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Evaluation of the effect of flexible demand and wave energy converters on the design of Hybrid Energy Systems

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Abstract: Many islands have high electricity prices due to the reliance on imported diesel. However, Hybrid Energy Systems (HES) which combine renewable generation with backup generators and energy storage are becoming cost competitive. Diesel usually provides about 10% of the demand because most renewables are non-dispatchable and thus the complete decarbonisation requires massively oversized renewable generation and storage. By including renewables with different resource profiles and Demand Side Management (DSM) the diesel consumption could be decreased without increasing storage and renewable generation capacities. Here a framework for the design and optimisation of HES using wind, wave and solar generation and DSM is introduced. For the Mediterranean it is shown that wave energy isn't competitive but that DSM reduces the emissions and costs by 21% and 8%. In the North Sea, DSM has lower benefits because waves act as an energy store for the wind. Thus the combination of WECs and wind turbines significantly reduces the need for backup generation and energy storage which leads to large reductions in costs (up to 40%) and emissions (up to 60%). DSM and WECs can both simultaneously reduce the cost and emissions of HES but need to be designed for the particular circumstances.

1. Introduction

In many remote locations electricity is generated locally with diesel generators and thus the system is reliant on imported and often expensive fossil fuels with the resulting problems: high electricity costs and local pollution. On the other hand, many of these locations have excellent renewable resources which could provide enough electricity to fulfil the demand without pollution and independent of fuel imports. With the recent cost-reductions in renewable generation and energy storage this option is becoming competitive with conventional generators. In fact, in recent years an increasing number of so called Hybrid Energy Systems (HES) which combine renewable electricity generation with energy storage and backup generation, have been installed [1].

While it is desirable to use only renewable energy, the variable and more importantly non-dispatchable nature of most renewable electricity generation (biomass is one exception) requires massively oversized generation capacity to fulfil the demand at all times. The integration of energy storage enables the shifting of renewable energy from times when the renewable supply is larger than the demand (this electricity would otherwise be wasted) to times with higher demand than supply. This increases the utilisation of the renewable generators as well as the renewable fraction, i.e. fraction of the total energy demand covered from renewables. However, a very large battery system is required to achieve a fully renewable system and large parts of this battery would only be used infrequently. Thus most HES have a fossil fuel based backup generator which provides around 10% of the electricity demand [1, 2]. Two options to reduce the diesel fraction as well as the size of the energy storage are the integration of different forms of renewable generation and the introduction of Demand Side Management (DSM). By integrating different forms of renewable generation with different resource profiles the fluctuations in electricity generation and in particular the length of times with very low production could be reduced. This allows a reduction in the battery capacity while keeping the renewable fraction constant. In addition, DSM measures can be used to shave the demand peaks, to fill the demand troughs and, particularly in HES, to follow the renewable supply. Thus DSM can fulfil similar roles to energy storage units.

The development of HES for off-grid applications started in the late 1970s [3] and has seen significant growth in recent years due to the cost reduction in renewable generation and energy storage. However, significant challenges remain in the design of HES with economic and ecological benefits [4]. A careful consideration of the renewable resource, demand and available equipment is crucial to design and size a HES which can provide reliable energy at the lowest possible cost. It was realised from the beginning that simulation tools are required to evaluate and optimise these potentially conflicting objectives which depend on a large number of design parameters [2, 3]: system parameters and costs for each generator; conversion and energy storage type; demand profiles; renewable resource profiles. The optimal sizing [5, 6] and control [7] of HES has been a continuous focus of many studies in recent years and an overview of software tools is given by Sinha and Chandel [8]. The de-facto standard for HES simulation is HOMER [9]. However, HOMER has limitations in the integration of DSM and novel renewable generators such as wave energy converters (WECs).

While the wind/PV/diesel/battery HES is the most common system [5, 7, 10], the integration of ocean renewable energy, such as offshore wind and WECs, into HES is offering a large list of synergies [11]: common grid and foundation infrastructure, shared logistics and smoother power output. In addition, many of the remote locations are islands with a very good wave resource. A recent study has designed a HES for a Greek island combining wind turbines with a WEC highlighting the potential and opportunities for such a system [12]. This study uses the JONSWAP formulation for wave height and period calculations based on the fetch area and estimates the general performance of the system with a daily resolution. The dynamic response and power production of a device which combines a Wavestar type WEC [13] with a wind turbine was recently evaluated [14]. A number of further studies investigated the joint exploitation of offshore wind and wave resources [15, 16]. It was shown that the intermittency and variability of the combined resource is lower than for each individual resource. The results encourage the further evaluation of the wind/wave HES in a systematic design and optimisation study.

The previous studies [12, 15] are based on data measured with buoys and using wave reconstruction with empirical spectra. However, there is only a small number of wave buoys which are often deployed in areas unsuitable for wave energy deployments and thus significant extrapolation of the data is required. In addition, wave buoys have long measuring intervals and are often missing data [17]. The reconstruction of the wave height and period with the JONSWAP spectrum often fails to capture the swell and mixed seas and can lead to significant errors. Thus the estimated production is prone to increased errors.

These errors can be reduced by using calibrated and validated wind/wave data [18, 19] and high-fidelity numerical models. These enable also the tailored generation of resource data for specific locations which take local conditions, e.g. sheltering and depth breaking effects, into account. A recent study which used third generation wave models to examine the impact of co-located wind/wave devices, showed that these can reduce variability [20]. While this study is focused on the quantification of cross-correlation of the wind/wave resource, we are not aware of any study which uses data from high-fidelity numerical models for the design of HES. Such a combination can be used for the accurate and systematic optimisation of wind/wave HES.

In recent years DSM has received increased attention for the wider energy system [21] and also for HES [22, 23]. DSM can play a similar role to energy storage in balancing the demand and supply but compared to energy storage can be a low cost solution with no inherent energy losses. The ability to significantly reduce demand peaks is particularly relevant for HES which have a large demand coincidence factor [21]. Gudi et al. [24] optimise the distribution of energy generated by a given HES to various loads and achieve a cost reduction of around 16%. Krumdieck and Frye [22] use HOMER with a custom DSM modelling tool to evaluate the potential of shifting the laundry load for the New Zealand research station at Scott Base in Antarctica to times with surplus renewable supply. The difficulty of integrating wave energy and DSM in HOMER shows that there is a need for a HES design tool that can handle different renewable resources and integrates a flexible DSM model.

