A Review on Energy Storage and Demand Side Management Solutions in Smart Energy Islands

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ABSTRACT

European Union has definitely identified the priorities towards sustainable and low-carbon energy systems recognizing a key role to islands that have been described as ideal sites to develop and test innovative strategies and solutions that will then boost the transition on the mainland. Nevertheless, the integration of Variable Renewable Energy Sources (vRES) into the electricity grid are already causing technical problems to island grids thus making the grid flexibility a key topic. In the past, since power plants were completely manageable while the load was unpredictable, the grid flexibility was supplied by traditional power plants; but now, due to vRES, the variability and unpredictability has moved to the generation side and the opposite shift has happened to flexibility agents. This paper deals with solutions that improve the ability of the grid to cope with vRES unpredictability such as energy storage technologies and all the solutions offered by sector coupling strategies. Particularly, this research focus on solutions that deals with such solutions in the insular contexts. Several solutions have been presented concluding that battery energy systems and pumped hydro energy storage are the most used technologies in islands. As regard sector coupling and Demand Side Management solutions, all the analysed solutions showed relevant results in terms of i) reduction of excess electricity production and ii) increased grid ability of hosting vRES. Nevertheless, some of the current gaps in literature have been pinpointed and future research challenge and opportunities have been suggested.

Highlights

- review on the effects of energy storage technologies on insular grid flexibility
- review on demand side management solutions to handle vRES in insular energy systems
- review of flexibility and sector coupling solutions for smart energy islands

Keywords

Sector Coupling; Smart Energy System; Smart Energy Island; Demand Side Management; Energy Storage; Grid Flexibility

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List of abbreviations

Full name	Acronym	Full name	Acronym
Renewable Energy Sources	RES	Thermal Energy Storages	TESs
Variable Renewable Energy Sources	vRES	Pumped Hydro Storage System	PHES
Levelised Cost of Electricity	LCOE	Batter Energy Storage System	BESS
Demand Side Management	DSM	underwater compressed air energy storage	UWCAES
Electrical Energy Storages	EESs	hydrogen energy storage	HES
Smart Energy Systems	SESs	Diesel Engines	DEs
Net Present Value	NPV	Pay Back Period	PBP
Demand Response	DR	Ocean Thermal Energy Conversion	OTEC
Domestic Hot Water	DHW	Reverse Osmosis	RO
Electric Boilers	EBs	Solar Thermal	ST
Annual Energy Consumption	AEC	Heat Pumps	HPs
Fuel Cell Electric Buses	FCEBs	Electric Vehicles	EVs
Photovoltaic	PV	Wind Turbine Generator	WTG
Power to Gas	P2G	Vehicle-to-Grid	V2G

1. Introduction

European Union (EU) interest on islands energy issue is currently at its peak. In the last years many key steps have been made towards the development of sustainable insular energy systems. Starting from the Smart Island Initiative and proceeding with the Valletta Declaration, islands have been identified as perfect location to prove the technical and economic feasibility of high variable Renewable Energy Sources (vRES) energy systems. Research, political and market interests over islands is not new. In the 90s, the interest was very high as it is proved by [1]. According to [1], several islands were already betting on

RES, mostly on hydro, wind and biomass. Several other works have been developed during that period, among others, Balaras et al. [2] focused on Greek islands while Yu and Tapling [3] on Pacific islands. In the early 21th century, the large use of feed-in-tariffs and the fast-growing market shifted the attention to large grids on the mainland [4]. As above-mentioned, in the last years islands have obtained a central role and it is now possible to find extensive work on Small Islands Developing States (SIDSs) all over the world such as Mauritius [5], Barbados [6] and the Philippines [7] and review regarding all SIDS [8] as well as small islands, e.g. Canary [9], Zhoushan [10], Dong'ao [11] and the Pico island [12].

As the RES share in the electric grid raised, concerns over the grid balance grid flexibility have consequently grown too. Indeed, the high percentage of vRES into the electricity grid causes technical issues to insular electric grids that often are antiquate and unable to host such instability.

Grid flexibility represents the ability of the system to rapidly respond to unpredicted variations. The stability condition is translated in the need for power load and supply to match at each time. Historically, this requirement has been fulfilled by managing the power plant output, especially the ones that are able to rapidly ramp up and down, to match the variable and non-predictable electric load. With the advent of vRES generators, the unpredictability has moved from the demand to the generation side and as a response to this, flexibility agents have conversely migrated to the demand side. Nevertheless, the current systems still provide flexibility by managing power plants output, with vRES this has translated into curtailment thus losing clean energy. Several researches have proven the enormous cost of curtailment that brings to an increased Levelised Cost of Electricity (LCOE) that often is not considered for feasibility studies and energy planning purposes [13]. Various researches have analysed the increasing need for curtailment in case other solutions are not undertaken. For instance, [14] analysed the need for curtailment due to the carbon tax, and [15] optimised future scenarios by analysing an aggregated energy system model or [16] where authors discussed the potential benefits of valorising the curtailed energy by reallocating it into the transport and/or heating sector.

At EU level, the idea is to create a shared European market for providing ancillary services to the grid. Particularly, the European Network of Transmission Service Operators for Electricity (ENTSO-E) is currently developing the "Trans European Replacement Reserve Exchange" (TERRE) project [17] whose main aim is to develop a mechanism to enable Countries to share their tertiary reserves in a more effective way. The interconnection of grids and markets has been proven to be beneficial in terms of system economy [18] and reliability [19]. Nevertheless, some studies such as [20] found that Demand Response (DR) strategies might be even more beneficial.

Interconnection can also be viable for islands and remote areas, but this is not always the case. According to Neves et al. [21], 71% of small islands that are not connected to the mainland grid will not do so because of economic or technical reasons. In [22], Ramos-Real et al. evaluated several scenarios regarding the possible interconnection Tenerife–La Gomera and concluded that is not always technically possible and cost-effective to connect small energy system to the national grid. Thus, it is even more relevant for small islands to identify alternative solutions to improve the energy management strategies to increase the grid flexibility. The use of Electrical Energy Storages (EESs) have been proved to be an interesting option in cases of off-grid [23] or grid connected layouts [24]. The same can be said about Smart Energy Systems (SESs) adopting power-to-X solutions (where X can stand for gas, transport, heating, hydrogen, water). Several researches confirm the validity of such solutions at regional [25], urban [26] and building level [27].

Those topics have been already dealt with in detail; some discusses about energy storage technologies [28], some consider specific technologies such as Pumped Hydro Energy

Storage (PHES) [29], thermal energy storage [30], hydrogen technologies [31]; others specifically analyse control strategies [32] and sizing techniques [33]. As regards Demand Side Management (DSM), the literature is not as broad but it is worth mentioning some of the most recent works such as [34] that discusses the DSM potential at Country level (i.e. Germany and Finland); and [35] that analyses smart grids and DSM focusing on the operation principles and briefly describing the main components and the technical challenges and barriers.

Nevertheless, very few works specifically focus on geographical islands. [36] mostly focuses on RES potential, business models and policies without deeply analysing storage systems and DSM solutions. [37] studies EESs in islands but mostly about the supporting schemes that could boost their deployment. [21] has a specific section on islands energy systems that are statistically analysed without considering DSM and sector coupling. [38] also focuses on RE governance and its link to actual RE penetration specifically in islands but it narrows its spectrum on Pacific islands. [39] focuses on isolated energy systems, such as islands, and specifically on forecasting models, modelling approaches, RES systems and policies. In the section tailored to hybrid energy systems, with vRES generators and EESs, it focuses on the entire energy system without identifying and discussing specifically EESs impacts. Once again, DSM and sector coupling are not dealt with and the same can be said for [40] that expands its spectrum over all SIDS and for [41], which investigated RES and EES focusing on Mediterranean Islands only.

Thus, even if literature is rich of papers on EESs and, to a lesser extent, on DSM; there are not reviews that properly address these topics on the peculiar context of geographical islands. This is especially true about DSM involving sector coupling solutions that, when it is dealt with, is not critically and thoroughly discussed but just mentioned.

