a brief classification of bottom-up energy system models is provided. Bottom-up energy system models can be classified depending on the temporal horizon [92]. Static or short-term models distinguish from long-term models. The first models adopt a short temporal horizon and typically their scope is the analysis of the energy system in a future target year. The latter ones adopt a longer temporal horizon analyzing the whole transition from the current state of the energy system up to the target year.

Additional features can further classify energy system models. These are the following: energy sectors covered, geographical coverage, time resolution, methodology and programming technique.

- Energy sectors covered. Some models focus on specific sectors of the energy system while others implement sector-coupling by including all sectors (electricity, heat, transports) and their interactions. Aalborg university [93] conceived the smart energy system concept demonstrating the benefits of analyzing the interactions and synergies among different energy sectors. They demonstrated the role of sector-coupling approach in reducing wastes and maximizing system efficiency [94]. Nastasi highlighted the advantages provided by the synergies between the thermal and electricity sectors by means of hydrogen synthesis [95] and power-to-gas [96]. Another study [97] showed the advantages of the interconnections of thermal and electricity sectors by means of heat pumps and cogeneration power plants.
- Geographical coverage is identified by the level of spatial detail with whom the modelling activity is performed. Single and multi-node are the two main approaches which define this feature. Single-node approach does not consider internal bottlenecks or constraints in the transport of goods (electricity, natural gas, hydrocarbons). It considers an ideal perfect transport of goods without losses or bottlenecks. The use of this type of approach especially for large countries or continents produces some simplifications and inaccuracies [98]. The use of this approach at insular level is largely adopted because of the limited size of the case studies. However, single-node models are not able to study congestion problems and therefore to inspect the potential beneficial effects of the introduction of balancing and storage technologies.
- Time resolution is particularly delicate in this type of models. First of all, the definition of time-slice needs to be formulated. The time-slice concept is defined as stylized temporal representation which corresponds to the number of time splits in which is divided the simulation year [99]. Bottom-up energy system models traditionally adopt a low number of time-slices. This is due to the increase of computational effort at the increase of the number of time slices and to the fact that energy systems were mostly based on fossil fuels in the past and did not have to manage the variability introduced by variable renewable energy sources (VRES). The spread of VRES in the energy system, balancing and storage technologies and demand side management (DSM) has introduced the need for higher temporal resolution in order to be able to correctly catch their behavior. The impact of temporal resolution has been largely studied. Deane et al. [100] have developed a model by soft-linking a power systems model with high time resolution to an energy systems model with lower time resolution. This has been done to demonstrate that adopting a low temporal resolution could underestimate VRES curtailments and overestimate the use of baseload plant. Haydt et al. [18] demonstrated how a low temporal resolution can result in overestimation of the renewable energy share and underestimation of the CO_2 emissions from the electricity sector. Poncelet et al. [101] demonstrated how improving temporal resolution is of particular importance for the accuracy of the final results and how it should be prioritized compared to techno-economic operational detail. In these studies the hourly timestep applied at energy system modelling is considered as the highest temporal resolution.
- The methodology implemented by the model is another element useful for classification. The main approaches are simulation, dispatch optimization (or operational optimization), single-objective investment optimization (or single-objective expansion capacity optimization) and multi-objective investment optimization models (or multi-objective expansion capacity optimization). A simulation model is usually adopted to test a certain configuration of the energy system. It achieves the dispatch thanks to simple heuristic technique such as internal priorities between the different sources. A dispatch optimization model achieves the results following a merit-order logic between the different generation sources. Investment optimization models perform expansion capacity optimization. They usually implement also the annual dispatch. Therefore this article, for simplicity, classify expansion capacity optimization models also performing operational optimization as investment optimization models. These models can be divided between single-objective (SO) and multi-objective (MO) optimization approaches [102].
- The programming technique or mathematical approach in bottom-up energy system models can be various. The most used are Linear programming (LP), mixed integer linear programming (MILP), dynamic programming and heuristic techniques. LP is a modelling technique in which a linear function subjected to some constraints is minimized or maximized [103]. MILP, an extension of LP, which allows the include not only continuous variables but also integer variables (Yes/No, (0/1) decisions or integer variables such as the number of units) [104]. Dynamic programming subdivides the problem in sub-problems for which an optimal solution can be easily achieved [105]. Heuristic techniques [106] reach a sub-optimal solution in a very short computational time.

The above-mentioned features are common to all bottom-up energy system models independently of the application to which they are applied. Depending on the case study there are then additional features which need to be taken into account. When Bottom-up energy system models are applied at insular level, the following additional characteristics and constraints acquire particular importance: reliability and robustness of the power grid, water desalination, vehicle to grid, demand response and maritime transport. The following paragraphs describe in more detail these features and why they are particularly relevant when considering insular case studies.