In this contribution a simulation framework for the design and optimisation of HES which integrates wave energy converters (WEC) and demand side management (DSM) is presented. The framework is used with wind/wave data from accurate numerical models to generate optimised designs of HES consisting of wind turbines, solar PV panels, WECs, energy storage and diesel units for various levels of DSM. The resulting Pareto fronts for the Greek island Astypalaia and the island Westray in the North of Scotland show the trade-off between electricity cost and CO_2 emissions. These results show that both WECs and DSM can lower the cost and emissions of HES but that the impact depends strongly on the resource and demand profiles.

2. HES simulation and optimisation framework

The schematic of the HES considered in this contribution is shown in Figure 1. The main components of the HES are the wind turbines, WECs, solar PV panels, batteries, diesel generator and DSM. The renewable generators are connected to a DC bus from which the AC load is supplied through a DC/AC converter. A simple control scheme controls the operation of the batteries, diesel generators and DSM.

The individual components are modelled with parametrised power flow models [4]. More complex models might be closer to the actual component performance but require a larger number of parameters to achieve this higher accuracy and are computationally more expensive. On the other hand, the parametrised models have a lower accuracy but can be run with hourly time steps which enables the simulation of annual operation. Since this contribution is interested in showing the relative benefits of including WECs and DSM in HES parameterised models offer a good balance between complexity and accuracy. In addition to the units presented in the following sections and used in this contribution the framework also contains heat generation units (gas boilers, heat pumps, resistive heating, solar thermal) as well as thermal energy storage units. Together this forms the Hybrid Electricity And Thermal Simulation (HEATS) framework which will be introduced in a future contribution.

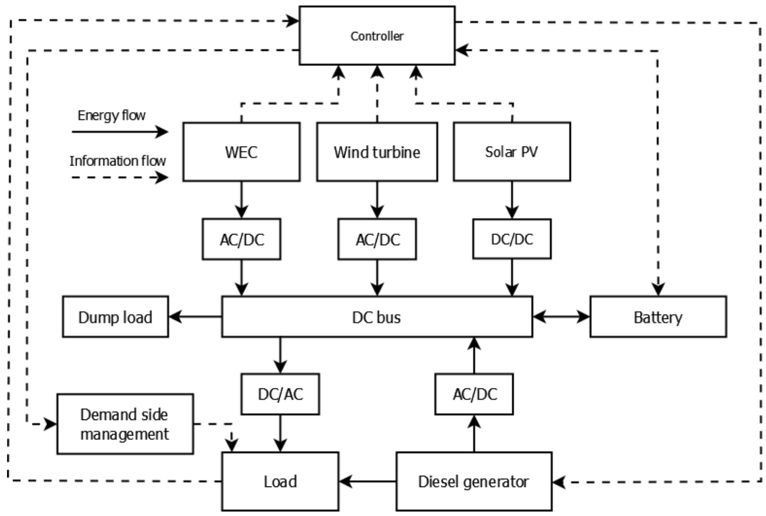

Fig. 1. *Schematic of the proposed HES with demand side management.*

2.1. Wind turbine model

The performance of the wind turbine depends on the wind speed at hub height and on the design of the wind turbine [4]. The wind speed at hub height can be calculated from the following power law

$$v_T = v_m \left(\frac{h_T}{h_m}\right)^{0.13}$$

where v and h are the wind speed and the hub height and the subscripts m and T indicate the measured values and the wind turbine, respectively. The power output of the wind turbine can be calculated from the power curve which is given by

$$P = \begin{cases} 0, \quad v < v_{ci} \\ aP_r(v^3 - v_{ci}^3), \quad v_{ci} < v < v_r \\ P_r, \quad v_r < v < v_{co} \\ 0, \quad v > v_{co} \end{cases}$$

here P_r is the rated power and v_{ci}, v_r and v_{co} are the cut-in, rated and cut-out wind speeds at hub height, respectively. The parameter a is calculated by $a = (v_r^3 - v_{ci}^3)^{-1}$. The power the wind turbine provides to the DC grid is given by $P_{wind} = \eta P$ where η is the efficiency of the inverter.

2.2. Wave energy converter model

The sea state and the energy content of waves depend on the wave height H_{sig} and the wave energy period T_e. The wave power per unit length of wave crest for deep water can be calculated from the formula

$$P = \frac{\rho g^2}{64\pi} H_{sig}^2 T_e$$

where ρ is the fluid density and g the acceleration by gravity.

An overview of different WEC concepts and technologies is given in [25, 26]. While different WECs use different principles to extract the energy from the waves, the wave energy conversion can be parameterised through a power matrix which links the wave height and wave energy period to the power output. This power matrix has cut in and cut out wave heights and periods. The power matrix can be calculated based on numerical models of the WEC [27] or taken from experimental data. In this study the bottom-fixed heave-buoy array Wavestar 600kW is used [13]. This WEC has a relatively low cut-in wave height and wave energy period and is thus suitable for both the Mediterranean and the North Sea. The WEC power is calculated with the power matrix from [13] and the power to the DC bus is given by $P_{wave} = \eta P$.

2.3. Solar PV model

The power output of a solar PV module depends on the solar irradiance, the panel temperature and voltage and can be calculated by equivalent circuit models [28]. However, these models are computationally expensive and for the hourly time steps a simplified parametric model is acceptable [7]. In this model, the power output of a solar PV module can be calculated as

$$P_{PV} = \eta \eta_{PV} A G$$

where η is the inverter efficiency, η_{PV} is the solar panel efficiency, A is the panel area and G is the tilted solar irradiance, i.e. solar irradiance perpendicular to the panel surface [5].