The present paper thus provides an update to the present body of reviews on EESs in insular contexts also adding a detailed analysis of DSM and sector coupling strategies that have been applied or studied on island territories deeply analysing and discussing the results and impact of each technology/solution on the whole island energy system. Differently from other researches and reviews that tend to focus on RES based system and to consider energy management strategies (e.g. EESs and sector coupling through DSM) as part of the whole system without thoroughly discussing the share that each energy management solution has on the general outcome, this review focuses specifically on the effect of different energy management strategies in terms of improved system flexibility and economic and environmental impact. The analysis also discusses the most used indicators to assess the impact of the adopted flexibility strategies. Hence, this research aims at providing an in-depth analysis of this specific topic in islands that cannot currently be found in literature.

The work presents solutions that deal with i) EES and ii) SESs exploiting DSM schemes using power-to-X and sector coupling solutions.

2. Grid flexibility solutions in islands

Two trends addressing the problem of grid flexibility on islands can be observed:

1. EES systems, i.e. all those solutions that can absorb and supply electricity from and to the grid;
2. SES: the integration of different energy sectors, namely:
    a. thermal sector with the use of Thermal Energy Storages (TESs);
    b. transport with the use of different energy vectors; and
    c. to the water production and management sector.

The review aims at giving an overview of the several solutions to increase the grid flexibility in the insular context. When addressed in the original researches, the review has resumed the impact of the different solutions on the electric grid in terms of:

a. ability to increase the RES share;
b. decreased excess electricity production;
c. reduced RES curtailment;
d. reduction/management of peak load;
e. economic aspect.

2.1 Electrical Energy Storage Systems

In this section, an overview of research involving different EES technologies for geographical island energy systems is given. The chapter is arranged to cover first the research dealing with PHES, then different types of Batter Energy Storage System (BESS) and finally hybrid systems with underwater compressed air energy storage (UWCAES) and hydrogen energy storage (HES) systems.

Perez-Diaz et al. [42] reviewed the trends in PHES and main challenges for its implementation, particularly its capability to provide power-frequency control and regulation through different configurations. PHES facilities will have to adapt to new scheduling and bidding models on a spot-market influenced by vRES and ancillary services markets, which will change their previous standard operation. Bueno and Carta [43] studied El Hierro, Spain, proposing the most economically viable configuration of the system consisting of WTG and PHES. Results show the possibility of annual vRES penetration of 68.40% leading to saving of 7,364 m^3 of diesel and 20.91 kt of CO_2 emissions. Such system is competitive with traditional systems with fuel cost at 0.283 €/l. Kapsali et al. [44] investigated the role of large-scale WTGs with local energy storage in planning the interconnection of Lesbos with the mainland grid. According to the results obtained, island's project of interconnection with the mainland can be economically viable only if it is accompanied by large-scale wind energy deployment. The addition of PHES unit results in reductions of WTG curtailments, while a portion of energy import from the mainland can be covered by PHES.

In [45], the impact of different PHES configuration on the scheduling costs and vRES curtailment in the Gran Canary island was studied by applying a generation scheduling of the power system based on next-day forecast. Results show that novel configurations still offer valuable contribution and reduce the cost of scheduling while increasing the integrated vRES. A recent research of Nikolaou et al. [46] also offers a dynamic mathematical model to use PHES for excess electricity production from WTGs on the island of Crete. Results have shown the economic viability of investment in such a system at energy prices of 60 €/MWh. Katsaprakakis and Voumvoulakis [47] present a techno-economic analysis of a hybrid system designed to provide 100% electricity supply for the independent island of Sifnos, Greece, exploiting the high wind potential and seawater PHES. Regardless of the modest power consumption (peak demand of 6.5 MW), PHES is shown to be the optimal storage technology, with specific cost of 30 €/kWh.

A brief summary of researches regarding PHES is provided in Table 1.

Table 1 Summary of the research regarding PHES systems

Reference	*Location*	*Research activity and method*	*Results*
[42]	-	General trends in PHES	PHES need to adapt to new market conditions
[43]	El Hierro	RES and storage system modelling, optimization	Increase of RES penetration obtained with PHES

		algorithm	
[44]	Lesbos	Analysis of WTG in grid-connected conditions, optimization algorithm	Local PHES is a good combination with WTGs increasing the capacity factor even in grid-connected systems
[45]	Canary Islands	Different PHES configurations	Novel configurations offer less curtailment and cheaper scheduling.
[46]	Crete	Dynamic modelling of energy system	PHES as a solution for the excess electricity from local RES.
[47]	Sifnos	System modelling, iterative simulation algorithm	100% RES island with PHES

A multi-objective particle swarm optimizer was used in [48], Duchaud et al. proposed an optimization method for various power plant configurations on two case studies of Tilos and Ajaccio. Tilos case's import cost is 200 €/MWh and the export cost of 30 €/MWh, selling 2.3 GWh in excess, the production cost is 63.6 €/MWh. Comparable system in Ajaccio had selling excess energy production cost of 129 €/MWh, which is less than the production cost in Corsica. In [49], Zhao et al. introduced three real case microgrids developed on different islands in the East China Sea. Attention was given to the selection of storage technologies for systems in the range from 200-2000 kW of installed production capacity. For smallest production capacities, lead-acid batteries were used, while lead-acid/lithium iron phosphate and lithium-iron phosphate configurations were used for systems with 800-2500 kW installed capacities. RES penetration was also considered and 60% was achieved in each system, while the largest one had penetration of over 100% in some hours. In [50], Zhao et al. analysed an optimal unit sizing method using genetic algorithms aiming at maximising vRES integration taking into account components' lifecycle while minimising pollutants emissions. The approach has been tested for the implementation of an existent microgrid on Dongfushan Island, China. Components of the microgrid were WTG, PV, diesel generators, desalination plant and BESS. The optimization problem aimed at sizing/designing the vRES generators, the Diesel Engines and the BESS, not the Desalination plant. The scenario with 55% vRES share had a generation cost equal to the scenario with just diesel engines. In [51], Kavadias et al. investigate the hydrogen production from electrolysis and storage through the use of an optimisation algorithm. The area of the Aegean Sea has been analysed, since it has considerable vRES potential and blackouts, due to lack of interconnection between islands. Overall, 9 islands are taken into account in the developed algorithm. The obtained results indicate the optimum size of the hydrogen-based configuration, with minimization of curtailment of vRES. Barbaro and Castro [52] proposed an optimised design for Faial's energy system, in the Azores archipelago, maximising RES penetration. The optimal configuration consisted of 5.5 MW of geothermal generators and 6.2 MWh of BESS capacity, on top of already installed traditional generators and 4.25 MW of WTGs. Three scenarios using energy storage were investigated by Al-Ghussain et al. [53] analysing a micro-grid on a Mediterranean island with the objective of identifying the optimal size of PVs and WTGs using (i) PHES as seasonal storage, (ii) BESS for short-term reactions, and (iii) without EES. The annual RES fraction was maximised, with marginal energy cost less or equal to the baseline tariff. The optimal hybrid system was constituted by an 8 MW-WTG and 4.2 MW PV system together with an 89.5 MWh-PHES leading to a vRES share of 88%. Lorenzi et al. [54] analysed the island of Terceira, Azores, and the possibility to install two BESS, vanadium flow batteries and lithium-ion. Batteries are compared for the obtained Net Present Values (NPVs) and the return on investment showing that both can lead to advantageous results. Particularly, vanadium flow batteries lead to an NPV that is equal to the 430% of the investment and a return on investment of 35%. In this scenario, the vRES share can reach values of 46% (i.e. 20% more than the baseline). Ma et al. [55] propose a model to analyse the effect of saturation of different sources on BESS performance and economy. Three different system configurations are observed, varying WTG sizes, to analyse different configurations of the energy system. Results reveal that WTG size up to 2 kW with 90% availability of wind energy is the most economical solution. Kougias et al. [56] investigated island grids of the Aegean Sea. Selected island's energy systems were analysed for years 2016 to 2036. A Harmony Search Algorithm was used to examine how to increase islands' energy independency through an increased RES penetration and BESS. The best scenario resulted in an increase of the installed production capacities by 40-70% to accommodate a 30% increase of consumption. Ocon and Bertheau [57] considered the hybrid system configurations for small island grids in the Philippines. Results show that an average LCOE reduction of 20% can be obtained if the energy system shifts from diesel to PV-BESS-diesel. Nikolaidis et al. [58] evaluated the impact of vRES on overall production cost, using annual data for the energy system of Cyprus. The selected EES technologies were studied through a life-cycle cost analysis and EES was used to enhance the grid flexibility. The results showed that the highest NPV can be achieved using vanadium-redox flow battery, while sodium-sulphur are the safest investment, followed by lead-acid.

