Mobility Concepts Using Excess Power from Proposed Renewable Energy Supply System on Graciosa Island, Azores Archipelago

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ABSTRACT

The use of excess energy from the planned renewable electricity generation system of Graciosa Island, Azores Archipelago, has been examined focussing on its use as energy source for mobility concepts. Battery-electric vehicles with different load management and vehicle-to-grid schemes as well as renewable power methane fuelled vehicles have been considered against a baseline scenario featuring conventional diesel vehicles. The simulation results include related costs and carbon dioxide emissions as well as the size of energy storage and amount of backup fuels needed. Both alternative vehicle types can benefit from using excess energy and may significantly reduce the need for imported fossil fuels.

MOTIVATION

Graciosa is to be provided with a power system based mainly on photovoltaics (PV) and wind energy. This system will include stationary sodium-sulphur battery storage and a diesel backup generator and will produce electricity covering about 85% of demand by renewable sources. Sizing of the components will lead to an excess energy of about 30% of the total electricity produced. The current concept focuses exclusively on the supply of stationary loads. In this paper the possibility of using the excess energy in regards to mobility concepts will be the topic of discussion.

APPROACH

Graciosa Energy System

Boundary conditions for this work are to use excess electricity from the island-wide grid produced by renewable sources during time of fully charged stationary batteries and of excessive supply only. Time series of excess power and energy for an average year with stationary battery capacity of 18 MWh, 1 MWp installed PV and 9 MW of wind power are shown in figure 1. This system is planned to be installed in 2013 [1]. The current power supply is covered by wind energy (15%) and diesel generators (85%) and has to supply a maximum load in the island grid of slightly less than 3 MW for about 4,500 inhabitants.

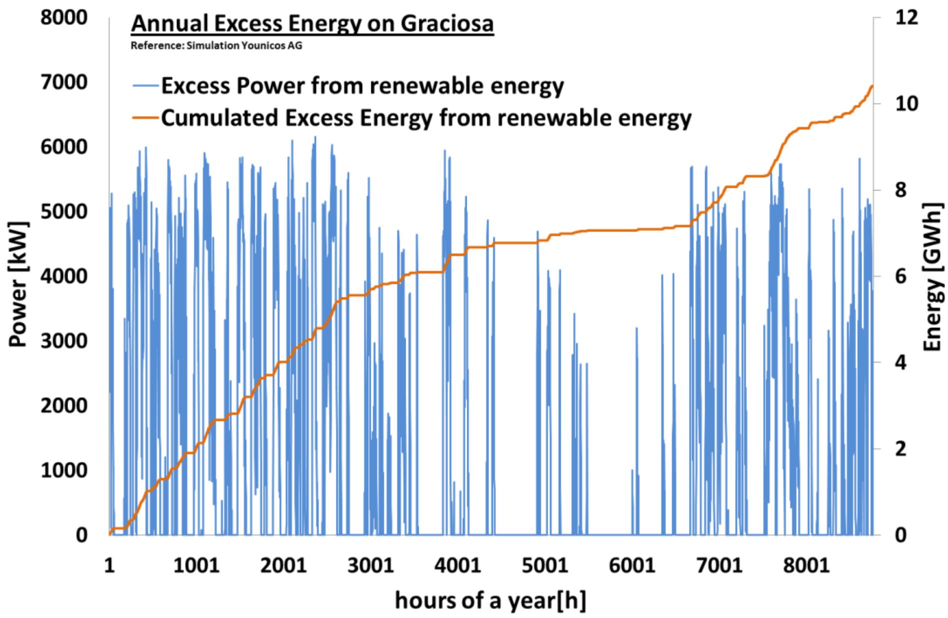

Figure 1: Excess power (blue, left scale) and cumulated excess energy (orange, right scale) for the electricity generation system envisioned for Graciosa Island [1]. Excess power strongly fluctuates being zero more than 60% of times and reaching 6 MW peaks. The energy curve shows low availability of excess power between hours 4000 and 6500 (mid June to end of September) but a more or less constant supply on a weekly scale from hours 7000 to 3000 (October to April).

Total annual excess energy amounts to 10.4 GWh which is 43% of electricity demand on Graciosa. Excess power peaks at 6.2 MW, averages 1.2 MW and is zero at 5413 hours per year (62% of time). In case excess energy is not sufficient for the mobility concept considered the deficit may be covered by imported diesel fuel.

Propulsion Concepts

In this paper conventional diesel-powered vehicles are the baseline scenario. In addition to this, two alternative propulsion concepts are examined: Battery-electric vehicles and cars with renewable power methane (RPM) fuelled internal combustion engines. These concepts are investigated in detail regarding fuel demand. Depending on the particular circumstances the amount of excess energy used and fuel to be imported is determined. Economic feasibility is checked using a detailed cost model and CO_2 emissions are estimated.

1 Diesel Internal Combustion Engine (Diesel)

The baseline concept considered in this paper consists of a fleet of conventional vehicles with internal combustion engines powered by diesel fuel.