2.4. Battery model

The battery is modelled with a state of charge (SoC) model [4]. In each time step the SoC is modified by taking the self-discharge rate η_{self} into account and the amount charged/discharged during this time step. The charge/discharge amounts include the charging efficiencies and also depend on the operation of the HES and the limits of the battery, e.g. maximum SoC reached or the battery is empty.

$$SoC_i = SoC_{i-1} * \eta_{self} + charge_i - discharge_i$$

2.5. Diesel generator model

The diesel generators provide the backup power generation when the renewable generation, battery bank and DSM can't fulfil the power demand. The power output of diesel generators is calculated based on the efficiency at a particular load factor. Here the diesel generators are always either switched off or run at their rated capacity; thus the diesel generators run at a fixed efficiency.

2.6. Demand side management

The DSM measures are modeled similar to the model developed by Krumdieck and Frye [22]. In this model the flexible demand is defined by the amount of shiftable demand and by the size of the shift window. Here the shiftable demand is given as a percentage of the total demand and the shift window is the maximum time the shiftable demand can be held back. In every time step of the simulation this flexible demand is checked before utilising the backup diesel generators or before curtailing the renewable generation. The fulfilment of the flexible demand depends on the balance between the renewable supply and fixed demand. If there is a supply shortage only the flexible demand at the end of the shift window is fulfilled, i.e. for a shift window of 5 hours only the shiftable demand which has already been delayed for 5 hours is fulfilled. On the other hand, if there is surplus renewable supply as much as possible of the flexible demand is fulfilled.

This contribution considers only a single flexible demand defined through the shift percentage and shift window length, i.e. 5% DSM for 5 hours means that 5% of the total demand is shiftable demand with a shift window length of 5 hours. In addition, no losses or costs are associated with the DSM measures. This simplification enables the evaluation of the maximum potential of DSM. However, the simulation framework can account for losses and can simulate different flexible demands, e.g. time of day or different shift windows.

2.7. Control scheme

The simulation framework takes the resource and demand data from an input file and steps through the simulation time with the given step size (in this contribution the step size is one hour). At each time step a simple control scheme ensures that the fixed demand and the flexible demand at the end of the shift window is met through a combination of the renewable generators, energy storage and backup generators. Briefly, the non-dispatchable renewable electricity generation is used to supply the fixed demand and the flexible demand at the end of the shift window. Any surplus electricity is first used to fulfil the flexible demand and then to charge the batteries. If there is a shortage of renewable electricity, this is supplied by discharging the batteries if these have a sufficiently high state of charge. If the batteries can't fulfil this load diesel generators are switched on. In this case the remaining load is first fulfilled by the diesel generators which are running at their nominal power rating and the remainder is provided by the batteries.

2.8. Optimisation of the HES

The framework is linked to a multi-objective optimisation method in a similar way to previous studies [5, 7]. This enables the optimisation of the HES with respect to multiple and often conflicting objectives such as cost and emissions. The flowchart in Figure 2 gives an overview of this approach. Here the objectives are the levelised cost of electricity (LCOE) and the CO_2 emissions of the diesel generator. The LCOE is calculated from the total electricity demand, fuel costs and the annualised capital costs C

$$C = K\left[\frac{r(1+r)^n}{(1+r)^n - 1} + OM\right]$$

where K is the initial capital cost, r is the interest rate, n is the asset lifetime and OM are the operation and maintenance costs. The annual interest rate is fixed at 6% and the annual operation and maintenance at 2%.

The optimisation routine in this contribution is the multi-objective genetic algorithm NSGA2 from the Python module inspyred [29]. The population size and number of generations are set to 240 and 16, respectively, while the other parameters are left at the default values. The multi-objective optimisation produces a number of Pareto optimal solutions which are equivalent in the Pareto sense and present the compromise between the different objectives [30]. In a further step one of these solutions needs to be picked based on social, political and other criteria not included in the optimisation. This step goes beyond the scope of this contribution and thus the complete Pareto fronts are shown.

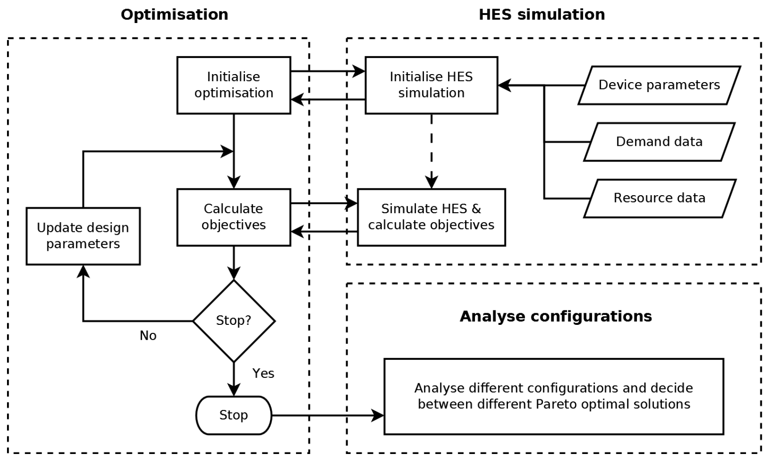

Fig. 2. *Schematic of the HES simulation linked to multi-objective optimisation and subsequent analysis.*

3. Case studies

Two case studies will be used to evaluate the effect of including WECs and DSM in HES: the Greek island Astypalaia and the island Westray in the North of Scotland.

3.1. Astypalaia

Most of the Greek islands have isolated electricity grids which are dependent on oil fired electricity generation. The resulting high electricity costs have led to proposals to develop HES to achieve greater energy autonomy [31]. In recent years, a number of systems have been proposed for Greek islands, e.g. Lemnos Island [32].