In Kumar et al. [59], algorithm for the optimization of BESS size for the Åland Islands was developed for the optimal design of a Li-ion BESS. Using the model on the real data for the case study demonstrated how this approach can solve the problem of BESS location and size so as to supply the load of different new electric ferries charging in the harbour of Åland. Integrating BESS with vRES increases the system reliability and reduce investments for upgrading the grid.

El-Bidairi et al. [60] proposed an approach for optimization of BESS size on an islanded micro-grid using meta-heuristic optimization showing that optimum BESS size selection strongly mitigates frequency response.

Chen et al. [61] investigated the pathways for small islands to replace fossil fuels with vRES, with the emphasis on BESS. Simulations show that Li-ion BESS can be used to reach high share of RES in an economical way. Two phases were observed, 2020-2030 and 2030-2055. For the first phase, implementation of up to 30% RES is not challenging, while in phase 2 the 100% RES system can be achieved if investors capitalize on the developments in RES and BESS cost declines.

A summary of the research regarding BESS use is given in Table 2.

Table 2 Summary of researches involving battery storage technologies

Reference	***Location***	***Research activity and method***	***Results***
[48]	Ajaccio and Tilos	Hybrid plant sizing, multi-objective particle swarm optimization algorithm	Comparison of EES systems for different geographic locations
[49]	East China Sea	Microgrid optimization – operation mode switch algorithm	Optimal sizing and types of BESS.
[50]	Dongfushan	Microgrid optimization	Optimal sizing and types of BESS.
[51]	Aegean Sea	Optimisation of the system configuration for high RES share.	EES and HES are used.

[52]	Faial, Azores	Microgrid optimisation in two steps: simulation model iterated through optimisation algorithm	Small system configuration with batteries.
[53]	Mediterranean island	System modelling with different storage technologies – optimization algorithms	PHES used for seasonal storage, battery EES for short term storage.
[54]	Terceira, Azores	Techno-economic analysis	Utility-scale energy storage in island settings.
[55]	-	Scenario analysis, optimization of the storage size	Benefits of a hybrid system with precise BESS sizing.
[56]	Aegean islands	A metaheuristic optimisation technique, the Harmony Search Algorithm	Islands achieved energy self-sufficiency.
[57]	Philippines	Techno-economic analysis using a Python-based energy systems simulation tool and HOMER	System with EES achieves lower LCOE.
[58]	Cyprus	A life-cycle cost analysis	Comparison of various types of batteries according to NPV.
[59]	Åland Islands	Modelling of BESS performance, iterative simulation algorithm	New model for optimization of BESS size and location
[60]	Flinders Island	Optimization of BESS operation, Grey Wolf optimization technique, real time simulation algorithm	Optimum BESS size selection mitigates frequency response and improves it.
[61]	Jamaica	Integration of BESS in energy transition plans, DIgSILENT/Power Factory	Dynamics of BESS integration – cheaper BESS is expected to be available at the later stage

Swingler and Hall [62] compared options for long-duration energy storage for Prince Edward Island's electricity system powered by vRES. Using HOMER, the authors compared lithium battery technology (efficient, but costly) with a less efficient but low-cost TES combined with a steam-turbine; both technologies were sized to be able to reach a 100% RES electricity share. The TES-turbine configuration was shown to be competitive, taking into account declining cost projections for lithium battery technologies. Yue et al. [63] used EnergyPLAN to model the energy system of Wang-An Island. The RES potential was assumed to be 458.1 GWh annually (of which 299.7 GWh of electricity). The 2.68 GWh energy deficit was compensated by EES or biomass energy, showing that storage can satisfy most of the island electricity demand. Petrakopoulou et al. [64] investigated stand-alone operation of distant islands, with the goal to make Mediterranean islands energy self-sufficient. The considered power plant was simulated over 1-year period. The plant consists of a PV array with WTGs and EES and additional hydrogen generation plant to offer stabilization capabilities. It was

concluded that stand-alone hybrid power plant offers reliable alternative to traditional energy solutions.
Katsaprakakis et al. [65] investigated the optimal EES technology through a techno-economic feasibility analysis for small islands' electrical grids, powered by vRES. Particularly, three different technologies were studied: PHES and BESS (i.e. lead acid and Li-ion). Three autonomous Greek islands were used as case studies, with annual peak demands under 4 MW: Symi, Astypalaia and Kastelorizo. WTGs and PVs were considered as the potential vRES units. The dimensioning of those plants is optimized to achieve RES penetration over 70%. It was obtained that wind-PHES represents a competitive alternative for larger islands, while in the case of smaller islands, such as Kastelorizo, a WTG-PV-batteries mix was shown to be the optimal option. With BESS, the RES annual penetration can be between 80 and 90%. The PBP is estimated between 6 and 10 years. Wang et al. [66] investigated the UWCAES system for island's energy system. The analyses have found that a round-trip efficiency of 58.9% can be achieved. Katsaprakakis et. al. [67] show the perspective for the Faroe Islands energy system to become 100% RES. Two wind/PV power plants and PHES are examined on the case of two systems, the main grid comprising 11 interconnected islands and the autonomous island of Suðuroy, which has 10% of the population. It was found that vRES penetration of over 90% can be reached with storages in technically and economically feasible way. Khosravi et al. [68] conducted a research on a novel system combining ocean thermal energy conversion (OTEC) and PV with HES system. System's configuration included a turbine, evaporator, condenser, pumps, generator, PV, electrolyser, hydrogen tanks, fuel cell and converter. The overall energy efficiency for the energy system was 3.32%, while the overall energy efficiency of the OTEC system, without the HES, was equal to 2.75%. The obtained exergy efficiency of the hybrid system was 18.35% and the PBP around 8 years. Electricity cost was 0.168 $/kWh, which is 40% lower compared to 0.28 $/kWh of the previous system. Caralis et al. [69] investigated the potential integration of vRES through use of various storage technologies on the island of Crete in Greece. This represents a case of non-interconnected islands and techno-economic evaluation of the energy storage technologies of CAES, PHES and sodium–sulphur batteries was performed for use of otherwise curtailed energy. The CAES system was shown to have the lowest LCOE, 0.21 €/kWh. It produced 105.59 GWh of electrical energy discharged to the island's grid per year. For the case of Crete, CAES system appears to be 20% and 50% cheaper compared to PHES and BESS respectively. Zhao et al. [70] studied the integration of hydrogen application into the energy through the life cycle analysis of costs of hydrogen production using polymer electrolyte membrane electrolysis and applications for electricity and mobility purposes. Scenario analysis through 5 cases compared the cost of hydrogen with conventional energy sources considering CO_2 emission cost. The analysis has shown that the cost of using hydrogen for energy purposes is still higher than the cost of fossil fuels, due to cost of electricity consumed. Padrón et al. [71] analysed the feasibility of a Hybrid Renewable Energy Systems on two islands in the Canary Archipelago using techno-economic analysis. The system was proposed for securing the energy supply of a desalination unit, which produces up to 50 m^3 of water per day on the Lanzarote island. Both systems were simulated in HOMER and the results show that both systems were highly renewable, with 96% and 92% of vRES supply respectively, with Fuerteventura having 50% larger generator and 25% larger battery pack.
In Lee et al. [72], the policy approach for the energy transition of Hawaii was analysed, identifying different layers of needed transformation, but also underlining the interconnection of RES, battery storage and Vehicle-to-Grid (V2G) as main components of the future smart grid. The smart grid will be implemented if the multilevel governance is appropriately implemented. Socio-technical innovations underlined by the research are valid for the emerging island energy transition efforts worldwide.