3.1. Reliability and robustness of the power grid

The reliability and robustness of the power grid is particularly relevant for micro-grids not interconnected with the mainland power grid. In order to better consider the reliability of the power grid, several factors need to be taken into account. Reserve is a relevant variable for the robustness of the power grid. It is possible to define three different types of reserve. i) Primary reserve, or frequency containment reserve, is given by the potential change of rotating speed generators. This allows the stabilization of the frequency of the system (it operates within 30 s). ii) Secondary reserve, or supplemental reserve, is the fastest extra-generating capacity which is not connected to the grid (complete activation within 5 min). iii) Tertiary reserve, or replacement reserve, is the extra-capacity not connected to the grid and that requires longer start-up time. The scope is to substitute secondary reserve capacity once the frequency has been restored. It is used to solve congestion problems (it operates between 15 and 60 min) [107]. Another important variable to be considered in the sphere of grid stability is conventional power plant cycling. In this field it is important to consider: a) ramp constraints of conventional power plants, b) partial load operation and decay of efficiency at partial load and c) start-up costs. W. P. Schill et al. [108] have demonstrated how the importance of start-up costs could increase in the future as a consequence of variable renewable energy spread. However, they also highlighted the opportunities introduced by flexibility options in containing the cycling costs of conventional units. These aspects are particularly relevant at insular level which presents electricity grid structures weaker than the ones on the mainland. This makes islands more sensitive to frequency and voltage deviations especially if the penetration level of RES is high due to the volatile nature of these sources. Moreover, system security reasons limit the size of conventional generators. As a consequence, higher reserve capacity than in mainland networks should be taken into account.

3.2. Water desalination

The provision of fresh water is a problem that affects different areas of the world. Islands, particularly small ones, are a very delicate case toward this issue. Desalination represents one of the most used and at the same time the most promising solution to face the water shortening challenge. Desalinise means to remove salt from the water in order to purify it and to bring the total solid dissolved matter below a certain permissible threshold. This can be obtained with different methods and technologies but all of them are energy intensive [109]. Generally, desalination technologies adopt i) phase change membranes, and are also called thermal processes because the process needs a thermal resource, or ii) semi-permeable membranes in which electricity is used to achieve the separation of solvent and solutes [110]. It is important to consider desalination plants when analysing insular energy systems because they represent one of the highest loads; this is especially true in small islands where, most of the time, the industrial sector is not relevant. Furthermore, as far as electricity driven desalination plants are concerned, they also offer interesting flexibility potential [111] thus, enabling a higher ability for the grid to manage and thus host variable RES. In facts, plants that rely on electricity are the most common plants and in particular Reverse Osmosis (RO) plants represent 65% of the overall installed capacity worldwide [112]. That is why, desalination plants have been studied as potential flexibility providers as discussed in Ref. [113]. In the United States of America, their flexibility potential has been studied by Liu and Mauter [114] concluding that the further electrification of the sector will increase the grid flexibility. Karakitsios et al. [115] analysed the use of a desalination plant in the island of Kythnos concluding that a 22% RES curtailment reduction could be achieved with a smart management of the desalination plant.

Aside from the social benefits that the possibility to produce fresh water directly on the island brings to islanders and the potential benefits in terms of grid flexibility in case desalination plants are included in Demand Response programmes, they would also lead to a reduced energy consumption for the water delivery from the mainland to the island as better explained in Section 3.5 Maritime transport.

3.3. Vehicle to grid

Electric vehicles (EVs) represent a sustainable alternative to traditional transportation that entails lower energy consumption due to higher efficiency, lower emissions both local and global and reduced noise pollution [116]. Furthermore, they can also provide several services to the power grid depending on the strategies that are enabled that can lead to lower operating costs, higher RES penetration and improved grid stability [117]. The charging/discharging strategies that could be implemented are multiple. The simplest one is the so-called dump charge, in which vehicles charge as soon as they are connected to a charging station at fixed rate. Another option is the smart charge, also called unidirectional Vehicle to grid (V2G) [118], where vehicles can regulate their charging rate depending on the grid needs and in doing so they could provide flexibility services for congestion management, grid overloading, system instability and voltage drop issues [119]. The most evolved, complete and complex strategies is V2G; here, vehicles work as electricity storages and thus are also able to inject energy into the grid providing additional services such as spinning reserve [120], power factor regulation [119], peak load shaving and load levelling [121], reactive power support and voltage regulation [122].

These many potential roles and services leads to different control strategies. Given the amount of data and the system complexity due to contrasting objectives and several constraints, optimization techniques are usually adopted to analyse the issue [119]. These problems can thus aim at optimising different objectives that can generally be divided into the ones towards grid management [123] or economic maximisation [124].

Nevertheless, the use of EVs and particularly the adoption of V2G have not spread yet due to different barriers such as high investment price, both for private user and the service providers for the charging infrastructure, limited driving range (even though this is not a major issue in small towns and islands) and long battery recharge time (fast charging time are not a technical issue for vehicles nor charging stations but mostly for the grid) [125]. Furthermore, V2G also raises several issues in terms of regulation, data ownership, business models, issues related to the high degradation rate due to the continuous charge-discharge cycles as well as the security of users that will most likely make available just a small part of the battery state of charge in case of emergencies and this would drastically affect the V2G flexibility potential [126]. Thus, the role of V2G is particularly interesting for insular systems whose grids have high frequency variability due to their low inertia and so are particularly fragile towards suffering instability issues [127]. Additionally, the use of EVs would decrease the need for delivery of fuels from the mainland thus further reducing the overall energy consumption and emissions.