The resource and demand data for Astypalaia was given previously at OSES2015 [33]. Briefly, Astypalaia is an island in the Dodecanese Archipelago in the south of the Aegean Sea with about 1300 inhabitants. The island has an isolated electricity grid and the electricity is provided by a small fossil fuel power plant. In 2003 the island had a peak demand of 1.78 MW and an annual electricity consumption of 5419 MWh [34]. An average daily demand profile was extracted from [34] and overlaid with the daily variations typical for Greek islands from [31] plus a small random element. The resulting synthetic demand profile and the resource profiles are given in Figure 3. The wind datasets were provided by NCAR/NCEP [35] and are a result of global wind and precipitation models which have been validated and used in various meteorological applications [19]. The wave energy resources were calculated with SWAN [36]. The wave numerical model SWAN is a third generation spectral phase averaged model appropriate for coastal and nearshore locations. The model was nested twice and used all non-linear and depth to wave interactions in order to provide high accuracy for the final coastal resource around Astypalaia [37]. The initial mesh covered all the Mediterranean and used to provide spectral information for the subsequent finer resolution run.

For a large part of the year the wind speed is above 3 $\mathrm{m\,s^{-1}}$ which is favourable for wind turbines. The wave resource on the other hand is not as favourable with the wave height around 1.5 metres with a wave energy period of around 3.5 seconds for large parts of the year. On the other hand, the solar resource is high throughout the year with a slight summer peak. While this summer peak coincides with the summer demand peak, its increase is modest compared to the doubling of the demand in summer. This high summer demand is due to an increase in tourism and the

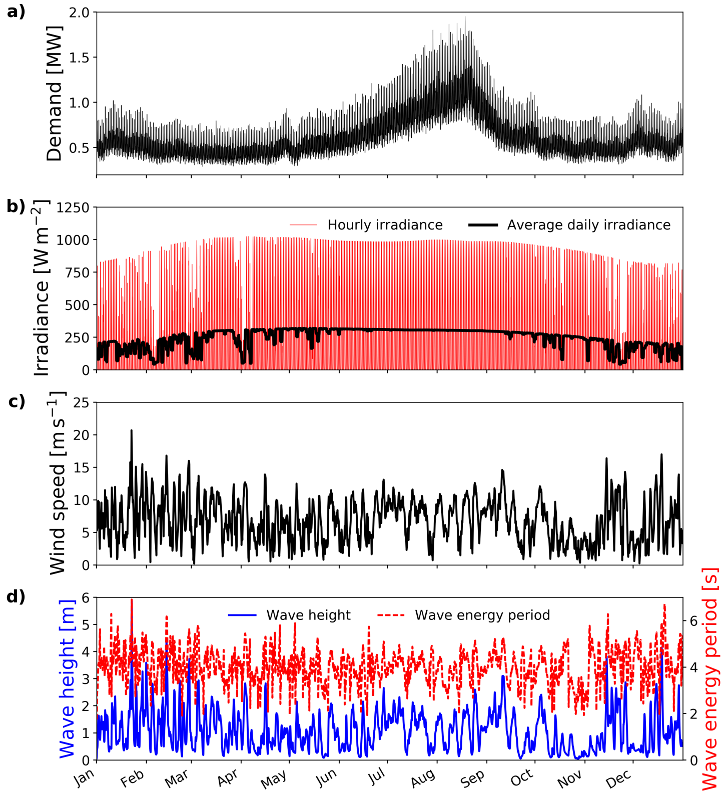

Fig. 3. *Input data for Astypalaia: a) hourly synthetic electricity demand for 2003, b) hourly solar irradiance for 2005 [38], c) hourly wind speed at 10 metre above sea level and d) hourly wave height and wave energy period. The wind and wave data is for 2013.*

increased use of air conditioners. However, these air conditioners offer the potential to shift some of the electricity demand to periods with a surplus of renewable electricity if a moderate variation in indoor temperature is acceptable.

3.2. Westray

The island Westray in the Orkney Islands in the North of Scotland has around 600 inhabitants. According to statistics from the National Grid Westray has 363 electricity metres and in 2013 the annual domestic electricity consumption in Westray was around 1909 MWh [39]. The UK electricity demand is scaled to this yearly demand and given in Figure 4 together with the solar, wind and wave resource. The Westray wave data, was produced by a high resolution SWAN model with a customised solution for the sea around Scotland. The numerical wave model underwent calibration analysis and re-tuning for non-linear deep water physics, wind schemes, bottom friction, and all nearshore components (i.e. triad interaction) [18]. The wind and wave resource shows some overlap with the electricity demand in Figure 4. This is due to the increase in wind speeds during the winter in the North of Scotland. On the other hand, the solar resource in Figure 4 has its peak during the summer and is much smaller than the solar resource in Astypalaia shown in Figure 3.

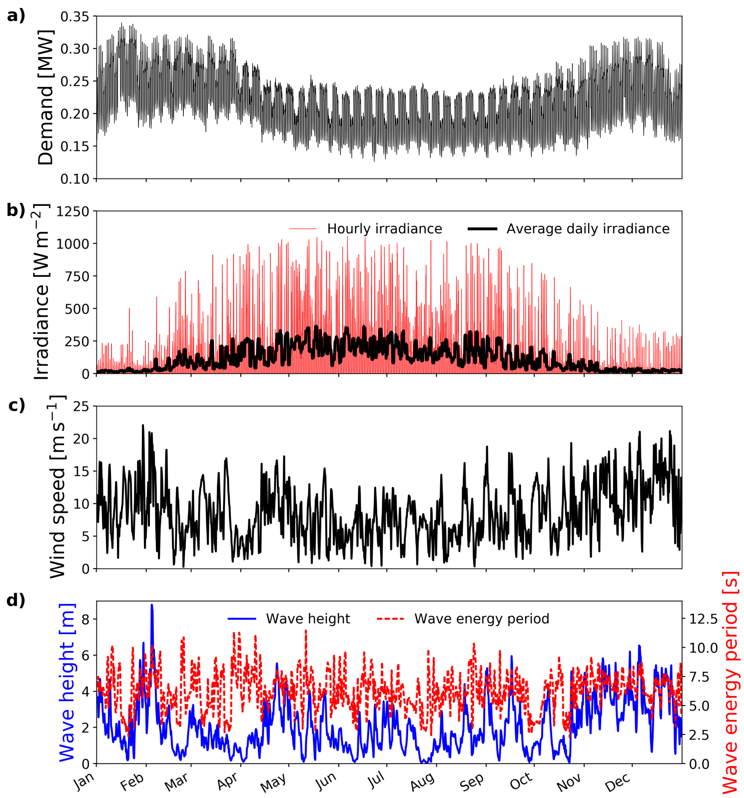

Fig. 4. *Input data for Westray in the North of Scotland: a) hourly synthetic electricity demand, b) hourly solar irradiance for 2005 [38], c) hourly wind speed at 10 metre above sea level and d) hourly wave height and wave energy period. Except for the solar irradiance all data is for 2013.*

