Optimising a Renewables Based Island Grid and Integrating a Battery Electric Vehicles Concept on the Example of Graciosa Island, Azores Archipelago

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MOTIVATION

Graciosa, an island of the Azores is to be provided with an electricity generation system based mainly on photovoltaics (PV) and wind energy [1]. This system includes a stationary battery-electric storage and a diesel backup generator and will produce electricity with more than 80 % of demand covered by renewable sources. The most economic sizing of the components will lead to excess energy amounting to about one third of the total electricity produced. Incorporating more flexible consumers will match demand closer to production and reduce overall costs per energy consumed. This paper looks into the possibility of electric vehicles (EV) as additional demanders and an active part of the system.

RESULTS

A model of the system used is shown in figure 1. Simulation was performed using tools based on Matlab^{TM} [2] considering time steps of one hour for one year. With knowledge of the power demand of the grid which averages 1.58 MW or 13.8 GJ/a, peaks at 2.41 MW and has a minimum of 840 kW [3] for Graciosa, the cost of the system components and of fuel as well as the solar and wind resource data [4] of the intended site the levelised cost of electricity (LCOE) can be calculated depending on the system sizing. The nominal output of the diesel generator is assumed to be large enough to be able to power the maximum load solely. The current electricity supply system on Graciosa nearly exclusively relies on diesel so this assumption is valid and causes no extra costs. The principle of the LCOE calculation is similar to the one used by software as e.g. HOMER [5] or RETScreen [6] and documented in more detail by Arnhold et al. [7], Breyer et al. [8] and Werner et al. [9].

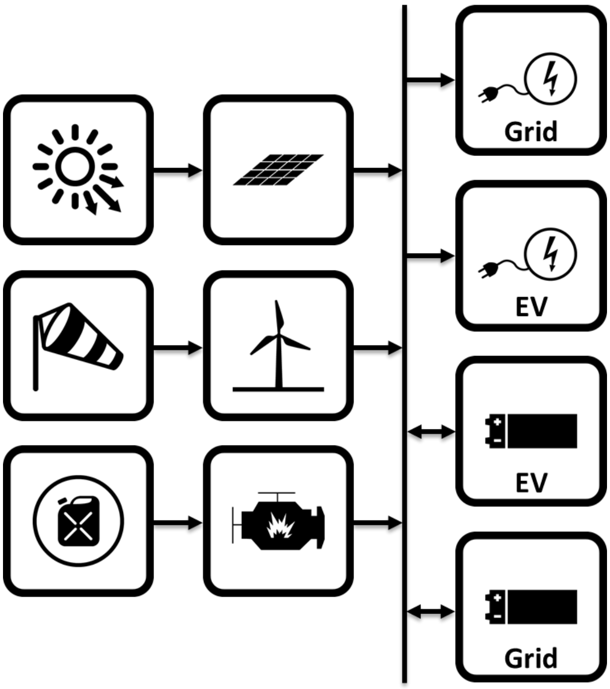

Figure 1: System model. Three different kinds of electricity generators are considered: Solar powered PV, wind powered wind turbines and diesel powered gensets. These are connected via a bus to consumers and storages. Scenarios differ in what loads or batteries are considered.

Figure 2 shows the LCOE in the 3-dimensional space of system sizing for a set of chosen parameters[1], the three dimensions being the installed powers of PV and wind generation and the battery capacity. A minimal LCOE solution exists around 3.5 MW wind, 3.1 MW PV and 5.9 MWh storage leading to electricity costs of 0.139 €/kWh (Scenario A). Settings and results for the various scenarios considered in this paper are summarised in table 1.

[1] Capital expenditure (Capex) for PV: 2,000 €/kWp, for wind: 1,200 €/kW, for stationary battery: 150 €/kWh, for diesel: negligible; operating costs: negligible; fuel cost for diesel: 0.35 €/kWh$_{el}$; lifetimes: 8 years for battery, 20 years otherwise; weighted cost of capital (WACC): 6 % p.a.; stationary battery cycle efficiency: 86 % and energy-to-power-ratio: 5 h.