3.4. Demand response

Demand Side Management (DSM) is defined as the set of all those strategies that cause an alteration of the energy demand of consumers; these comprehend energy efficiency measures, back-up or on-site solutions (generators, storages or power-to-gas) and Demand Response (DR) strategies [128]. DR is described as the modification of the electricity load at consumers' level as a response to incentives (Incentive Based Demand Response – IBDR) or to the electricity price (Price Based Demand Response - PBDR) [129]. While in PBDR programmes the electricity price works as a signal for consumers to adapt their consumption, in IBDR consumers are rewarded for the provided flexibility in case of need. Thus, one strategy could be considered to be "consumption-based" while the second one is "flexibility-based". For this reason, IBDR can easily be merged with PBDR programmes since they can provide services to the grid that cannot be performed through PBDR programmes (e.g. congestion management, overloads, frequency and voltage management and so on) [130]. Also, some of the PBDR programmes, e.g. the so-called Critical Peak Pricing (CPP), can also coexist and be merged with other PBDR, such as Time-of-Use (ToU) tariffs, since it aims at exploiting DR flexibilities just when certain, critical, conditions are met or close to be met [131].

Optimization algorithms are usually preferred to analyse DR problems since they are able to consider a large number of variables and also to evaluate both present and future conditions so as to control shiftable loads accordingly [132]. Over the last decades, a particular interest has been paid to algorithms based on Artificial Intelligence (AI) and Machine Learning (ML) approaches both for planning and control purposes [133].

DR can be provided by several sources and can be a link between different energy consuming sectors such as the thermal sector through HPs or EBs [134]; the transport sector through V2G programmes [135] or the production of alternative fuels [136]; the water production and management sector through desalination plants [137] or the control of the whole water distribution system [138]; the residential sector through shiftable loads such as dishwasher, washing machines, lighting and other [139]; the gas sector through electrolysers and other means [140]. In this research, given the particular importance that V2G studies have gained in literature and the special importance that desalination plants represent in insular contexts, DR from these two sources has been considered separately. Thus, in this paper, DR refers only to flexibility services deriving from loads connected to the thermal sectors, other loads in the residential sector and the one deriving from energy intensive industrial facilities. There is no distinction between IBDR and PBDR since in most of the models this feature is not specified, and loads are controlled simply to optimise energy usage. The importance of studying DR in insular systems relies in its potential role to improve grid stability and reliability that, as previously mentioned, is one of the most critical features for insular energy systems.

3.5. Maritime transport

Maritime transport is a key aspect of islands' economy that strongly affects their ability to invest in potential solutions [141], the smaller the island the higher the relative importance of this sector. Furthermore, this also represents one of the main sources of emissions and pollution near ports and harbours [142]; once again, this is especially critical for small islands and archipelagos where also the transport between islands is an important factor [143]. When planning energy systems at Country level, international transportation is not accounted for [144]. When analysing island's energy systems, the usual approach is the same but, in this case, the relative impact of maritime transportation over the whole system consumption is much greater than for non-island Countries. For instance, the case of Favignana island can be considered; here, the 60% of the island's primary energy consumption is connected to maritime transport [145]. Indeed, several researches can be found in literature studying sustainable solutions for maritime transport such as Gaber et al. [146], who analysed AC/DC microgrids with electric ships and fuel cells, and Mahmud et al. [147] that studied the possibility to provide ancillary services to the grid with electric boats.

Nevertheless, maritime transportation should be considered in further ways. Indeed, insularity leads to a higher cost of fossil fuels than the mainland due to the marine transportation that also causes additional energy consumption and emissions. Furthermore, the energy consumption and emissions related to maritime transport should also be considered in analysis related to desalination plants and waste-related researches (e.g. waste-to-power, waste-to-gas, etc.). Indeed, the production of drinkable water on the island, as well as the treatment of waste directly on the island leads to energy savings and economic advantages because of the avoided transport from and to the mainland for water delivery and waste treatment, respectively. The same can be said in general for the power sector. Indeed, each solution that leads to a reduced use of fossil fuels indirectly triggers additional savings for the reduced energy consumption for transporting fossil fuels to the island. By not considering this feature, the energy consumption savings as well as the emissions saved are underestimated when considering the benefits of a) high RES penetration systems, b) desalination plants and c) waste-to-X scenarios.

4. Classification of existing literature review

Table 2 presents the considered studies mapping them based on short-term or long-term approach, energy sectors covered, geographical coverage, time resolution, methodology, objective function, programming technique, reliability and robustness of the power grid, water desalination, demand response and vehicle to grid. Fig. 2 graphically shows the content of Table 2 highlighting the main characteristics of the reviewed studies. From Table 2 it is possible to derive some considerations on bottom-up energy system modelling applied at insular level:

- The majority of these models are static or short-term models which focus on a specific future target year and are thus characterized by a horizon of one year. The only studies which implement a long-term approach are those using TIMES or OSeMOSYS bottom-up energy system models. These latter are characterized by a longer horizon which goes from the current status of the energy system to a future target year.
- The different studies can be divided into approaches which integrate the main sectors of the energy system and methods which focus on the electricity sector only. The integration of different sectors produces an increase of computational effort. On the other hand, the integration of different sectors allows the exploitation of the synergies between sectors and it increases the overall flexibility options of the systems. The majority of the analysed models concentrate on the power sector. However, some of the studies implement sector coupling mainly through the use of EnergyPLAN software.
- All studies implement a single-node approach. There are models like TIMES, Plexos that can be used in multi-node mode. However, in these applications the single-node approach is always chosen. This means that most of the times in an island the assumption of a perfect ideal transmission grid is adopted. Small islands have transmission grids which do not present serious bottlenecks to require the use of a multi-node approach. However, bottom-up energy system models applied at islands of a certain size would require the adoption of multi-node approach to properly model transmission grid bottlenecks and congestion problems which, as already mentioned, are particularly delicate for insular power systems.
- The implemented time resolution is usually characterized by an hourly modelling approach. This is considered a high temporal resolution in the energy system modelling topic. In only 4 over 43 studies a time-slice approach has been chosen. It is important to underline that this has been done in those studies implementing a long-term approach. Thus, this choice has been driven by the need to lower the computational burden which is higher in long-term problems.
- About the methodology, simulation, dispatch optimization and SO investment optimization are the most adopted, while MO optimization is used in only four cases. The most used methods are simulation and SO investment optimization. The most adopted models for achieving simulation method are EnergyPLAN and H2RES. The models implementing operational optimization are UC models while the ones applying SO investment optimization are a mix of TIMES, OSeMOSYS, HOMER, UC models and a couple of studies using EnergyPLAN with a brute-force search technique. The same programming technique is adopted using EnergyPLAN to achieve a MO investment optimization in two cases. In only one case the MO investment optimization is achieved coupling EnergyPLAN with a Multi-Objective Evolutionary Algorithm.
- The most used programming technique in studies applying bottom-up energy system models at insular level is heuristic method, mainly adopted by studies using EnergyPLAN and H2RES. At the second place, the brute-force search which is used in studies using HOMER and in four using EnergyPLAN. Then it is possible to find linear programming techniques used by TIMES, OSeMOSYS and by

Table 2
Bottom-up energy system models applied at island level: main features, methodologies, programming techniques, stability of the grid and water desalination. (abbreviations: Ref. = Reference).

Authors	Ref.	Model name	Short-term vs Long-term	Energy sectors covered	Geographical coverage	Time resolution	Methodology		Programming technique	Reliability and robustness of the power grid		Water desalination	Demand response	Vehicle to grid (V2G)
							Simulation, dispatch optimization, SO inv. optimization, MO inv. optimization	Objective function	Linear, non-linear, dynamic, mixed-integer, heuristic, other	Power plants additional constraints: a) Ramp constraints, b) partial load operation and c) start-up costs	Type of considered reserve: i) primary ii) secondary iii) tertiary			
Meschede et al.	[53]	EnergyPLAN	Short-term	Power	Single-node	Hourly	Simulation	–	heuristic	–	–	–	–	–
Dorotić et al.	[54]	EnergyPLAN	Short-term	All sectors	Single-node	Hourly	MO inv. optimization	Inv. costs, electric import	Brute-force search	–	–	–	–	Yes
Marczinkowski et al.	[55]	EnergyPLAN	Short-term	All sectors	Single-node	Hourly	Simulation	–	heuristic	–	–	–	–	–
Marczinkowski et al.	[56]	EnergyPLAN	Short-term	All sectors	Single-node	Hourly	Simulation	–	heuristic	–	–	–	–	–
Østergaard et al.	[57]	EnergyPLAN, energyPRO	Short-term	All sectors	Single-node	Hourly	Simulation	–	heuristic	–	–	–	–	–
Cabrera et al.	[58]	EnergyPLAN	Short-term	All sectors	Single-node	Hourly	Simulation	–	heuristic	–	–	Yes	–	Yes
Haydt et al.	[18]	EnergyPLAN	Short-term	Power	Single-node	Hourly	Simulation	–	heuristic	–	–	–	–	–
Yue et al.	[59]	EnergyPLAN	Short-term	All sectors	Single-node	Hourly	SO inv. optimization	Excess electricity production	Brute-force search	–	–	–	–	–
Medić et al.	[60]	EnergyPLAN	Short-term	All sectors	Single-node	Hourly	Simulation	–	heuristic	–	–	–	–	–
Alves et al.	[61]	EnergyPLAN	Short-term	Power	Single-node	Hourly	SO inv. optimization	Total annual costs	Brute-force search	–	–	–	–	–
Alves et al.	[62]	EnergyPLAN	Short-term	Power	Single-node	Hourly	Simulation	–	heuristic	–	–	–	–	–
Child et al.	[63]	EnergyPLAN	Short-term	All sectors	Single-node	Hourly	Simulation	–	heuristic	–	–	–	–	Yes
Groppi et al.	[64]	EnergyPLAN	Short-term	All sectors	Single-node	Hourly	Simulation	–	heuristic	–	–	–	–	Yes
Groppi et al.	[65]	EnergyPLAN	Short-term	All sectors	Single-node	Hourly	MO inv. optimization	Total annual costs and annual CO_2 emissions	heuristic	–	–	–	–	Yes
Cabrera et al.	[66]	EnergyPLAN	Short-term	Power	Single-node	Hourly	MO inv. optimization	Maximizing renewable energy contribution and minimizing CO2 emissions, fossil fuel use and total annual costs	Brute-force search	–	–	Yes	–	–
Thomas et al.	[67]	HOMER	Short-term	Power	Single-node	Hourly	SO inv. optimization	Net Present Cost	Brute-force search	–	–	–	–	–
Sadrul Islam et al.	[68]	HOMER	Short-term	Power	Single-node	Hourly	SO inv. optimization	Cost of electricity	Brute-force search	–	–	–	–	–
Hall et al.	[69]	HOMER		Power	Single-node	Hourly				–	–	–	–	–

(continued on next page)

Table 2 (*continued*)