Tariq [73] analysed the storage use in remote island of Bonaire to achieve the high share of RES. Analysis was performed using HOMER software and focusing on lithium-iron phosphate batteries. The results show that vRES lower the use of diesel-powered generator from 65.78% to 0.53%, with the system LCOE of 12.55€cents/kWh. Another scenario uses hydrogen as a seasonal storage and shows its feasibility.
In [74], Hunt et al. use the case study of Molokai Island, Hawaii, to show the potential of a novel storage technology: Mountain Gravity Energy Storage (MGES). MGES follows the basic concept of PHES but, instead of water, it relies on the potential energy of sand or gravel that is thus moved from a lower to an upper elevation to store and release energy. MGES advantages over PHES is the fact that no reservoirs are needed but there are several other technical features that have to be coped with for large systems. MGES unit cost ranges between 50 and 100 $/MWh per stored energy and 1–2 M$/MW per installed capacity and it is stated that it could be a feasible solution for micro-grid applications on small islands.

A summary of the research regarding various hybrid storage systems is given in Table 3.

Table 3 Summary of the research regarding various other energy storage systems and hybrid systems

Reference	*Energy storage technology*	*Location*	*Research activity and method*	*Results*
[62]	Electricity, heat	Prince Edward Island	Techno-economic modelling of the energy system	The thermal storage turbine concept was shown to be competitive with lithium battery technologies.
[63]	Various	Wang-An Island	Energy system modelling	Increased exploitation of RES through energy storage.
[64]	Electricity, hydrogen	Skyros (Greece)	Simulation and exergetic evaluation of a hybrid power plant	A stand-alone hybrid power plant is an alternative to the current conventional energy system.
[65]	BESS, PHES	Symi, Astypalaia and Kastelorizo (Greece)	Techno-economic analysis of various technologies. Computational simulation of the hybrid power plants	Economic feasibility of storage technologies for various islands.
[66]	Underwater compressed air energy storage		Techno-economic analysis of UWCAES	Parameters relevant for UWCAES's round-trip efficiency.
[67]	BESS, PHES	Faroe Islands	Energy system modelling, hybrid power plant algorithm	RES annual penetration higher than 90% can be reached with RES – storage power plants in technically and economically feasible way
[68]	Electricity, heat, hydrogen	-	Techno-economic analysis of an OTEC and PV with HES.	The obtained exergy efficiency of the hybrid system was 18.35%, the PBP of about 8 years, the cost of electricity 0.168 $/kWh (i.e. 0.112$/kWh less than the baseline).
[69]	Compressed air energy storage, PHES and BESS	Crete (Greece)	Techno-economic analysis through LCOE comparison.	The CAES system was shown to have the lowest LCOE equal to 0.21 €/kWh, while supplying 105.59 GWh/y of electricity to the island's grid.
[70]	Hydrogen	Orkney Islands	Life cycle analysis, scenario approach vs. conventional energy sources	Hydrogen cost for energy purposes is still not competitive with traditional fossil fuels

[71]	Hybrid RES, BESS	Canary Archipelago	Techo-economic analysis	Optimal size of BESS for islands energy systems with high RES share.
[72]	BESS, V2G	Hawaii	Strategic analysis and planning for smart grids	BESS and V2G will be key components in smart grids.
[73]	BESS, HES	Bonaire island	HOMER modelling of the energy system	BESS more favourable in short time frame, HES for seasonal storage.
[74]	MGES	Molokai Island	Novel storage concept economics and operation	MGES cost 50 to 100 $/MWh and may represent a feasible solution for islands applications

Overall, the body of research in this review investigated various solutions for energy storage, reaching from traditional PHES, which was shown to be an interesting solution for larger islands or islands with good geographical features, over the various types of BESS, to novel solutions including distributed batteries, CAES, thermal storage, hybrid power plants with buffer storage. At the end, also hydrogen economy was an interesting option. Overview of technologies that were a subject of research quoted in this section is given in Figure 1.

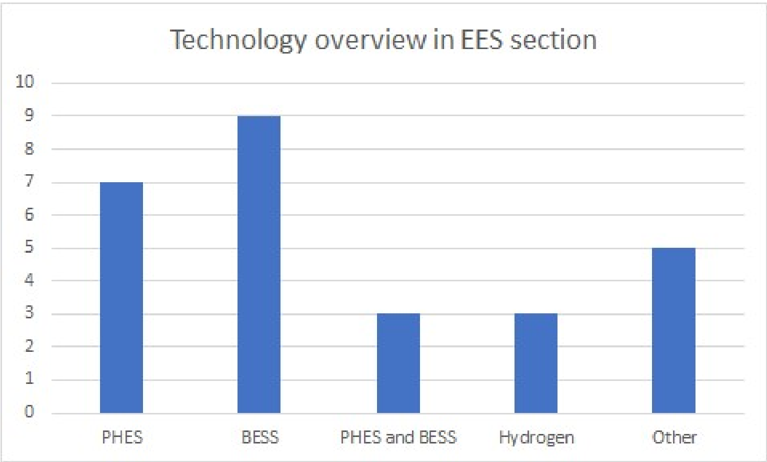

Figure 1 Overview of technologies used for research in EES section

Methodologically, the most common approach was scenario analysis in energy system modelling, using various methods for optimization algorithms and commercial software packages but also important was the life-cycle analysis and techno-economic analysis of novel concepts. Overview of these methods is given in Figure 2.

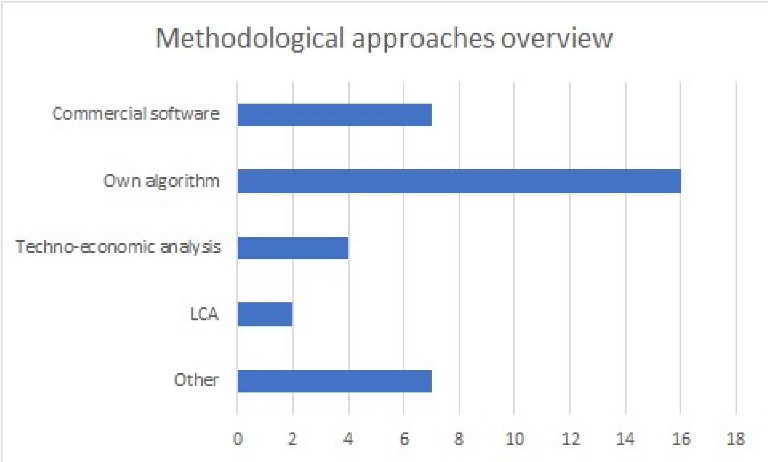

Figure 2 Overview of methodological approaches used for research in EES section in insular energy systems

Notable differences in research concern the natural diversity of islands in terms of size, technical conditions (technical: grid connected or not, near mainland systems or isolated), climate conditions, etc., of which all shape the optimal solutions and influence the technical and economic feasibility of storage technologies. This indicates that more complex storage technologies mix and new markets for such technologies could be expected in future research.

2.2 Smart Energy Systems – Demand Side Management and sector coupling solutions

The present section deals with researches regard solutions that increase the grid flexibility by coupling the power sector to other energy consuming sectors such as transport, building and thermal, and water production and management by means of DSM strategies. The main objective of this section is to investigate on the flexibility potential of each separate "sector". Indeed, in literature, several works studied integrated solutions without analysing the impact of each one of them. For instance, Croce et al. [75] analysed the island of Lampedusa considering that 40% of the residential loads is deferrable and realising that in most of the situations (i.e. 90%) deferring loads for 1.5–2.5 hours is enough to obtain the requested peak shaving.