3.3. HES components

The electricity demand of the two case studies is between 0.15 MW and 1.8MW thus for the design of the HES electricity generation units which can supply this demand are picked. The specifics of the units are:

- Perkins 175 kW diesel generator: hourly diesel consumption at rated capacity is 48 litres;

lifetime 20 years; cost $25000£$ [40]; fuel cost 1 $£l^{-1}$ of diesel;

- Solar PV panels with an efficiency of 16%; lifetime 20 years; cost $1250£\,\mathrm{kW}^{-1}$ [41];
- Li-Ion battery with charging and discharging efficiency of 95% and self-discharge rate of $\eta_{self} = 0.0005\%\,\mathrm{h}^{-1}$; lifetime 5 years; $700£\,\mathrm{kWh}^{-1}$ [42];
- Inverters have an efficiency of 97%;
- Vestas V27 wind turbine: hub height 35 m; rated power 225 kW; cut-in, rated and cut-out speed of 3.5, 14 and 25 m/s; lifetime 20 years; cost $300000£$ [41];
- Wavestar 600kW wave energy converter; lifetime 20 years; cost $1000000£$.

There are some small scale and prototype applications of WECs, however no exact information on installation costs is available [43]. Thus the cost for the WEC has been based on the cost per installed kW of the wind turbine with a mark-up of 25%. While the first commercial WEC will be more expensive, a cost similar to wind turbines is necessary to achieve cost parity.

4. Results and discussion

The two case studies are optimised without DSM and with various levels of DSM: 5% for 5 hours; 10% for 5 hours; 20% for 5 hours; and 10% for 10 hours. While the resource and demand data for the two case studies are for different years (see Figures 3 and 4), the results are still qualitatively correct because the correlated data sets, i.e. wind and wave data, are for the same year and location.

4.1. Results for Astypalaia

The Pareto front in Figure 5 shows that a HES with and without DSM can reach cost parity with the conventional energy system while also producing less than 10% of the CO_2 emissions of the convention energy system, i.e. diesel only case. The introduction of a small amount of DSM moves the Pareto front in the direction of the origin, i.e. reduces both the electricity cost and the emissions.

The effect of adding DSM to a HES with a fixed configuration is shown in Table 1 for the HES configuration which without DSM achieves cost parity with the conventional system. It is evident that in this case the emissions drop more significantly compared to the cost. The main costs are the capital costs which stay constant in this case and thus the low drop in electricity costs is only due to the reduced fuel use. On the other hand, the emissions are reduced by up to 16%. For a fixed shift window length, the emissions reductions are almost linear with increasing shiftable load.

Table 1 Emissions and LCOE of the HES with DSM for the configuration of the HES without DSM which achieves cost parity with the diesel only case.

	Emissions [kgCO_2/kWh]	LCOE [£/kWh]
No DSM	0.0597	0.288
5%, 5 hours	0.0572	0.287
10%, 5 hours	0.0552	0.286
20%, 5 hours	0.0509	0.285
10%, 10 hours	0.0499	0.284

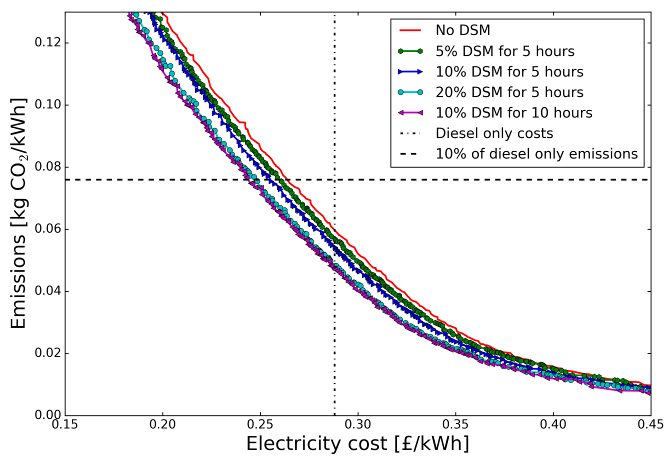

Fig. 5. *Pareto front for the HES for Astypalaia with and without DSM.*

Table 2 shows results for systems with the same LCOE or emissions, respectively, but with varying configurations. The left column shows that the HES with DSM can achieve emissions savings up to 21% compared to the system without DSM if cost parity with the diesel only configuration is required, i.e. the table gives the crossing points of the Pareto fronts with the dash-dotted line in Figure 5. The right column shows that DSM can reduce the LCOE by up to 8% compared to the system without DSM if up to 10% of the diesel only emissions are allowed, i.e. the crossing points of the Pareto fronts and the dashed line in Figure 5.

Table 2 Emissions and LCOE of the HES at the LCOE of the diesel only system and with 10% of the diesel only emissions, respectively.

	Emissions at LCOE as the diesel only case [kgCO_2/kWh]	LCOE at 10 % diesel emissions [£/kWh]
No DSM	0.0597	0.264
5%, 5 hours	0.0569	0.260
10%, 5 hours	0.0544	0.255
20%, 5 hours	0.0484	0.248
10%, 10 hours	0.0470	0.244

It is interesting to note that the Pareto front in Figure 5 becomes flatter for LCOE larger than 0.35 £/kWh, i.e. there is a long tail with low but non-zero emissions. This is due to the large seasonal variation in demand: to meet the summer demand peak would require a massively oversized renewable generation capacity or long term energy storage.