Authors	Ref.	Model name	Short-term vs Long-term	Energy sectors covered	Geographical coverage	Time resolution	Methodology		Programming technique	Reliability and robustness of the power grid		Water desalination	Demand response	Vehicle to grid (V2G)
							Simulation, dispatch optimization, SO inv. optimization, MO inv. optimization	Objective function	Linear, non-linear, dynamic, mixed-integer, heuristic, other	Power plants additional constraints: a) Ramp constraints, b) partial load operation and c) start-up costs	Type of considered reserve: i) primary ii) secondary iii) tertiary			
			Short-term				SO inv. optimization	Cost of electricity	Brute-force search					
Pfeifer et al.	[70]	HOMER	Short-term	Power	Single-node	Hourly	SO inv. optimization	Cost of electricity	Brute-force search	–	–	–	–	–
Henderson et al.	[71]	HOMER	Short-term	Power	Single-node	Hourly	SO inv. optimization	Cost of electricity	Brute-force search	–	–	Yes	–	–
Groppi et al.	[72]	HOMER	Short-term	Power	Single-node	Hourly	SO inv. optimization	Cost of electricity	Brute-force search	–	–	–	–	–
Uwineza et al.	[73]	HOMER	Short-term	Power	Single-node	Hourly	SO inv. optimization	Cost of electricity	Brute-force search	–	–	–	–	–
Krajačić et al.	[74]	H_2RES	Short-term	Power	Single-node	Hourly	Simulation	–	heuristic	–	–	yes	–	–
Antoine et al.	[75]	H_2RES	Short-term	Power	Single-node	Hourly	Simulation	–	heuristic	–	–	–	–	–
Duić et al.	[76]	H_2RES	Short-term	Power	Single-node	Hourly	Simulation	–	heuristic	–	–	yes	–	–
Segurado et al.	[38]	H_2RES	Short-term	Power	Single-node	Hourly	Simulation	–	heuristic	–	–	yes	–	–
Maïzi et al.	[77]	TIMES	Long-term	Power	Single-node	3 h	SO inv. optimization	Discounted global system cost	LP	–	i)	–	Yes	–
Selosse et al.	[45]	TIMES	Long-term	Power	Single-node	3 h	SO inv. optimization	Discounted global system cost	LP	–	–	–	–	–
Selosse et al.	[78]	TIMES	Long-term	Power	Single-node	3 h	SO inv. optimization	Discounted global system cost	LP	–	–	–	–	–
Timmons et al.	[50]	OSeMOSYS	Long-term	Power	Single-node	732 time-slices	SO inv. optimization	levelized cost of electricity	LP	–	–	–	Yes	–
Taliotis et al.	[51]	OSeMOSYS	Long-term	All sectors	Single-node	Hourly	SO inv. optimization	Discounted global system cost	LP	–	–	–	–	Yes
Karl Critz et al.	[79]	UC - WILMAR	Short-term	Power	Single-node	Hourly	Operational optimization	Annual operational costs	LP	a), b), c)	ii), iii)	–	Yes	–
Dominkovic et al.	[80]	UC - PLEXOS	Short-term	All sectors	Single-node	Hourly	Operational optimization	Annual operational costs	MILP	–	–	Yes	–	Yes
Taibi et al.	[81]	UC - PLEXOS	Short-term	Power	Single-node	Hourly	Operational optimization	Annual operational costs	MILP	–	i)	–	Yes	–
Loisel et al.	[82]	UC	Short-term	Power	Single-node	Hourly	SO inv. optimization	Total Annual costs	LP	–	–	–	–	–
Hansen et al.	[83]	UC	Short-term	Power	Single-node	Hourly	Operational optimization	Annual operational costs	MILP	a), b), c)	i), ii), iii)	–	–	–

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Table 2 (*continued*)

Authors	Ref.	Model name	Short-term vs Long-term	Energy sectors covered	Geographical coverage	Time resolution	Methodology		Programming technique	Reliability and robustness of the power grid		Water desalination	Demand response	Vehicle to grid (V2G)
							Simulation, dispatch optimization, SO inv. optimization, MO inv. optimization	Objective function	Linear, non-linear, dynamic, mixed-integer, heuristic, other	Power plants additional constraints: a) Ramp constraints, b) partial load operation and c) start-up costs	Type of considered reserve: i) primary ii) secondary iii) tertiary			
Sigrist et al.	[84]	UC	Short-term	Power	Single-node	Hourly	Operational optimization	Annual operational costs	MILP	a), b), c)	i), ii), iii)	–	–	–
Pezic et al.	[85]	UC	Short-term	Power	Single-node	Hourly	Operational optimization	Annual operational costs	MILP	c)	–	–	–	–
Psarros et al.	[86]	UC-ED	Short-term	Power	Single-node	Hourly	Operational optimization	Annual operational costs	MILP	a), b), c)	i), ii), iii)	–	–	–
Wang et al.	[87]	UC	Short-term	Power	Single-node	Hourly	SO inv. optimization	Total Annual costs	MILP	a), b), c)	–	Yes	–	–
Raveendran et al.	[88]	UC	Short-term	Power	Single-node	Hourly	Operational optimization	Annual operational costs	LP	–	ii)	–	–	Yes
Corsini et al.	[89]	TRNSYS	Short-term	Power	Single-node	Hourly	Simulation	–	dynamic programming method	–	–	Yes	–	–
Barone et al.	[90]	TRNSYS	Short-term	Power	Single-node	Hourly	MO inv. optimization	Payback period and primary energy savings	dynamic programming method	–	–	Yes	–	–

UC models, and MILP only used by UC models. Two studies adopt dynamic programming through the use of the TRNSYS software.

