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Comparative energy scenarios: Solving the capacity sizing problem on the French Atlantic Island of Yeu

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ABSTRACT

Remote island communities face problems caused by the continuity and reliability of their power supply, which tend to be exacerbated when they rely on fluctuating renewables. In this paper the sizing of supply-demand-storage schemes is addressed in respect of their economy and feasibility. In the case of the French Atlantic Island of Yeu, high electricity peaks are common, due to tourism and to the seasonal use of second homes. A power plant dispatching model is used to simulate energy scenarios in 2030, subject to the supply-demand power equilibrium and the requirements of hydrogen-powered boats. Interconnected Yeu Island could accommodate 30 MW of renewables without curtailment, ensuring an electricity independence rate of 86% and renewable energy generation rate of 131% in the load, made up of wind (42%), solar (10%), tidal (21%), wave energy (25%) and biomass (2%). Excess energy could be exported through bidirectional cables, which are also the key adjustment variable in the reserve margins. Energy transition costs amount to 112 M€ in renewable-hydrogen projects, and 3 M€ for demand-side measures achieving a 2.7% reduction in load. An island self-sufficient power system with Yeu load characteristics would require at least 40 MW of variable renewables and 1 GWh energy storage capacity, at costs of 1.15 Bln€.

1. Introduction: drivers for energy transition on islands

European islands are home to 10 million energy customers and 286 territories spread out over the European Union [15]. The energy transition of these islands is part of the overall EU strategy for energy efficiency, renewables, and carbon emission targets [16]. However, the attributes of island life make their energy schemes different from those found on the mainland, with local environmental commitments and specific policies of governance and finance.

Traditionally, islands have relied heavily on an external energy supply, and many of them opted for diesel as fuel for power generation [15]. This has proven to be unsustainable, due to local and global pollution, and costly due to the severe risk of oil price volatility and economic vulnerability [36]. The energy mix on an island is driven by specific attributes such as land area and population, remoteness, economic structure, and the capacity to develop interconnections. For instance, Spanish islands are isolated from the mainland grid system due to the volcanic topography of the seabed which makes difficult the installation of submarine cables [48]. The renewable energy potential of biomass, wave, tidal, solar, and wind could contribute to sustainable development and reduce carbon footprint, though not without challenges in terms of capital cost, system balancing, tourism threat, local opposition, and weak economies of scale [32].

From the perspective of energy policy, energy dependency covers several areas, such as a dependency on a single supplier with a monopoly as the usual form of competition; a dependency on one supply route or interconnection; a dependency on one major energy resource and an attendant vulnerability in the case of resource disruption; and a dependency on fossil fuels. An energy-independent system would guarantee autonomy when based only on local resources. Alternative options for power systems are autarky (so-called stand-alone systems or electrical island; [55,51]), or interconnection with the mainland and the export of excess power (autonomous systems, such as the Scottish Orkney Islands; [65]). From the carbon content point of view, energy independence could be sustainable when generation is based on renewables, or it could have different degrees of resource exhaustion when based on fossil fuels.

The literature on scenarios for islanded power systems is broadly made up of three work categories: studies addressing the energy transition on islands, works handling the renewable-storage sizing problem, and works on energy modelling in support to capacity planning.

The first literature type addresses the issue of islands as test cases for new technologies in attempts to prove feasibility, and islands which have already moved on from the testing phase to the commercial phase,

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adopting full-scale technologies [17,25]. A growing number of works present lessons learnt in terms of cost, energy mix, technology availability, and demand-side options: Notton [36] and Selosse et al. [62] on French islands; Giatrakos et al. [18] on Crete; Krajacic [24] on the Croatian island of Mljet; Demiroren and Yilmaz [11] on the Turkish island of Gökceada; Pina et al. [52] on the Portuguese Azores; Nielsen and Jørgensen [35] and Pillai et al. [51] on Danish islands.

The contribution of this paper provides orders of magnitudes of the scale of renewable energies required to meet the demand on islands with similar climate conditions and tourism factors as the Atlantic Island of Yeu. To that, a detailed description of the load is performed by usage, by day and by season, along with a detailed method for load energy management such as to anticipate social and technological load changes. In general, works on long-term projections of energy capacity assess the way the demand could accommodate the variable power supply through demand-side management [18,54]. Load management methods are used to assess the gains of appliance efficiency and the behavioural changes, but also the flexibility capability of the demand to face a variable energy-based supply [9].

Secondly, a relative large number of studies deal with the issue of sizing the storage and renewables in remote communities. An extensive review of literature on approaches and on the current status of renewables in islands is presented in Kuang et al. [25], Cross et al. [10], Rodrigues et al. [57], Lin et al. [26], Goel and Sharma [19], Blechinger et al. [3] etc. The usual forms of energy storage are batteries, compressed-air, pumped-storage hydroelectricity and hydrogen for long-term applications, and flywheels and supercapacitors for grid power quality control. The on-island power generation can relate to a single technology type or to a mix of technologies, see for instance 100% renewable scenario on a small remote island made of wind, PV, hydro power, batteries and hydrogen storage in Kennedy et al. [23].