The installed energy/power of the different units are shown in Figure 6. While the installed battery and solar PV capacity increase monotonically with increasing costs, the installed wind turbine capacity decreases before increasing again at high LCOE. At low LCOE and thus high emissions a significant fraction of the electricity is provided by the diesel generators and not much of the renewable generation is curtailed. This condition is beneficial for the wind generation which is about 10% cheaper per kWh than the solar PV generation. On the other hand, for high LCOE the emissions are low but also a significant part of the renewables needs to be curtailed. For this case the solar PV panels are advantageous due to the daily cycle and the good solar resource in Astypalaia (Figure 3). The WEC is only chosen for configurations with costs above 0.35 £/kWh.

This is due to the higher capital cost and lower capacity factor compared to the wind turbines.

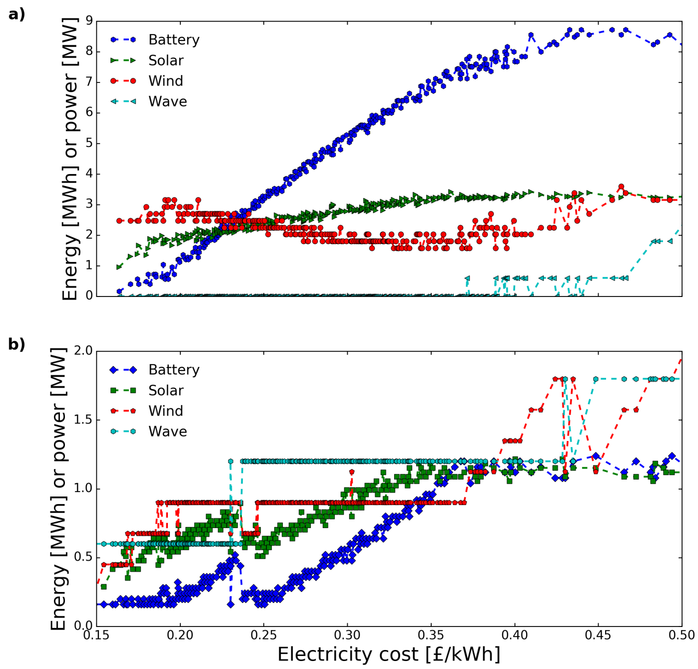

Fig. 6. *Installed energy/power capacity of the HES for the case with 5% DSM for 5 hours for (a) Astypalaia and (b) Westray.*

4.2. Results for Westray

The Pareto fronts for Westray shown in Figure 7 are moved significantly closer to the origin compared to the case of Astypalaia. This means that the system has both lower LCOE and emissions. However, the benefits of including DSM are less pronounced. The emissions savings (crossings of dash-dotted line) are only up to 13% and the cost savings (crossings of dashed line) are only up to 2% which is much lower than for the Astypalaia case. By optimising the HES without the WEC it becomes clear that the lower benefits of DSM are due to the presence of the WECs. In the case without WECs, DSM can reduce the emissions also by 13% but the costs are reduced by up to 8%.

This poses the question why the inclusion of WECs leads to cost reductions of over 40% and emissions reduction of over 60% compared to the case without WECs. For Westray both wind turbines and WECs have low LCOE of 0.038 £ kWh^{-1} and 0.049 £ kWh^{-1}, respectively, as well as good capacity factors of 42% and 45%, respectively. However, these values don't explain the massive improvements for the HES with WECs. This improvement is due to the fact that most waves are wind generated and that there is usually a time delay of several hours between the wind and wave energy resource: the waves act as an energy store for the wind. This resource delay ensures that the combined renewable generation of wind turbines and WECs is less variable than the output of either of the two technologies. Figure 6 shows that the optimal configurations for Westray have roughly equal wind turbine and WEC capacity. In such a configuration the combination of wind turbines and WECs provides a more stable electricity supply than each technology individually.

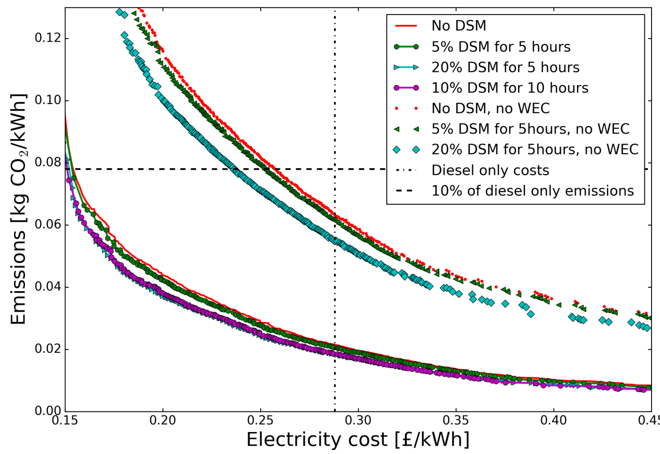

Fig. 7. *Pareto front for the HES for Westray with and without DSM.*

Thus the combination reduces both the required amount of backup generation and energy storage in comparison to a wind only HES. This is supported by the low emissions and the low amount of energy storage compared to the case for Astypalaia.

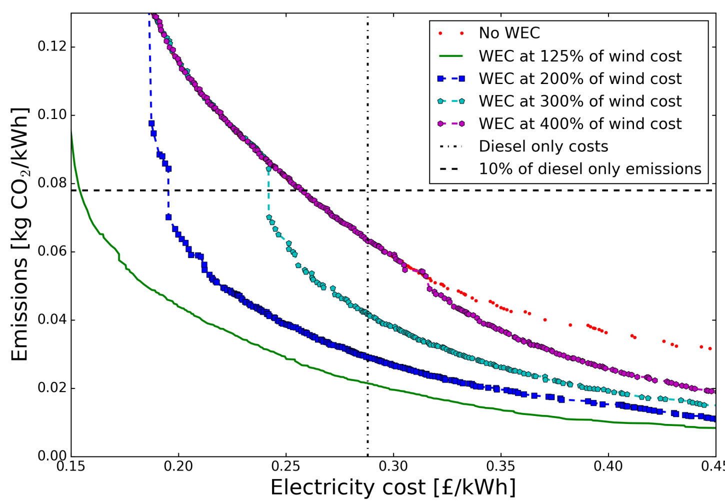

Fig. 8. *Pareto front for the HES for Westray for different WEC costs.*

While for the given unit costs the inclusion of WECs leads to huge cost and emissions reductions, it is interesting to see for which WEC cost range this is the case. Figure 8 shows Pareto fronts for different relative WEC costs. For a cost per installed kW of 3 times the wind turbine cost, the inclusion of WECs still shows significant emissions and cost reductions. For this case the WEC cost is $4\,\mathrm{m}£\,\mathrm{MW}^{-1}$ which is in the range of expected WEC costs given in the literature [43].