Fig. 3 shows the classification of the different studies through the methodology and programming technique features. It highlights that the majority of the considered studies use a simulation approach based on heuristic methods. Brute force search is also largely used to achieve Single-Objective investment optimization and less often to achieve Multi-Objective investment optimization. Linear Programming and Mixed Integer Linear Programming are largely used by TIMES, OSeMOSYS and UC models. These programming techniques are used to achieve operational optimization and Single-Objective investment optimization. It is interesting to see how Linear programming is used mostly to achieve Single-Objective investment optimization while Mixed Integer Linear Programming, which is computationally more expensive, focuses more on simpler operational optimization.

One of the scopes of the paper is to inspect the additional constraints or adaptations of energy system models to be applied to insular case studies. These additional constraints have been identified in the sphere of reliability and robustness of the power grid, water desalination, vehicle to grid, demand response and maritime transport.

Within reliability and robustness of the power grid, it is possible to identify constraints of the conventional power plants which regards ramps, operation at partial load with relative decay of efficiency and start-up costs. Other constraints about the stability of the grid are primary, secondary and tertiary reserve. These constraints are also taken into account at country level but assume an even higher importance at insular level and especially in a not interconnected case study. Fig. 2 shows that the majority of the selected studies do not consider stability constraints for the power grid and almost only UC models allow the inclusion of this type of constraints. In addition, frequently used models such as EnergyPLAN, HOMER and H2RES are not capable of taking

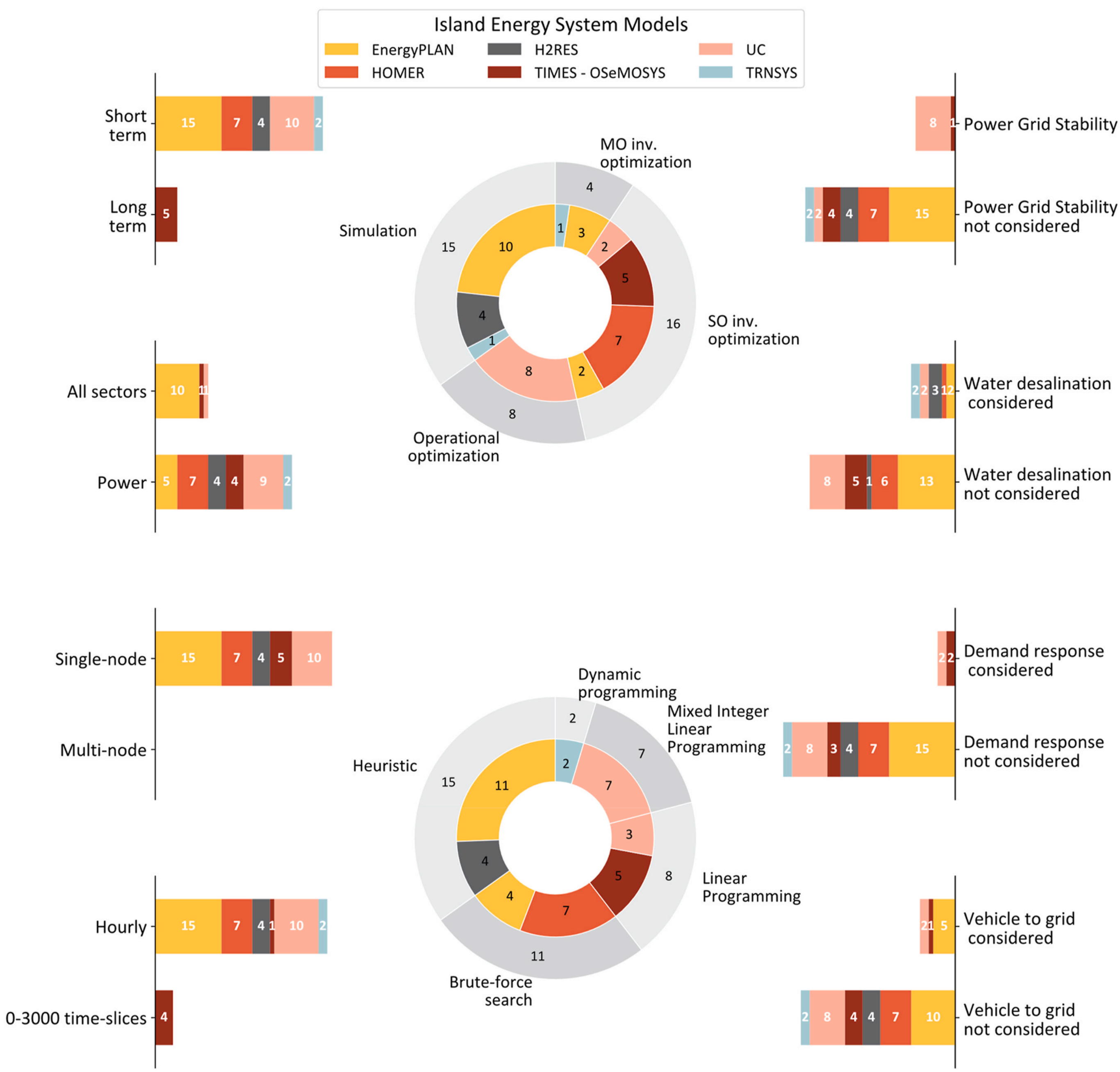

Fig. 2. Number of studies using bottom-up energy system models applied at island level for model type.

directly into account reliability and robustness of the power grid constraints. Nevertheless, they can be considered through the use of simplified indicators usually linked to the amount of synchronous generators that must always be online in relation to the VRES production or the overall supplied power. A similar approach has been used in Ref. [65]. Here, the authors considered within the multi-objective optimization analysis a constraint on the critical excess electricity production in order to ensure the reliability and robustness of the power grid.