Island power systems are typically characterised by a high ratio of total installed capacity over peak load and a low capacity factor [10]. For orders of magnitude, Ogunjuyigbe et al. [42] size the capacity requirements to meet the load of one household and find that 100% renewables' scenario could be effective with PV panels with nominal capacity of 570% of the user's maximum instantaneous load requirement and batteries with 30 days storage autonomy; or with wind turbines sized to 490% of the user's peak load and the same storage capacity as for the PV. A hybrid scenario would require capacities for PV, wind and diesel generators sized at 172%, 164% and 120% of the peak load respectively, and with battery storage of 6 days of autonomy.

Rodrigues et al. [56] size NaS (sodium sulphur) battery energy storage to wind power in Crete Island and find that 170 MW wind plant would require 288 MWh/40 MW of storage to optimally reduce the power curtailment and the annualized cost, e.g. the battery capacity is 23% of the nominal capacity of the wind plant.

Pflaum et al. [49] propose battery sizing with PV panels that provide guaranteed expected revenue in the French regulatory context. The energy is remunerated at flat tariff of 0.10 €/kWh, while penalties apply to deviations from the day-ahead predictions of PV energy injected into the grid. The optimal battery size maximizing the profit will depend on the battery cost, such that 5 MW PV plant would need a battery capacity of 200 kWh if the storage capacity cost is of 100 €/kWh, and no battery at all at higher capacity costs. That is, providing accurate variable renewable power leads to a PV:battery sizing ratio of 1:0.04 or a battery capacity of 4% of the PV nominal power. The ratio varies with the modelling choices, such as the proposed regulatory penalties for forecasting deviations (soft constraints) versus technical ramping rates (hard constraints) leading to a larger battery capacity such as 30% of the PV capacity in de la Parra [44].

This paper contributes to this literature with quantitative comparisons for given technology mix scenarios allowing stakeholders to select the renewable-storage combination that best fits policies and targets in terms of renewables' integration support, curtailment avoiding, utilisation factors of storage, and investment cost.

Finally, quite a lot of works address the issue of building scenarios for the generation capacity planning. The classical formulation of the optimal investment strategies is the cost-minimisation programming of building and operating power plants over the long term (10–40 years) or the cost-efficient dispatching by allocating installed power plants in a short term (1 day or several weeks, up to 1 year). While the former models are used to plan the best technology mix, the later type is used to check the feasibility of the obtained best mix and to draw a detailed operation pattern of power plants due to specific cycling and load-following features [41,47].

Works dedicated to energy planning modelling are reviewed by Sadeghi et al. [61], Oree et al. [41], Saboori et al. [60]. Some of the reviewed studies highlight the advantage of modelling the uncertainty of investment strategies by means of scenarios with respect to multi-criteria decision-making objectives. The most relevant indicators for renewable integration assessment are the overall system costs, emissions, the expected energy not supplied, the external energy dependency, the system reliability, the firm capacity added to the system, the forced outage rate of conventional units and capacity factors of power plants.

Combining both long and short-term planning decisions is usually done by soft linkage within an iterative approach or by means of integrating economic dispatch or unit commitment modules in the long-term investment schedule. For instance Pereira et al. [47] assess future mixes of power plants by means of an integrated model able to evaluate the hourly impact of renewables on thermal power plants efficiency. Integrated models usually solve a largescale, non-linear discrete and dynamic optimisation problem in highly constrained environments, which increases the computational time (between 10 and 18 h in the later study). For this reason, only representative days are simulated over the year. In line with this complexity, [29] develop the Reunion-TIMES model to evaluate the French Reunion Island's power system. To reach 100% renewable energy in 2030, several measures are required such as strengthen power grid capacities, demand-side programs to flatten the load curve, and on-grid storage technologies in support to frequency controls. By providing sound options for the long-term development based on a technology-rich representation, the model depicts the short-term by selecting only representative time-slices for an average day for each season every year over the entire simulation period.

In general, the computational time limit binds the modeller to make a trade-off between detailed long-term representation of the power plant capacity planning and detailed short-term depiction of power plant operation. Combining both would necessarily limit the explanatory power of one of them in order to reduce the computational complexity. The model built in this study belongs to the short-term dispatching model category that consists of testing several scenarios of generation capacities and selecting a set of possible optimal solutions constrained by political objectives. The model uses a detailed time decomposition to cover a huge diversity of loads of RES availability and power demand values, which seems to best describe the demand chronology over the year. By making a high temporal resolution, the model proposed is able to fully capture the renewable input availability and the generators operation. This choice is adapted to model the energy storage in particular, with respect to operational constraints. The storage dynamics described here over 8760 h is driven by the demand and renewables' loads and needs no hypothetical starting and ending storage filling values between two consecutive days as in models with representative time-slices. This eliminates the drawback of limited duration curves which assume a set of theoretical initial and terminal conditions of the state-of-charge of the storage or a desired state-of-charge pattern [49].

Relatively few contributions to our knowledge combine all three topics related to the load management and the assessment of a set of scenarios with storage and variable renewables (VRES) by means of dispatching modelling. The final outcome is the formulation of a multi-