In [76], the authors analysed the impact of DSM in the island of Flores, Azores. They varied the percentage of load that was available to provide flexibility services in the range of 1-20% and evaluated the "annual displacement of diesel-power plants" defined as the RES-energy consumed over the energy consumption. The actual displacement ranged between 39-77%. By introducing intra-day DR, the actual displacement would increase by 1.1-6.5% respectively for a DR availability ranging in 1-20%. By also adopting one-day DR the displacement is further increased by 0.2%-2.6% in the case of 1% and 20% of flexible demand availability.

Also, in [77], the DSM potential is analysed without specifying the involved technologies and sectors. Results show that DR reduces i) the use of power plants for peak coverage and ii) plants working at minimum load with low efficiency. Hence, DSM can save up to 27.7% of the overall daily operation costs. Moreover, Dietrich et al. assumed the cost of the transaction for DR services to be equal to the generation cost. Hence, consuming more energy during off-peak hours would cost less while extra consumption in peak hours would be more expensive. The outcomes show that DSM would decrease marginal prices by 9%. On average, during high wind production days, only the 1.4% of the daily demand is shifted. Moreover, the cost saving during high wind days are greater if no transaction cost is adopted. Contrarily, during

low wind days the adoption of a transaction cost would increase the cost savings shifting a greater amount of demand. The economic aspects of DR are the main topic in [78] while studying the Virgin Islands. They validate the possibility to use Direct-Load Control programmes to reduce DR's negative impacts on customers' lifestyle but underline the computational burden of such system and thus the investment costs on the control system. Another solution that has been proposed considers Voluntarily Demand Participation strategy where customers voluntarily identify devices that could be deferred without any reward. This solution leads to a system that could reach 70% vRES share with an excess electricity production lower than 10% and a lower cost than a system supplied by diesel generators [79].
Furthermore, in [80], Maizi et al. analysed the design of the Reunion island's 100% RES share energy system in 2030 concluding that DR enables to install 6% less capacity. An interesting feature of the research is the application of two indicators to ensure the system reliability and robustness. Those are the kinetic and the synchronism indicator. When considering that such indicators might be at least equal to the ones registered in the reference scenario, the capacity to be installed to reach 100% RES share is reduced only by 3%.
Also, Critz et al. [81] analyse the impact of DR considering that flexible loads capacity varied between 50 and 500 MW in the island of Oahu, Hawaii (peak load equal to 1.2 GW) without specifying the involved sectors. Authors considered the DR service cost to be equal to the cost of plants designated to cover peak loads; fast-DR receive a 25% bonus. Outcomes show a decrease in the annual cost up to 10%; 96% of the cost savings derive from an improvement of power plants efficiency due to a longer operation at nominal range; 3% is linked to reduced start and stops of power plants and only 1% to a better use of vRES.
Dominković et al. [82] investigated the integration of vRES into the energy system of a Caribbean island by means of an energy planning approach aiming at integrating energy sectors including i) the cooling sector by means of ice storages, ii) the transport sector through the adoption of smart charging or V2G, and iii) the water production sector exploiting a Reverse Osmosis (RO) desalination plant. Results showed that 84.6% of the overall electricity consumption was supplied by vRES with 1% curtailment, a peak increase of 17% and a primary energy supply reduction of 30%. The yearly economic cost of the whole energy system was 2.5% lower than the reference one when including carbon costs.

Table 4 summarises the review outcomes of researches that do not specify the technologies providing flexibility services and thus the coupled sectors.

Table 4. Summary of researches that do not specify the technologies used for DSM and coupled sectors.

Reference paper	*Analysed indicator to evaluate DSM impact on the grid*	*Indicator value with DSM*	*Type of research*	*Programming technique*	*Notes*
[76]	actual displacement of diesel-power plants	+9.1%	evaluation	N/A	Flexible load varied between 1-20% of the total load
[77]	marginal cost reduction peak reduction	9% 4.1-4.9%	simulation/evaluation	Unit commitment mixed integer linear programming (MILP)	Operational cost is reduced by 27.7%
[80]	vRES capacity	-6%	simulation/evaluation	Linear	Two indicators to

	installed to reach 100% RES share			programming (LP)	analyse the grid stability are adopted. If the grid stability must be equal to the reference scenario values, the vRES capacity reduction is only 3%
[81]	annual cost curtailed energy RES share	-10% -3.6% +1%	simulation/evaluation	dispatch optimization with LP	Flexible load capacity varied between 50-500 MW.
[82]	curtailed energy peak power total economic cost primary energy supply	1% +17% -2.5% -30%	simulation/evaluation	dispatch optimization with MILP	Electricity consumption remain unaltered except for the introduction of Electric Vehicles (EVs).

Regarding the potential synergies obtainable by coupling the electricity and thermal sectors, an important contribution is given by Neves and Silva in two different works regarding the Corvo island, Azores [83][84].

In [83], Neves and Silva analysed several solutions to supply Domestic Hot Water (DHW) and their impact on the grid management by adopting an optimization technique with the objective of minimising the cost for energy generation and dispatching while avoiding high peak loads. Across the two papers the authors analysed the installation of Solar Thermal (ST) collectors with back-up Electric Boilers (EBs), the use of Heat Pumps (HPs) and a mix of the two solutions. Furthermore, the authors also analysed different strategies for the control of the afore mentioned technologies, namely supply at demand, pre-scheduled supply and optimised strategy. Results are summarised in Table 5.

Table 5. Results of [83] and [84]

	Technology	*Dispatching strategy*	*Peak load*	*AEC*	*DHW Expenses*	*Dispatching and generation cost*
[83]	EBs as backup of ST (no DR)	at demand	+112% (in winter)	+1.4%	311 k€/y	baseload
	HPs	at demand	+46%	+9%	335 k€/y	-
	Mix of EBs+ST and HPs	off-peak functioning	+23.9%	+7.5%	330 k€/y	-
[84]	Mix of EBs+ST and HPs	Optimization to minimise cost and avoid peak loads	-	+7%	-	-1%

As depicted in Table 5, ST+EB leads to the lowest Annual Electricity Consumption (AEC) increase and the lowest DHW expenses. The downside to it is the very high peak load that makes this scenario unfeasible. On the other hand, HPs cause a smaller increase in peak load but the AEC increase and DHW expenses are much higher. It is noteworthy that the HPs scenario does not consider ST collectors, and this alone might justify the higher AEC and DHW expenses. Furthermore, the mixed scenario with a strategy based on off-peak or by using an optimisation dispatching algorithm show the possibility to optimally exploiting such technologies. Furthermore, [84] results show that an optimal dispatching strategy might reduce the operation cost by 1% equal to 12.9 k€/y.

Another interesting input has been provided in [85], Roy et al. designed a multi-source energy system powered by different vRES. The energy system also comprehended a BESS and exploited the DR potential of EBs for DHW and Electric Heaters (EHs) for space heating. The outcomes show that DR solutions decreased the hours of unmet load by 23 (14.3% of the baseline scenario) and the LCOE by -1.6% being equal to 0.458 €/kWh. This research has then been expanded in [86] adopting a multi-level DSM management algorithm that favours power-to-heat solutions and exploits load shedding when load shifting is not enough to avoid critical situations. In doing so, the goal of zero hours of unmet load is obtained.

In [87], Marczinkowski and Østergaard compared the effect of BESS and TES for the Samsø island, Denmark, and the Scottish Orkney islands. It was shown that coupling the power and the thermal sector via HPs and TESs has a greater effect on the energy system as a whole. Indeed, the TES/HP scenario leads to a reduction in the total annual cost equal to 2.2 and 3.1% while the BESS scenario results in an increase of 2.7 and 11% in Samsø and Orkney, respectively.

Related to the thermal sector is the building one, especially in small islands where the industrial sector is usually absent. Different studies analyse the residential sector DR potential as a whole, thus the thermal sector is considered as a part of it.