5. Conclusion

In this contribution the effect of demand side management and wave energy converters on the emissions and costs of HES was investigated with an in-house simulation and optimisation framework. The application of the framework to two cases studies is the first systematic optimisation of combined wind/wave HES under consideration of demand management and with accurate wind/wave resource data.

The framework is based on parameterised models for the different units of the HES and contains models for WECs and DSM. In contrast to previous publications, here the sea state was generated with the state of the art wave numerical model SWAN which has been validated for the near-shore region. The model produces a time series of wave heights and wave energy periods which can be used in the simulations with hourly step size. This enables for the first time the investigation of the effect of time delay in the wind and wave resource on the performance of a HES. The framework also includes DSM measures through flexible demand which is defined as a percentage of the total demand and a shift window. The simulation framework is linked to a multi-objective optimisation which enable the optimisation with respect to multiple and often conflicting objectives.

The simulation framework was used to evaluate the effect of different levels of DSM (shiftable demand and shift window length) on the LCOE and CO_2 emissions of HES for two islands: Astypalaia in the south of the Aegean Sea and Westray in the Orkney Islands. The multi-objective optimisations with respect to LCOE and emissions showed that low levels of DSM, e.g. 10% shiftable demand for 10 hours, can in the case of Astypalaia reduce the emissions by up to 21% or the costs by up to 8%. On the other hand, for the case of Westray the DSM measures can only reduce the emissions by up to 13% or the costs by up to 2%.

These lower benefits of DSM are due to the fact that the HES for Westray has much lower costs and emissions than in the Astypalaia case. It was shown that this lower cost is due to the presence of WECs in the system. The time delay between the wind and the wave resource enables a better utilisation of the renewable generation which leads to lower diesel consumption and less reliance on energy storage to fulfil the demand. For the base case this led to an emissions reduction of over 60% at the cost parity case or a cost reduction of over 40% for the case with 10% diesel only emissions. This shows for the first time, that the combination of wind turbines and WECs in a HES can lead to large cost and emissions reductions. While these reductions depend on the cost of the WEC, it was shown that WECs costing up to $4\,\mathrm{m}£\,\mathrm{MW}^{-1}$ offer significant benefits.

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References

[1] Zbigniew Chmiel and Subhes C. Bhattacharyya. “Analysis of off-grid electricity system at Isle of Eigg (Scotland): Lessons for developing countries”. In: *Renewable Energy* 81 (2015), pp. 578–588.

[2] John A. Castle, James M. Kallis, Sally M. Moite, et al. “Analysis of Merits of Hybrid Wind/Photovoltaic Concept for Stand-Alone Systems”. In: *Photovoltaic Specialists Conference* (1981), pp. 738–744.

[3] J. W. Andrews. “Energy-storage requirements reduced in coupled wind-solar generating systems”. In: *Solar Energy* 18.1 (1976), pp. 73–74.

[4] M.K. Deshmukh and S.S. Deshmukh. “Modeling of hybrid renewable energy systems”. In: *Renewable and Sustainable Energy Reviews* 12.1 (2008), pp. 235–249.

[5] A.T.D. Perera, R.A. Attalage, K.K.C.K. Perera, et al. “Designing standalone hybrid energy systems minimizing initial investment, life cycle cost and pollutant emission”. In: *Energy* 54 (2013), pp. 220–230.

[6] R. Luna-Rubio, M. Trejo-Perea, D. Vargas-Vázquez, et al. “Optimal sizing of renewable hybrids energy systems: A review of methodologies”. In: *Solar Energy* 86.4 (2012), pp. 1077–1088.

[7] José L. Bernal-Agustín and Rodolfo Dufo-López. “Multi-objective design and control of hybrid systems minimizing costs and unmet load”. In: *Electric Power Systems Research* 79.1 (2009), pp. 170–180.

[8] Sunanda Sinha and S. S. Chandel. “Review of software tools for hybrid renewable energy systems”. In: *Renewable and Sustainable Energy Reviews* 32 (2014), pp. 192–205.

[9] Tom Lambert, Paul Gilman, and Peter Lilienthal. “Micropower System Modeling with HOMER”. In: *Integration of Alternative Sources of Energy*. Ed. by Felix A. Farret and M. Godoy Simoes. John Wiley & Sons, 2006. Chap. 15, pp. 379–418.

[10] Payal Suhane, Saroj Rangnekar, Arvind Mittal, et al. “Sizing and performance analysis of standalone wind-photovoltaic based hybrid energy system using ant colony optimisation”. In: *IET Renewable Power Generation* 10.7 (2016), pp. 964 –972.

[11] C Pérez-Collazo, D Greaves, and G Iglesias. “A review of combined wave and offshore wind energy”. In: *Renewable and Sustainable Energy Reviews* 42 (2015), pp. 141–153.

[12] Artemis Ioannou, Anestis I Kalfas, and Theofanis V Karambas. “Integrated Overtopping Wave Energy Converter in a Hybrid Offshore Wind Turbine Power Generation System”. In: *Proceedings of ASME Turbo Expo 2014: Turbine Technical Conference and Exposition*. 2014.

[13] L Marquis, M M Kramer, J Kringelum, et al. “Introduction of Wavestar Wave Energy Converters at the Danish offshore wind power plant Horns Rev 2”. In: *4th International Conference on Ocean Energy* (2011), pp. 2–7.

[14] Madjid Karimirad. “WindWEC: Combining Wind and Wave Energy Inspired by Hywind and Wavestar”. In: *5th International Conference on Renewable Energy Research and Applications*. 2016.