Water desalination is also not considered by the majority of the selected papers. The papers which consider this type of technology utilise different models underlying the fact that different models have the ability to consider it. Also demand response is not considered by the majority of the selected papers. Only some studies utilizing TIMES, OSeMOSYS and UC models implement this feature. Vehicle to grid is also considered only by a small number of the selected papers. Among the papers implementing it, beyond the usual TIMES, OSeMOSYS and UC models, it is important to highlight the contribution of EnergyPLAN to the implementation of this feature.

It is possible to conclude that TIMES, OSeMOSYS and UC models are the most flexible in the integration of these additional features, particularly relevant at insular level. However, it is also important to underline that these features are yet implemented by the minority of the studies. Moreover, these features are rarely simultaneously adopted. Only four studies out of 43 implement simultaneously more than one of these additional features selected as of importance for insular case studies.

To the authors' knowledge, maritime transport has not been accounted for in any of the reviewed studies. The economic savings due to the avoided transportation of fossil fuels to the island are considered in different ways. Groppi et al. [64] indirectly considered the economic savings by assigning an overprice to all diesel consumption in order to consider the transportation cost. It is noteworthy that the EnergyPLAN software enables the user to specifically consider the transportation cost of fossil fuels. Nevertheless, it is not possible to consider such expense for water and waste delivery. Furthermore, it is not possible to consider the energy and emissions savings related to the avoided transportation [148]. To the author's knowledge, only few researches applying Life-Cycle Analysis (LCA) somehow considered this issue. For instance, Chary et al. [149] analysed different scenarios in order to evaluate the benefits of cultivating or importing biomass for a Combined Heat and Power (CHP) plant in Guadeloupe. In their study, the authors consider the energy consumption and the emissions for the transportation of biomass in the case of import; nevertheless, the transportation of the fossil fuels that is saved thanks to the biomass is not considered. Thus, the full benefits of the biomass are not considered. Also, Pettenella [150] compared the strategies of importing or producing woody biomasses in the Italian energy system concluding that "*transportation distances greatly affect the total CO2 and CO2 eq. emission amounts with respect to those produced by a shorter supply chain*" but still imported wood biomass are more sustainable than fossil fuels. Once again though, the benefits due to avoided transportation for the fossil fuel that are saved are not considered.

From Table 2 it is also possible to derive some more specific considerations looking at the different models and their modelling characteristics. It is important to mention the role of computational effort. The computational burden limits the resolution of the models implemented in these studies. For instance, if a high resolution in time and in sector-