In [88], the authors analysed different scenarios of energy retrofit in a hotel in the island of Lampedusa, Italy. The scenario comprehended the implementation of energy efficiency measures and the adoption of smart control for HPs for DHW and air conditioning purposes. The smart control reduces the AEC by 6% while the peak load is reduced by 16%. In [89], the authors implemented their analysis on the same hotel investigating the possibility to provide flexibility services to the grid. They concluded that hotels have a low flexibility availability due to the high comfort they must assure to their guests. Indeed, considering the high investment cost (i.e. 39,200€), the authors concluded that the benefits of such system would not justify the investment. In [89], the authors also extended the study of DR potential to the residential sector in Lampedusa analysing a typical residential house in the island. Specifically, HPs, EBs, dishwasher and washing machines DR potential was investigated. Regarding the house management strategy, two different objective functions have been analysed, namely: case A) minimizing the house daily energy consumption; and case B) minimising the house peak load. Results are summarised in Table 6.

Table 6. Results of [89]

	house consumption reduction [kWh/day]	*Grid energy losses reduction for 1 house [kWh/y]*	*Island grid energy losses reduction [MWh/y]*	*Houses reduced energy consumption [MWh/y]*	*Total reduced energy consumption [MWh/y]*	*1 substation peak load reduction (100 houses) [%]*
Case A	1.07	771	23	1136	1159	8
Case B	0.42	2649	79.5	517	596.5	22

Case A leads to a greater decrease of energy consumption, Case B shows the potential impact that the residential sector could have on the grid. Indeed, the whole island peak load might be reduced by 530 kW (i.e. 6.4% of the summer peak load and 10.6% of the winter peak load). Table 7 summarises the review outcomes of researches analysing the thermal sector.

Table 7. Summary of researches analysing the flexibility potential of the building sector with a focus on the thermal sector

Reference paper	*Analysed indicator to evaluate DSM impact on the grid*	*Indicator value with DSM*	*Type of research*	*Programming technique*	*Notes*
[83]	Peak load AEC annual DHW expenses	+23.9% +7.5% -21.4k€/y	Evaluation	N/A	Without DSM: • peak load would increase by 46-112%; • AEC would increase by 1.4-9%; • yearly DHW expenses savings would range between 16.4-40 k€/y
[84]	dispatching cost AEC	-1% +7%	simulation	LP	The same scenario as [90] is further analysed. Thus, the AEC is actually decreased by 0.5%
[86]	hours of unmet load LCOE	0 h -1.6%	simulation	Mixed-Integer Non Linear Programming	BESS lifetime was also increased
[87]	annual cost	-2.2-3.1%	simulation	heuristic	For the island of Samsø and Orkney, respectively. BESS scenario leads to increased annual cost.
[88]	yearly energy consumption load peak	-6% -17%	simulation	heuristic	HP used for both DHW and air conditioning were controlled with the objective of reducing the hotel yearly energy consumption
[89]	grid energy losses peak load (summer/winter)	-14.9% -6.4%/-10.6%	evaluation	N/A	Hotel was not appropriate for providing flexibility to the grid.

Regarding the use of desalination plants for enhancing the grid flexibility of insular energy systems, Carta et al. [90] studied the integration of a RO desalination plant supplied by a WTG in Gran Canaria. The most interesting result is that the produced water quality or volume were not affected by the unpredicted operation of the WTGs power profile. Moreover, neither the system components felt the effect of the discontinuous operation nor the anomalous voltage and frequency oscillations in terms of physical deterioration. In [91], Calise et al. studied a method for the optimal dispatch of PV using a desalination plant as deferrable load by means of TRNSYS in Pantelleria, Italy. Results show the PBP of the system to be 1.3 years, with water saving equal to 80%.

In [92], the use of a grid connected RO desalination plant was analysed by Corsini et al., on a case study of Ventotene island, Italy. Results show that the RO plant, by exploiting the excess energy production in wintertime, reduced the summer peak load by 29.5%. The solution was optimizing the operation using economic criteria, resulting in production of 48.5% of the freshwater demand and using 18.3% of the overall vRES production.

Another interesting study is provided in [93]. Meschede analysed the DR potential of a desalination plant and related pumping auxiliaries in the island of La Gomera, Spain. The analysis highlighted that the positive and negative flexibility potential is equal to 4.2 GWh and 7.9 GWh (i.e. 5.5% and 10.3%), respectively. Another interesting insight is that exploiting the DR potential of the water sector involves a reduced number of stakeholders compared to the residential sector and thus it might be easier to be adopted.

In [94], Torabi et al. studied the RO desalination plant in the island of Porto Santo in order to assess its potential to act as deferrable load proving that such management would lead to a remarkable decrease in GHG emissions. The study was then expanded in [95], by applying an evolutionary algorithm (EA) to optimally control the RO load. The main outcome is that the RO plant load does range between 2.5-5.5 MW without control and between 3-4.5 MW with optimised control.

Table 8 summarises the review outcomes of researches analysing the flexibility potential of the water sector.

Table 8. Summary of researches analysing the flexibility potential of the water sector (i.e. water production and management).

Reference paper	*Analysed indicator to evaluate DSM impact on the grid*	*Indicator value with DSM*	*Type of research*	*Programming technique*	*Notes*
[92]	peak load	-29.5%	simulation	heuristic	The load reduction is evaluated in comparison with the scenario with the same desalination plant without DSM
[91]	water savings	80%	simulation	heuristic	The water was produced by PV systems
[93]	flexibility range (positive/negative)	5.5%/10.3%	simulation	MILP	The water sector involves less stakeholders

					thus it is easier to realize
[95]	peak load	-18%	simulation	EA	-

Regarding the synergies with the transport sector, the greatest opportunities are offered by EVs and the use of hydrogen or biofuels.
Regarding the adoption of hydrogen solutions for transportation, a remarkable study has been developed by Krajacic et al. [96]. Here, several scenarios are simulated to analyse the impact of the hydrogen vector on the ability of island electric grids to host vRES. Scenarios were analysed for four different islands, namely: Mljet, Croatia; Porto Santo, Madeira; Terceira, Azores; and Malta. Generally, the introduction of the hydrogen energy vector in scenarios with limited penetration enabled the grid to host an increased RES penetration by 4-6%; furthermore, in small islands, hydrogen was also able to cover the whole transport demand.
In Gazey et al. [97], a pilot application of a HES on the Unst island in Scotland was investigated to balance WTGs. Once produced from excess energy from vRES (increasing the use of vRES for 18%), hydrogen was used as a fuel in transport sector. Result of this application is an annual energy saving of 21 MWh/y.
In [98], hydrogen was used as fuel in combination with natural gas for public transportation. Environmental benefits of several solutions were compared: a BESS, a HES whose hydrogen was used in Fuel Cell Electric Buses (FCEBs) or H_2NG-fuelled buses, or a combined system with BESS and HES. The first interesting output was that H_2NG-fuelled buses, in the case of low vRES, were a better solution than the FCEBs. Excess electricity was reduced from 1.1% to 0.7% using HES, while a combination BESS-HES was the best solution (excess production falls to 0.4%).