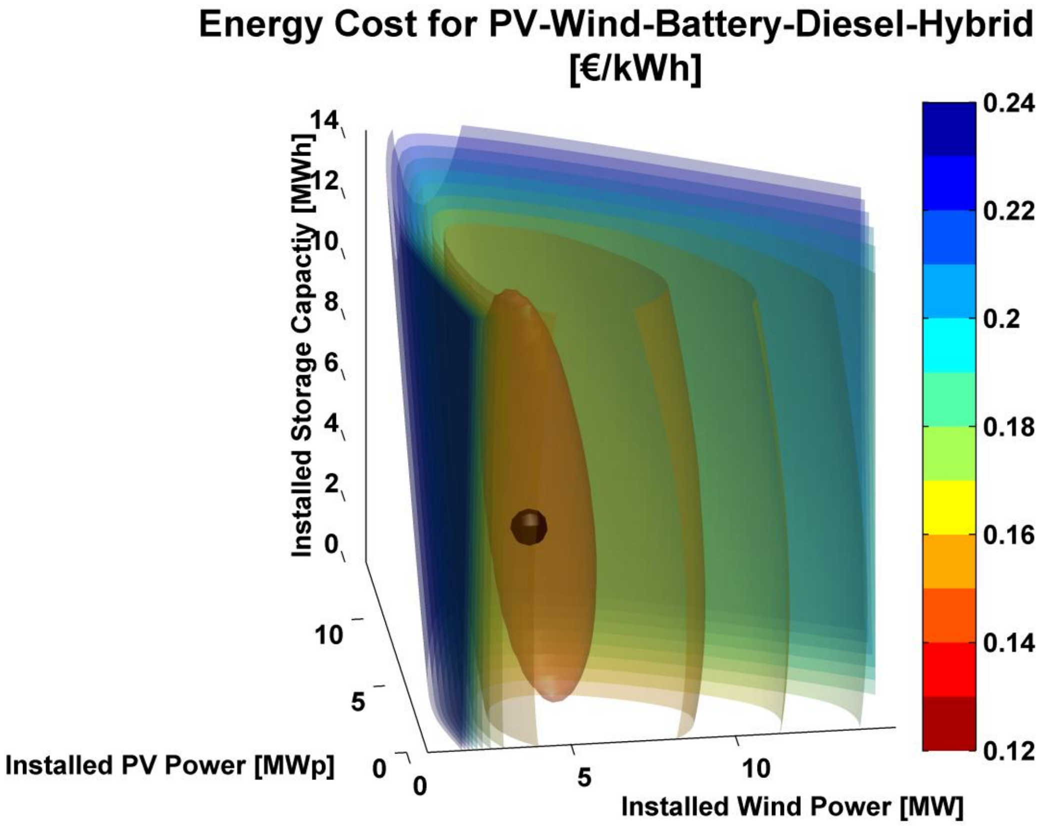

Figure 2: Cost optimised system sizing, Scenario A (no vehicles considered). The graph shows isocost planes over the size of the three system components PV, wind power and battery storage with the colour indicating the cost of electricity. The black sphere is located at the cheapest solution being 0.139 €/kWh. The isosurfaces are slightly tilted towards the left and backwards indicating a preference to PV over wind power with increasing storage capacity.

Table 1: Scenario settings and results of system optimisation for least cost.

Scen-ario	Load	Inst. PV MW	Inst. Wind MW	Station. Battery MWh	Vehicle Battery MWh	LCOE €/kWh	Excess Energy GWh/a	Diesel Share %
A	Grid	3.1	3.5	5.9	-	0.139	8.6	18.1
B	Grid+EV	3.1	3.5	5.9	-	0.141	6.9	22.4
C	Grid+EV	3.1	3.5	5.9	12	0.127	6.1	18.6
D	Grid+EV	3.1	3.5	5.9	40	0.112	5.3	14.4
E	Grid+EV	4.4	3.8	-	12	0.122	8.9	15.2

In scenario A the nominal installed powers of PV and wind generation by far exceed the peak load. Due to the fact that there are times when the battery is fully charged and renewable generators continue to produce power a certain amount of excess energy is available. The total annual excess energy amounts to 8.6 GWh or 62 % of total electricity demand.