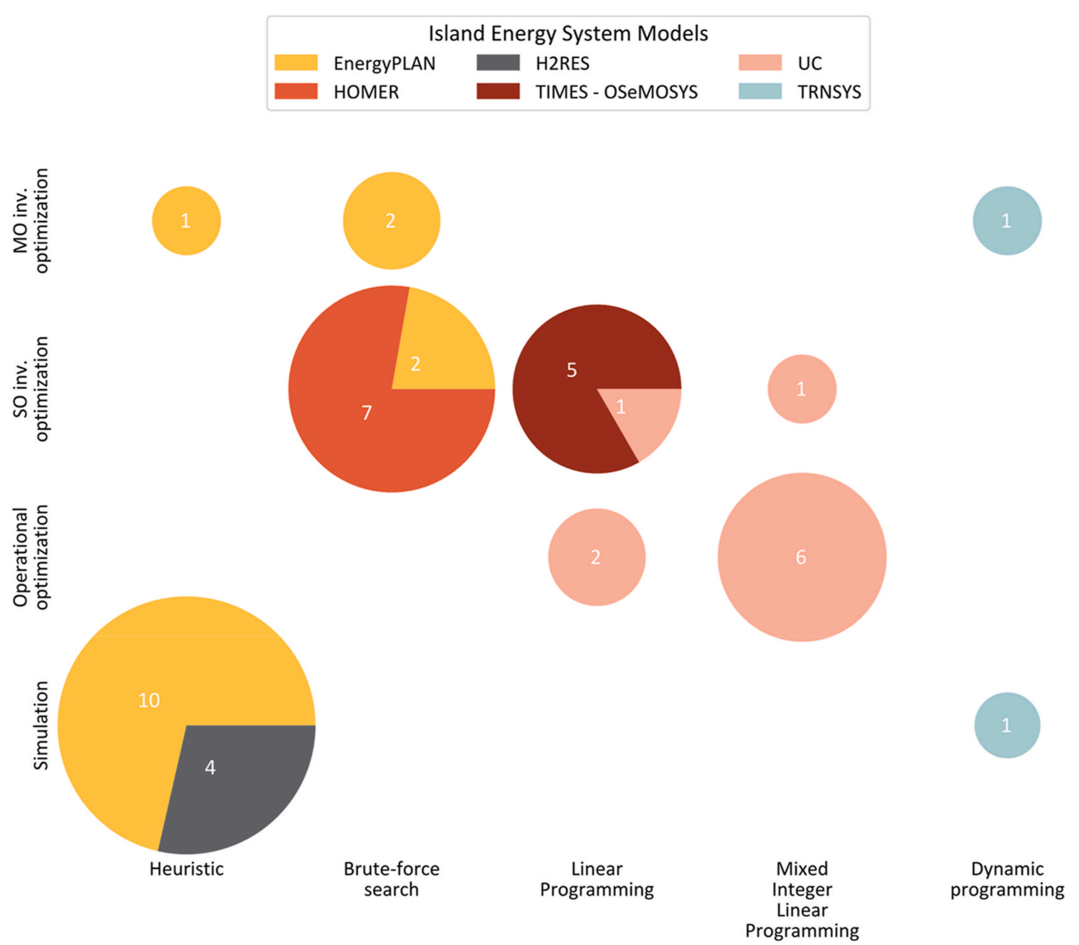

Fig. 3. Selected studies subdivided considering methodology and programming technique.

coupling is achieved, it is difficult to also realize a high resolution in techno-economic detail and thus the implementation of the constraints about the reliability and robustness of the power grid, or the additional components such as water desalination, vehicle to grid, demand response and maritime transport. The final challenge of this research field is thus the simultaneous implementation of high resolution in all these fields [151]. Each group of studies identified by the same used energy system model is analysed more in depth to highlight this statement.

Studies based on EnergyPLAN are generally characterized by high time resolution and integration of all sectors of the energy system. They usually adopt a simple simulation method and do not implement additional constraints about the reliability and robustness of the power grid, only one of them includes water desalination, no one include demand response, four consider vehicle to grid and no one maritime transport.

Studies using HOMER tool utilizes high time resolution concentrating on the only power sector. They implement single-objective investment optimization using as objective function the net present cost or the cost of electricity. Only one study of this type includes water desalination. Contributions using H_2RES method concentrate on the power sector with a high time resolution implementing a simulation technique. Most of them include water desalination to study its integration at the increase of renewable share but do not integrate constraints to take into account the stability of the power grid.

Studies with TIMES and OSeMOSYS models are the only ones implementing a long-term approach and thus concentrating on the whole transition instead of a single future target year. This adds to additional computational effort. These studies consider a 3-h time-step, they have a focus on the power sector and implement single-objective investment optimization with discounted global system cost of the transition as objective function. The additional constraints of the power grid and water desalination are not included with the exception of primary reserve in one of these studies. Two of them consider demand response and one of them vehicle to grid.

Studies using unit commitment models allows the achievement of a higher resolution in techno-economic detail with the implementation of power plants additional constraints such as ramp constraints, partial load operation and start-up costs together with different type of reserve taken into account. However, due to the computational burden, they have to decrease the resolution in sector-coupling focusing on the only power sector. They implement an hourly time resolution and dispatch optimization which usually considers annual operational costs as an objective function. An exception is the study of D. Dominkovic et al. [80] which achieve a high resolution in sector coupling (also with the integration of water desalination) and in time, but without evaluating the reliability and robustness of the power grid through the inclusion of power plant and reserve additional constraints.

5. Conclusions

43 different studies using energy system models applied at insular level have been analysed and compared in this review paper. From an initial classification it has been possible to derive that the most used models at insular level can be divided in: i) models designed to be applied at country level which are adapted to be used for insular applications, EnergyPLAN and TIMES are two valid examples, ii) models specifically designed for insular and micro-grid applications such as HOMER and H_2RES model, and iii) some UC models are designed for country level applications and some others are designed specifically for insular applications. Only 16 out of 43 studies present a model specifically designed for insular applications. The remaining part utilizes models originally designed for Country (20) or micro-grid (7) level applications.

The additional constraints required by insular applications have been identified to be in the sphere of reliability and robustness of the power grid, water desalination, vehicle to grid, demand response and maritime transport. The 43 studies selected for this review have been classified based on these additional constraints and on the characteristics of the models. These features are the following: short-term or long-term approach, the energy sector covered, the geographical coverage, time resolution, methodology, objective function and programming technique. The results have shown that the five additional constraints are more frequently implemented by models that are specifically designed for insular applications. This is especially the case of UC and TRNSYS models. In particular, UC models are capable to take directly into account reliability and robustness of the power grid constraints, while models such as EnergyPLAN, HOMER and H_2RES have to use alternative simplified methods based on the use of indicators to account for them.

It has been shown as the computational burden limits the resolution of the models. For example, if a high resolution in time and in sector-coupling is achieved it is difficult to have also a high resolution in techno-economic detail and thus the implementation of the constraints about the reliability and robustness of the power grid, or the additional components such as water desalination, vehicle to grid, demand response and maritime transport. Or if a higher techno-economic detail resolution is achieved through the implementation of the mentioned constraints usually the model has to lower the resolution in time or in sector-coupling by focusing only on the power sector. The final challenge of this research field is thus the simultaneous implementation of high resolution in all these fields.

Author contribution

Matteo Giacomo Prina: Conceptualization, Investigation, Methodology, Formal analysis, Resources, Visualization, Writing - Original draft, Writing - Review & Editing, Editing. Daniele Groppi: Resources, Investigation, Methodology, Writing - Original draft, Writing - Review & Editing. Benedetto Nastasi: Resources, Investigation, Methodology. Davide Astiaso Garcia: Supervision.

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.

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