Regarding the use of EVs, a larger number of works can be found. The possibility to use such technologies to provide flexibility services to the grid and to support the grid balance management in islands without affecting the transport operation has been proven. Zou et al. [99] presented a control scheme for an insular microgrid, using the batteries of EVs to enhance power balance and provide load-frequency control.
Taibi et al. [100] studied the introduction of EVs in the Caribbean island of Barbados whose predominant vRES is PV. The research's aim was to ease the integration of vRES avoiding curtailment and reducing the cost of electricity. The research analysed two EVs operation mode: scheduled charge and V2G. Scheduled charge can reduce the curtailment by 13% if only daily charge/discharge is allowed while night charge/discharge would increase the unpredictability and the EES size would be increased by 58%. V2G results to be the solution with the best marginal cost, reduced curtailment, required EES size (i.e. -20%).
A similar conclusion is obtained in [101] where the optimal size of PVs and WTGs on the island of Favignana, Italy, is analysed in different scenarios changing the EVs operation mode (i.e. scheduled charge or V2G). The most interesting result is that in scheduled charge-mode, varying the EV penetration within the total island transportation from 0 to 100%, the optimal vRES sizes remain almost unchanged thus showing a very small influence on the grid management. Indeed, the EVs load is supplied by the biomass plant at night. Conversely, in the V2G scenario, the vRES optimal size ranges between 6.8 MW_p and 2.4 MW_p, respectively for V2G penetration of 100% and 0%. On the other hand, it is also obvious as EVs charging mostly at night do not represent an optimal strategy for island whose primary RES is solar. The same result is confirmed by Atia et. al. [102] when studying the island of Okinawa, Japan. A different conclusion is obtained by Dominković et al. [82]. The authors demonstrated that smart charging can lead to similar benefit as V2G. Indeed, the curtailed

energy with V2G was equal to 7.01 GWh while with smart charging it was equal to 7.12 GWh. Nevertheless, it is worth mentioning that the analysis of V2G was a post-design sensitivity analysis. This approach might justify the different conclusion compared to all other researches. Indeed, the interesting case study presented in [82] might be further analysed to understand if considering V2G in the designing process will modify the optimal generation mix and the storages sizes eventually leading to a reduced curtailment and an increased vRES integration.
Furthermore, a high V2G penetration would cause a decreased need for long-term storages offering the same grid stability level [103]. Child et al evaluated that the annualised cost would decrease by 225 M€/y; the curtailed energy amount to only the 5% of the overall vRES production. Between the different storage solutions, V2G is the solution that is exploited the most supplying the grid with 78 GWh while gas storage input to the energy system (used for producing synthetic fuel for transport) is equal to 4 GWh. It is noteworthy that V2G absorbs 139.82 TWh from the grid, 36% is used for transport, other 8% is lost and the remaining 56% is supplied back to the grid. That statistics underline that V2G would have more benefits for grid management than for transportation.
In [104], Meschede et al. obtains similar results as the aforementioned researches in terms of greater grid flexibility and Primary Energy Demand reduction. Furthermore, Meschede at al. evaluates the DR cost of EVs considering the car's battery cost as a fixed cost of the grid operator. All scenarios result in lower annual costs; and the scenario integrating DSM, Hydrogen and V2G is the one with the lowest annual cost, demonstrating that SESs might offer economically better solutions.
As regard the influence of EVs on the peak load, Dorotic et al. [105] presented interesting insights while analysing the impact of V2G in the island of Korcula. The authors also considered to use an electric ferry working in V2G mode. The outcomes show how the EVs would increase the total electricity exchanged with the mainland without affecting the peak power exchanged. On the other hand, the electric ferry would largely increase the imported energy and the peak load. Thus, authors concluded that the introduction of electric ferry can be a foreseeable solution in islands with high electricity consumption. In [106], the authors obtain similar results evaluating the peak load variation due to EVs; a 20% penetration of EVs in the Jeju island would increase the peak load by 29% while a 40% rate of EVs would increase it by 60%.

Ahern et al. [107] analysed the potential benefits of Power-to-Gas (P2G) solutions in island energy system. They adopted a PLEXOS model obtaining that a 50MWe of P2G capacity within the Irish electrical grid may decrease wind curtailment by 5%.
In [108], an analysis was performed on the adoption of hydrogen-fuelled ferries, for long distance, and electric ones, for short distances. The main findings focused on the necessary changes in the smart island's energy system configuration to accommodate such zero-carbon ferry lines. The use of electric ferries is also considered in [109] where it is proved to be a reliable source for ancillary services in an insular grid.

Table 9 summarises the review outcomes of researches analysing the flexibility potential of the transport sector.

Table 9. Summary of researches analysing the flexibility potential of the transport sector

Reference paper	*Analysed indicator to evaluate DSM impact on the grid*	*Indicator value with DSM*	*Type of research*	*Programming technique*	*Notes*

[96]	vRES share	+4-6%	simulation	heuristic	several scenarios had been analysed; results were strictly connected to the island size
[97]	use of WTG energy	+18%	Applied in real environment	N/A	A small portion of the produced hydrogen was also used for mobile power generators
[98]	excess electricity	-0.7%	simulation	single-objective optimisation with Brute-force search	The excess electricity of the reference scenario was equal to 1.1%
[100]	curtailment size of the EES AEC	-7% -20% +70 GWh/y	simulation	dispatch optimization with MILP	V2G resulted to be a better solution than standard EVs. The overall gasoline consumption is reduced by 325 GWh/y
[101]	optimal RES capacity compared to reference scenario (no V2G) RES share	+183% +44%	simulation	Single-objective optimization with Brute-force search+heuristic	Scenarios used all the same excess electricity threshold of 5%.
[82]	curtailed energy with V2G compared to smart charging RES integration with V2G vs smart charging Peak Demand	-1.5% +0.1% +11.15%	simulation	dispatch optimization with MILP	The analysis was developed by means of the PLEXOS software with a 5 minutes resolution
[103]	Curtailed energy annualised cost	-5% -225 M€/y	simulation	heuristic	V2G provides short-term storage and it strongly affects

					the need for long-term storages
[106]	Peak load with 20% of EVs penetration	+29	simulation	heuristic	EVs are not enabled for smart charging nor V2G
[107]	curtailment	-5%	simulation	dispatch optimization with MILP	P2G solution comprehended both a methanation process and hydrogen production

In conclusion, it has been shown some of the several solutions that have been studied or applied in islands to couple different energy consuming sectors. Overview of coupled sectors and technologies that were a subject of research is showed respectively in Figures 3-4.

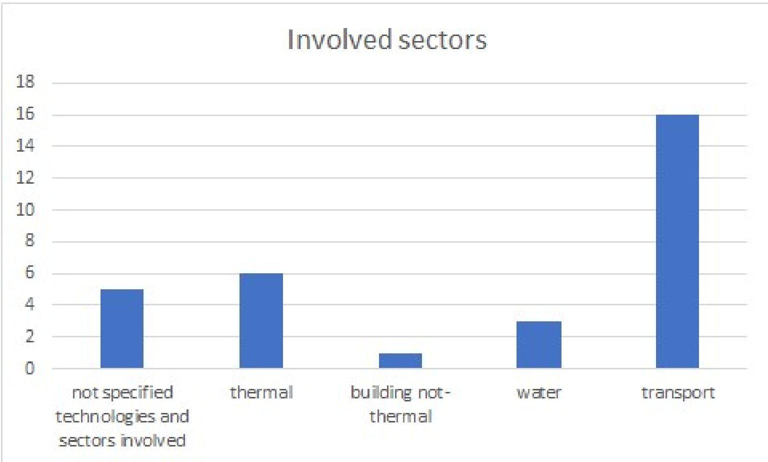

Figure 3 Overview of sector coupling solutions used for research in section 2.2

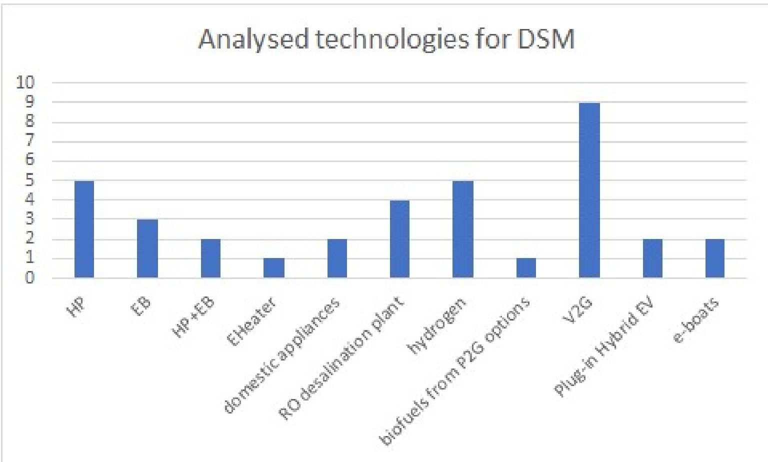

Figure 4 Overview of technologies used for research in section 2.2

Different energy vectors and several technologies able to respond to the grid necessity can be used to offer an increased flexibility to the grid and thus:

- increase the ability of the grid to host higher vRES share;
- reduce the need for vRES curtailment;
- manage the peak load.