On the other hand, there are times when unfavourable conditions lead to discharged batteries and insufficient renewable power output. The hours the diesel generator is needed to fill in these gaps amount to a share of 18.1 %.

Based on the currently existing fleet of combustion engine vehicles and their estimated usage the electricity demand for a corresponding fleet of electric cars is calculated [7]. This demand averages 8.2 MWh per day or 340 kW. While, the fleet would consist of 2,000 vehicles with 25 kWh battery capacity each, 50 MWh in total. Considering the usage of cars on Graciosa it is estimated that at least 80 % of all vehicles are hooked to the grid at any time corresponding to a virtual battery of 40 MWh capacity. The maximum power rating of this battery would be at least 5 MW if the cars are assumed to be hooked up at standard residential outlets of 3 kW ratings. This 5 MW power is by far sufficient to feed the stationary electricity load even when considering that part of this power is needed to average out the individual cars' batteries states of charges. For comparison the power rating of the stationary battery considered is only 1.2 MW.

A power generation system of this size, derived without considering electric vehicles can supply the cars with electricity (Scenario B) but will have to increase its share of diesel energy to 22.4 % if the cars are loaded instantly without considering the supply side of the electricity grid. If on the other hand, the collective battery capacity is used as an active part of the system, as in a vehicle-to-grid approach [10], positive effects can be observed. If a too large share of the cars' battery capacity is used by the grid the state of charge (SoC) may drop to low values stranding the vehicles.

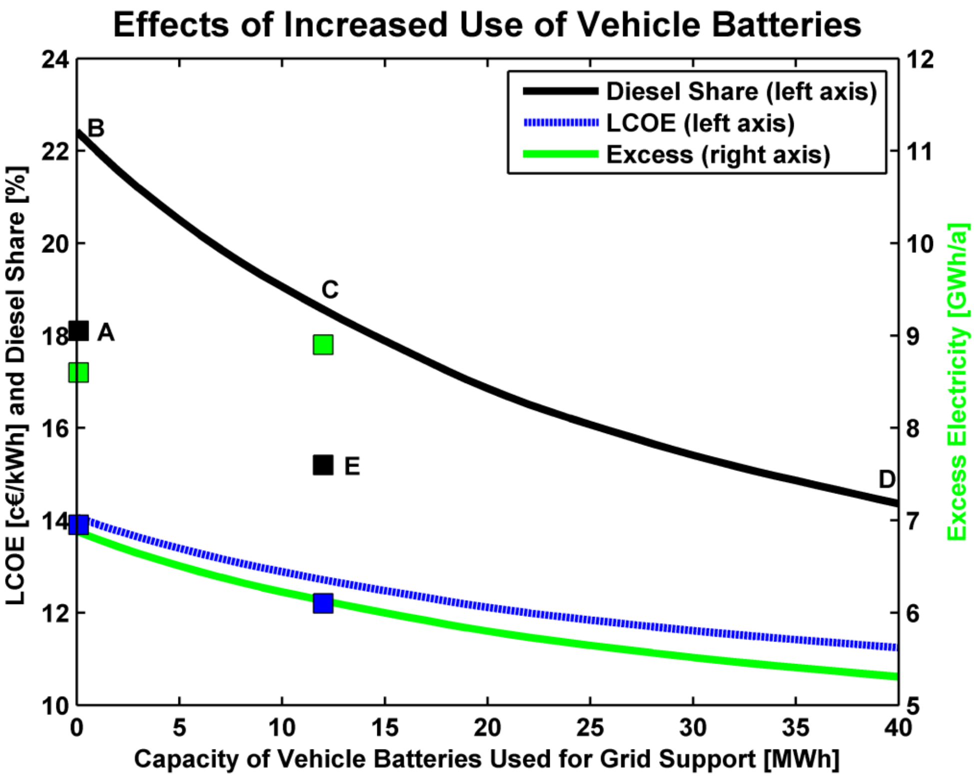

Figure 3: LCOE, diesel usage and excess energy decline with increased usage of the vehicles internal battery capacity connected to the grid. The values for scenarios B, C and D lie on the lines at battery capacity values marked by the letters while scenario values A and E are indicated by squares. To avoid crowding, the lettering has been applied to the diesel share only.