2 Battery-Electric Vehicles (BEV)

Battery-electric vehicles comprise an electric motor and an electrochemical energy storage system. Greatest advantage is the absence of local pollutant emissions and the ability to use locally produced electricity while current obstacles preventing market penetration are high battery cost and resulting low range. On an island as small as Graciosa (8 by 12 km) single trips of more than 60 km are unlikely which favours BEVs.

3 Renewable Power Methane Fuelled Internal Combustion Engines (RPM)

Methane is main constituent of natural gas. Its high hydrogen to carbon ratio makes it the cleanest hydrocarbon fuel. Due to its similar combustion properties other hydrocarbons e.g. petrol, are easily substituted by methane. In our scenarios methane is produced from hydrogen and carbon dioxide via the Sabatier reaction:

$$4\mathrm{H_2} + \mathrm{CO_2} \rightarrow \mathrm{CH_4} + 2\,\mathrm{H_2O} \qquad \text{(Eq. 1)}$$

Equation 1: Sabatier reaction for methane production.

The necessary hydrogen is produced by water electrolysis, a reaction for which commercial tools are available in a large range of sizes. Efficiency of the Sabatier process may reach 75% to 85% and with assumed electrolysis efficiency of 63% and considering CO_2 extraction from ambient air methane production efficiency averages 48% according to Sterner [2]. There is no natural gas grid on Graciosa Island so the scenario comprises a filling station compressing the methane of about 350 bar. As cars using compressed natural gas are commercially available this is a mature technology.

Simulation

The simulation run for this work was performed using the tools Matlab and Simulink by MathWorks. A simulation flow diagram is shown in figure 2.

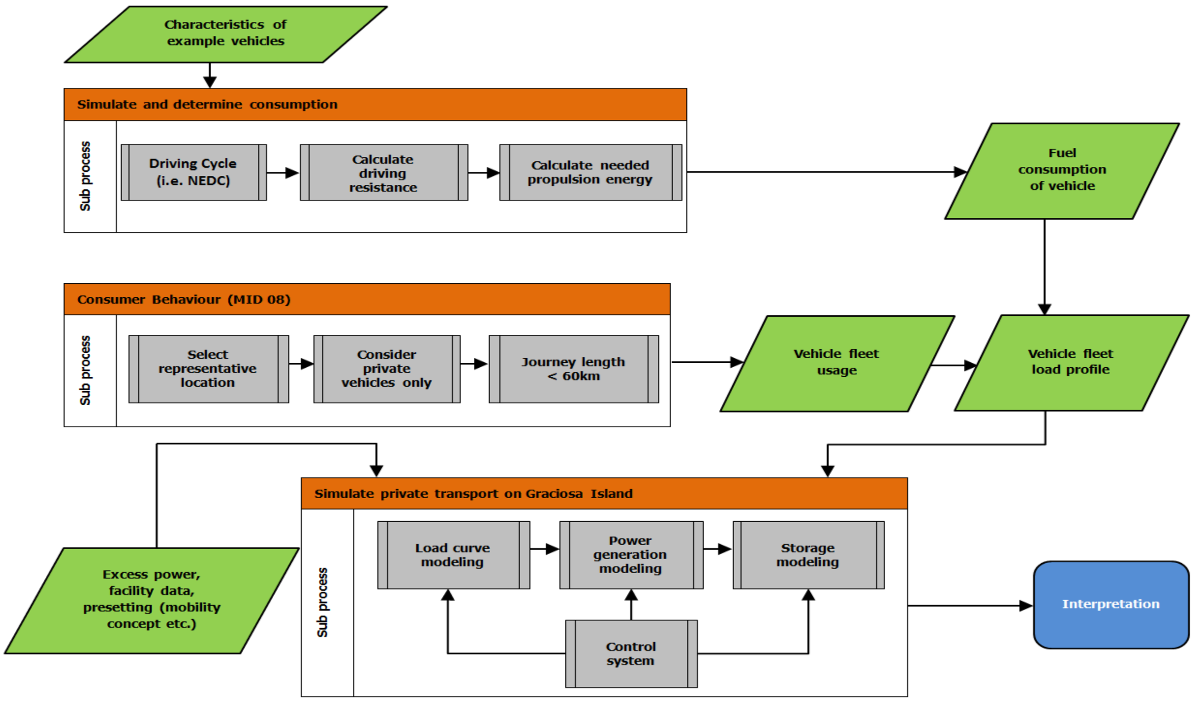

Figure 2: Simulation flow diagram. First the amount of needed fuel is derived from the characteristics of exemplary vehicles. Hourly mileage is calculated by adapting a study on car usage to the conditions of Graciosa. Both numbers are then combined to yield total fleet power demand. This value and excess power are input parameters for a detailed simulation of energy flows and storage concepts producing data on energy origin, costs and CO_2 emissions.