It has been discussed the potential offered by EVs, discussing on the differences of scheduled charging and V2G. The potential of hydrogen in the transport sector, pure or blended with natural gas or biogas, has been considered as well as the possibility that are offered by desalination plants and seasonal water storages. All the aforementioned solutions enable the grid to utilise electricity for sectors that are different from the power one, thus having different load curves and offer the possibility to shift part of those loads. It is noteworthy to underline that by electrifying other sectors and services, the electricity consumption is always increased while the overall primary energy demand is reduced. Nevertheless, the flexibility of the discussed technologies enables to shift and manage the load aiming at reducing peak values in order not to impact the island grid negatively.

Figure 5 depicts the results of researches analysing DSM potential that have been reviewed in this section; it considers indicators that were used by at least 3 different researches in order to provide a statistical relevant sample.

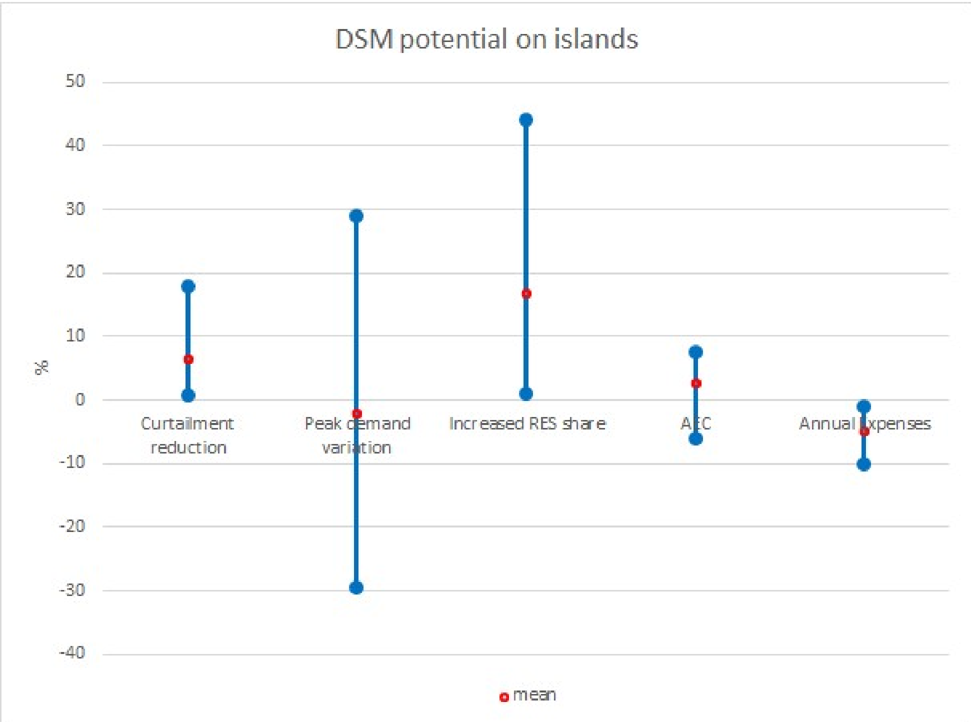

Figure 5 Overview of results obtained with DSM without specifying the sectors and technologies involved

Some clear trends can be identified:

- the vRES curtailment is always decreased thanks to electrification of consumption and increased flexibility offered by DSM. The transport sector is the one offering the highest potential (i.e. 18%);
- the peak demand can be both increased and diminished depending on the research assumption. Specifically, the peak demand is always increased when the enabler technologies for DSM are substituting old ones relying on fossil fuels that did not affect the electric grid at all (e.g. EVs and HPs or EBs instead of traditional cars and

boilers, respectively) reaching peak demand increase equal to 29% for the transport sector and 23.5% when considering the heating one. On the other hand, researches analysing the actual DSM potential of an island without adding new electric loads always results in a reduced peak load that can reach maximum values of -29.5% by means of RO desalination plants and -17% by exploiting the potential offered by the residential thermal sector;

- DSM and sector coupling solutions would increase the exploitation of vRES produced energy reaching peak values of +44% in the case of the transport sector;
- as regards the AEC, the obtained results vary between -6% and 7.5%; this indicator is only evaluated in researches studying the thermal sector;
- there is always a decrease in the yearly expenses when adopting DSM and sector coupling solutions up to a 10% savings. Particularly, this value is reached in a research that does not specify the nature of the DSM services.

The literature review has underlined some common trend and lacks in the actual research. First of all, most of the researches do not analyse the actual electricity grid and mostly use hourly time resolution; those features do not enable to analyse the impact of electrification and of DR at the single lines and substations levels. Thus, issues and opportunities linked to congestion management are not sufficiently studied. Also, the evaluation of the economic feasibility of such solutions is not adequately addressed mostly because of the lack of developed markets as well as the absence of clear legislative frameworks. Nevertheless, different methods for evaluating costs/rewards of DR services have been presented. Lastly, another feature that has been identified is the inconsistency of indicators that are analysed to discuss the DR impact and benefits on the energy system mainly because of the different topic that each research has. Nevertheless, a common set of indicators would help the comparison between different solutions as well as the replicability and scalability of the proposed solutions.

3. Conclusions

In the previous chapters several solutions for improving the capacity of the electric grid of hosting vRES have been presented. The EES systems and sector coupling represents the two main solutions for improving the energy system management in the insular context. Regarding EES systems, several solutions have been presented. Particularly, BESS represents a relevant option for small-medium scale systems; PHES are especially advantageous for larger systems with available natural reservoir (vRES penetration rate is increased in the range of 1.93-37%); also, the use of TES connected to a steam turbine has been presented. Regarding SESs and the use of sector coupling, solutions that analyse the thermal, water and transport sectors have been discussed. All the analysed solutions showed relevant results in terms of i) reduction of excess electricity production and vRES curtailment, and ii) increased grid capacity of hosting vRES. Power-to-heat solutions represent an interesting solution. Particularly, the use of HPs that generates a twofold effect on the grid energy management and the buildings energy efficiency. It is worth mentioning that the effect of cooling systems and its potential as a flexibility provider has to be further analysed. Indeed, depending on the climatic conditions, it might offer flexibility services to the grid as much as, or even greater than, heating systems. Regarding the water sector, it represents a key solution for islands since it offers a load that can be shifted without affecting the water quality and the system efficiency while decreasing the need for water delivery. Particularly, RO plants enable to store the electricity in form of water and, in case of touristic islands, to store it in non-touristic season and then release it during touristic seasons reducing the peak load and improving the

exploitation of vRES generators. Further, the consumption linked to pumping systems offer great opportunity since those loads are easy to shift.
The synergies with the transport sector by mean of power-to-transport solutions are the ones that have been studied the most. The present review paper discussed on the use of hydrogen in Fuel Cell EVs, as well as the use of vehicles fuelled by hydrogen-gas mixtures; it analysed the synergies offered by maritime transport through hydrogen-fuelled ferries and electric ones; and it largely tackled the topic of EVs dealing with the different operation modes such as scheduled charging, smart charging and V2G. The transport sector could largely benefit from one of these solutions. The outcomes largely depend on the island size and, with regard to EVs, the charging mode.
One of the main lacks in the analysed researches is the lack of analysis on the local impact of the grid. This is particularly relevant for EVs and slightly for HPs, since those two solutions comprehend a large number of machineries that are spread on the territory with a relatively high peak demand. Thus, a specific analysis on the grid response to such solutions in terms of grid congestion should be performed. In order to do that, future researches should integrate the grid management into the analysed models as well as reduce the time resolution since most of the stability and reliability constraints cannot be perceived with hourly time scale.
Furthermore, most of the time researches do not handle the economic sphere; this is mostly due to the lack of a clear capacity market for DR. Also, the researches use many different indicators to assess the impact of the strategies that are analysed. Thus, a unified and harmonised set of indicators able to fully evaluate the impact of DR solutions on the whole energy system, not just the power sector, should be established. Those gaps could be further analysed in future researches.

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