If, e.g., only 12 of the total 40 MWh battery capacity are used (Scenario C), leaving the SoC above 70 % at all times, diesel usage drops to 18.6 %, average electricity cost drops to 0.127 €/kWh and the amount of wasted energy decreases by 0.8 GWh as shown in figure 3. Diesel share here would then be near that of the initial system without cars and electricity costs per kWh would have decreased by 9 %. If more of the cars' battery capacity was used (Scenario D) diesel share could drop to below 15 %, costs to 0.112 €/kWh and excess energy by another 0.8 GWh.

Figure 4 shows the SoC duration curve of the vehicles' batteries illustrating with what probability a driver will find a certain SoC after successful charging of his car's battery. About half the time the vehicle battery will be totally charged. The chance of finding his vehicle battery at the specified lower limit SoC is about 20 % and nearly independent of how low this level actually is.

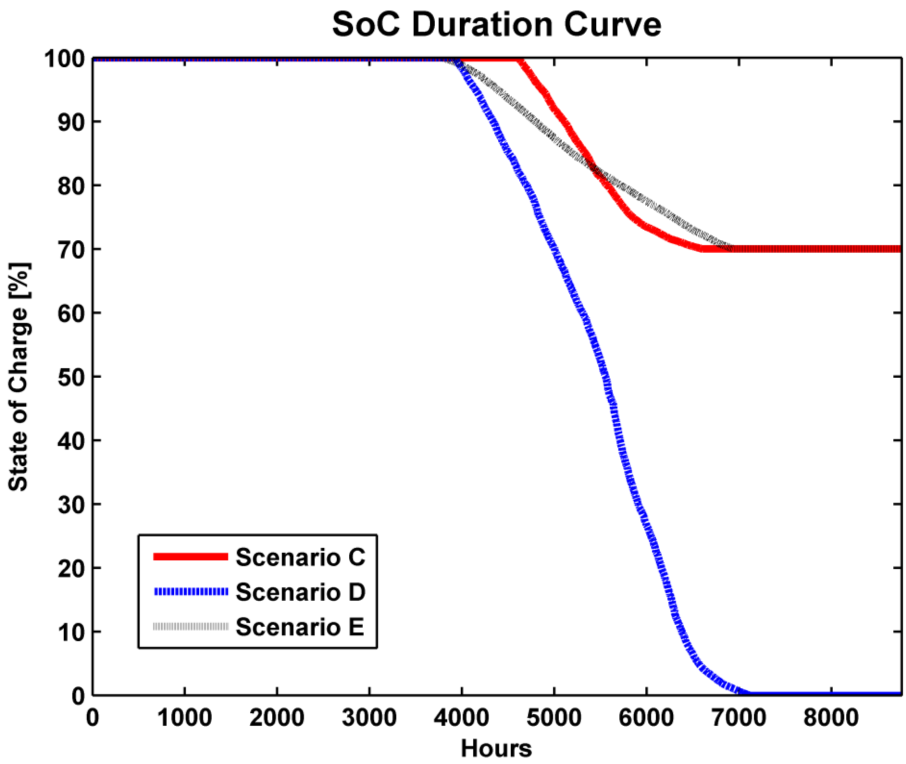

Figure 4: State of Charge (SoC) of the virtual 40 MWh battery composed of grid connected vehicle batteries. In this display the values for all hours of the year have been sorted by SoC to show a duration curve. The SoC of this virtual battery corresponds to the charging target of all vehicle batteries currently connected to the grid. Newly arrived vehicles might have a lower SoC. Vehicles with higher SoC will be discharged to align all SoC values maintaining the average.

If the total system including 12 MWh of the car batteries used as grid stabilisation is considered and optimised (Scenario E), the optimum sizing of the power plants for serving the total load now averaging 1.94 MW or 17 GJ/a and having a range of 962 kW to 3.17 MW, shifts to 4.4 MW PV and 3.8 MW wind with no additional stationary battery needed. This reduces LCOE to 0.122 €/kWh, a further reduction of 4 % compared to scenario C and increases excess energy to 8.9 GWh/a. Though this decrease in cost might not be significant the increase in renewables capacity will lead to a reduced diesel share of only 15.2 % and restores excess energy to more than the initial value. This enables the excess energy to be harvested by the next business case, e.g., substitute fossil fuel based heating with direct electric heating, desalinate seawater or generate renewable fuels such as hydrogen or methane.