[15] Francesco Fusco, Gary Nolan, and John V. Ringwood. “Variability reduction through optimal combination of wind/wave resources - An Irish case study”. In: *Energy* 35.1 (2010), pp. 314–325.

[16] L Cradden, H Mouslim, O Duperray, et al. “Joint exploitation of wave and offshore wind power”. In: *In: Proceedings of the nineth European wave and tidal energy conference (EWTEC)* (2011), pp. 1–10.

[17] Luigi Cavaleri and Mauro Sclavo. "The calibration of wind and wave model data in the Mediterranean Sea". In: *Coastal Engineering* 53.7 (2006), pp. 613–627.

[18] George Lavidas, Vengatesan Venugopal, and Daniel Friedrich. "Sensitivity of a numerical wave model on wind re-analysis datasets". In: *Dynamics of Atmospheres and Oceans* 77 (2017), pp. 1–16.

[19] Suranjana Saha, Shrinivas Moorthi, Hua Lu Pan, et al. "The NCEP climate forecast system reanalysis". In: *Bulletin of the American Meteorological Society* 91.8 (2010), pp. 1015–1057.

[20] S. Astariz and G. Iglesias. "Selecting optimum locations for co-located wave and wind energy farms. Part II: A case study". In: *Energy Conversion and Management* 122 (2016), pp. 599–608.

[21] Goran Strbac. "Demand side management: Benefits and challenges". In: *Energy Policy* 36.12 (2008), pp. 4419–4426.

[22] Susan Krumdieck and Jake Frye. "Optimizing Wind-Diesel Hybrid Energy Systems Including a Demand Side Management Strategy". In: *1st International e-Conference on Energies*. 2014.

[23] Félix Iglesias Vazquez, Peter Palensky, Sergio Cantos, et al. "Demand Side Management for Stand-Alone Hybrid Power Systems Based on Load Identification". In: *Energies* 5.12 (2012), pp. 4517–4532.

[24] Nikhil Gudi, Lingfeng Wang, Vijay Devabhaktuni, et al. "A demand-side management simulation platform incorporating optimal management of distributed renewable resources". In: *2011 IEEE/PES Power Systems Conference and Exposition* (2011), pp. 1–7.

[25] Johannes Falnes. "A review of wave-energy extraction". In: *Marine Structures* 20.4 (2007), pp. 185–201.

[26] António F De O Falcão. "Wave energy utilization: A review of the technologies". In: *Renewable and Sustainable Energy Reviews* 14.3 (2010), pp. 899–918.

[27] A. Babarit, J. Hals, M. J. Muliawan, et al. "Numerical benchmarking study of a selection of wave energy converters". In: *Renewable Energy* 41 (2012), pp. 44–63.

[28] G. K. Singh. "Solar power generation by PV (photovoltaic) technology: A review". In: *Energy* 53 (2013), pp. 1–13.

[29] Aaron Garrett. *inspyred: Bio-inspired Algorithms in Python*. URL: `https://pypi.python.org/pypi/inspyred` (visited on 11/28/2016).

[30] V. Pareto. *Manuale di economia politica con una introduzione alla scienza sociale*. Milano: Societa Editrice Libraria, 1906.

[31] D. Zafirakis, K. A. Kavadias, S. Efthymiadis, et al. "100% RES integration in the island of Agios Efstratios-Greece with the use of different wind-energy storage systems". In: *EWEA 2012 Annual Event*. 2012, pp. 1–10.

[32] C. Koroneos, G. Xydis, and A. Polyzakis. "The Optimal use of Renewable Energy Sources-The Case of Lemnos Island". In: *International Journal of Green Energy* 10.8 (2013), pp. 860–875.

[33] Daniel Friedrich and George Lavidas. "Combining offshore and onshore renewables with energy storage and diesel generators in a stand-alone Hybrid Energy System". In: *OSES2015*. Edinburgh, 2015.

[34] Dimitris Al Katsaprakakis and Pr Dimitris G Christakis. "A Wind Parks, Pumped Storage and Diesel Engines Power System for the electric power production in Astypalaia". In: *EWEC 2006*. 2006, pp. 1–16.

[35] NOAA U.S. Department of Commerce National Centers for Environmental Prediction National Weather Service. *NCEP ADP Global Upper Air and Surface Weather Observations (PREPBUFR format), May 1997 - Continuing*. 2008. URL: http://rda.ucar.edu/datasets/ds337.0/ (visited on 11/28/2016).

[36] N Booij, L H Holthuijsen, and R C Ris. "The SWAN Wave Model for Shallow Water". In: *Coastal Engineering Proceedings*. 1996.

[37] George Lavidas, Vengatesan Venugopal, and Daniel Friedrich. "Investigating the opportunities for wave energy in the Aegean Sea". In: *7th International Scientific Conference on Energy and Climate Change*. Athens, 2014.

[38] SoDa Service. URL: http://www.soda-pro.com/home (visited on 06/20/2016).

[39] GOV.UK. *Postcode level electricity estimates: 2013 (experimental) - Publications - GOV.UK*. URL: https://www.gov.uk/government/statistics/postcode-level-electricity-estimates-2013-experimental (visited on 11/28/2016).

[40] Hardy Diesel. *Perkins 140-175kW three phase Diesel generators*. URL: http://www.hardydiesel.com/diesel-generators/perkins-120-250.html (visited on 11/28/2016).

[41] Parsons Brinckerhoff. *Small-Scale Generation Cost Update*. Tech. rep. August. 2015, p. 83. URL: https://www.gov.uk/government/uploads/system/uploads/attachment{_}data/file/456187/DECC{_}Small-Scale{_}Generation{_}Costs{_}Update{_}FINAL.PDF.

[42] Behnam Zakeri and Sanna Syri. "Electrical energy storage systems: A comparative life cycle cost analysis". In: *Renewable and Sustainable Energy Reviews* 42 (2015), pp. 569–596.

[43] S. Astariz and G. Iglesias. "The economics of wave energy: A review". In: *Renewable Sustainable Energy Reviews* 45 (2015), pp. 397–408.