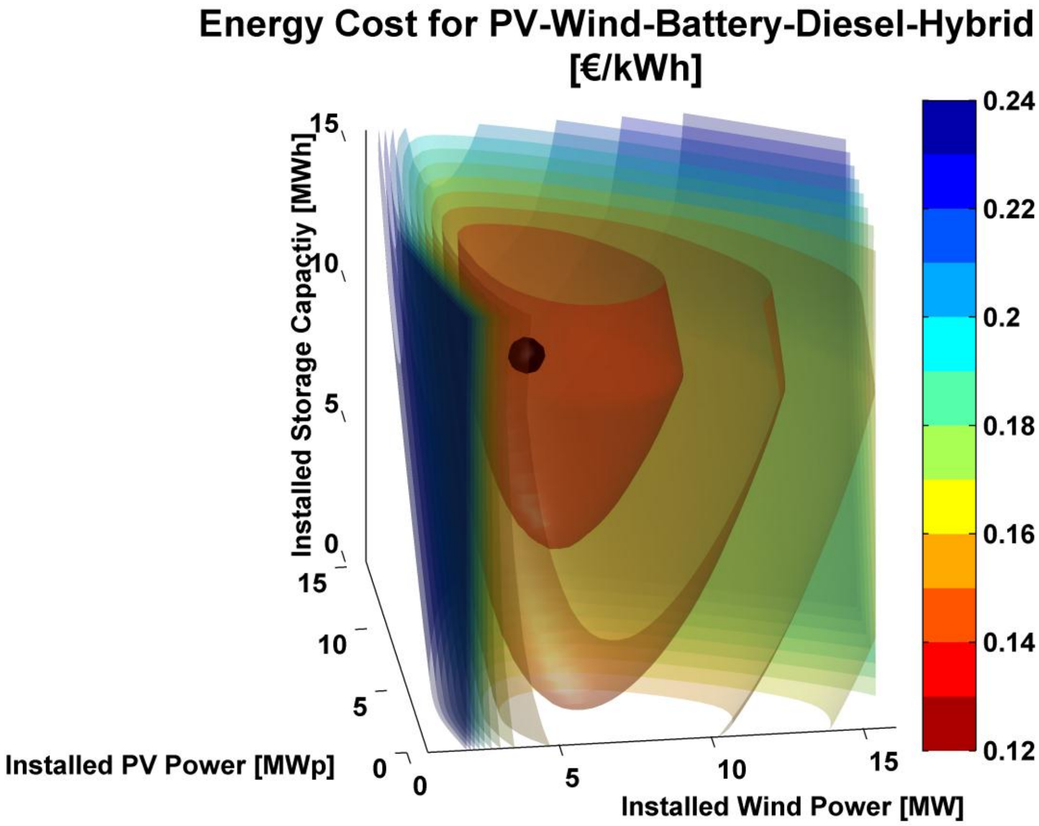

Figure 5: LCOE optimised system sizing, Scenario E. Here up to 12 MWh of vehicle batteries may be used for grid stabilisation and are considered for free. The black sphere is located at the cheapest solution being 0.122 €/kWh and exactly at 12 MWh used storage capacity. A kink in the isosurfaces at 12 MWh battery capacity is observed indicating the transition from the free vehicle batteries to non-free additional stationary batteries.

CONCLUSIONS

A tool for optimal sizing of hybrid system components has been developed and tested on the scenario of incorporating electric vehicles into a renewables based generation grid. Using only 12 of the total 50 MWh capacity of the EV batteries for grid stabilisation is sufficient to reduce diesel share by nearly a third and electricity costs by 13 %. This would reduce vehicle range at the worst by 30 % or, e.g., from 120 km to 84 km, still far enough for an island the size of 7 by 10 km. Generally electric vehicles can contribute to stabilising small electricity grids and reduce overall costs and emissions.

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