The model chiefly consists of two parts, the first of which is determining the vehicle fleet load profile. To determine the annual vehicle mileage, data from the Portuguese Automotive Society [3] and the Regional Secretariat of Science [4] are used approximating vehicle usage on Graciosa by omitting journeys longer than 60 km and considering private car usage only. The results of this approximation were verified with driving profiles from similar rural regions in Germany described by Follmer et al. [5]. The specific energy demand per km is determined for a set of example vehicles in the New European Driving Cycle (NEDC). Both values combined yield the hourly fleet energy demand.

In the second part of the simulation fleet power demand is compared to excess power. Based thereupon it is determined whether to produce additional energy from diesel and how to run different load management or storage schemes. All power flow calculations are done in one hour time step resolution.

Cost Model

The scenario’s economics are compared by calculating levelized cost of mobility (LCOM). The LCOM approach is an analogy to the levelized cost of electricity approach [6]. This figure translates all initial and future cash flows into one figure of merit describing average costs per kilometre. Equation 2 shows how LCOM is derived from the single input parameters.

$$\mathrm{LCOM} = \frac{\mathrm{Capex_{Vehicle}} * \mathrm{crf_{Vehicle}} + \mathrm{Capex_{Infr.}} * \mathrm{crf_{Infr.}} + \mathrm{Opex_{fix}}}{\mathrm{FD}} + \mathrm{Opex_{var}} + \mathrm{Opex_{fuel}} \qquad \text{(Eq. 2a)}$$

$$\mathrm{crf_{Vehicle}} = \frac{\mathrm{WACC} * (1+\mathrm{WACC})^{N_{\mathrm{Vehicle}}}}{(1+\mathrm{WACC})^{N_{\mathrm{Vehicle}}} - 1} \qquad \text{(Eq. 2b)}$$

$$\mathrm{crf_{Infr.}} = \frac{\mathrm{WACC} * (1+\mathrm{WACC})^{N}}{(1+\mathrm{WACC})^{N} - 1} \qquad \text{(Eq. 2c)}$$

$$\mathrm{WACC} = \frac{\mathrm{E}}{\mathrm{E+D}} * \mathrm{k_E} + \frac{\mathrm{D}}{\mathrm{E+D}} * \mathrm{k_D} \qquad \text{(Eq. 2d)}$$

$$\mathrm{Opex_{fuel}} = \mathrm{Fuel_i} * \frac{\sum_{i=1}^{N}(1+\mathrm{r_{Fuel}})^i}{\sum_{i=1}^{N}(1+\mathrm{WACC})^i} \qquad \text{(Eq. 2e)}$$

Equation 2: Levelized cost of mobility (LCOM). Abbreviations represent: total fleet mileage (FD), vehicle lifetime ($N_{Vehicle}$), infrastructure lifetime (N), control variable for years (i), capital expenditures for vehicles ($Capex_{Vehicle}$), capital expenditures for infrastructure ($Capex_{Infr.}$), annual fixed operational expenditures for infrastructure maintenance ($Opex_{fix}$), annual variable operational expenditures for vehicle maintenance ($Opex_{var}$), annuity factor for vehicles ($crf_{Vehicle}$), annuity factor for infrastructure (crf_{Infr}), weighted average cost of capital (WACC), equity (E), debt (D), debt interest rate (k_D), return on equity (k_E), fuel cost per km in year i ($Fuel_i$), average fuel cost per km ($Opex_{fuel}$), annual nominal oil price increase (r_{Fuel})

Energy costs are assumed to be nil for the use of excess energy and 0.27 €/kWh_{el} for diesel generated electricity. This corresponds to a diesel price of 0.65 €/l and 30% efficiency resulting in CO_2 emissions of 900 g/kWh. Costs for the vehicles were taken from the German National Platform for Electric Mobility (NPE) [7]. NPE estimated the net listed price for conventional diesel vehicles in 2014 to 19615 € (compact class) and 33497 € (station wagon and van). Prices for methane fuelled cars are assumed to be 110% of diesel powered ones. The price of BEV is also based on NEP [7] but was standardised to the above mentioned vehicle classes. The following results for BEV were achieved with 33065 € for compact class vehicles and 48533 € for station wagons and vans. Infrastructure costs for renewable power methane production (2.000 €/kW_{el} for 5-10 MW) and maintenance (60 - 180 € per year and kW_{el}) were taken from Sterner [2]. Costs for storage RPM (38 €/m^3) were taken from Wietschel and Bünger [8].

RESULTS

Battery-electric vehicles

For BEV various possible charging schemes exist. Default case would be charging the battery as soon as the vehicle is connected to the grid. This exerts high loads on generation because at certain times of day many cars end their journeys simultaneously.

A method to avoid this problem is load management (LM) as described by Rotering and Ilic [9], i.e. decreasing charging power if no excess energy is available. We define LM utilisation of 40% as reducing load by 40% during times of no excess energy. We allow the batteries to accumulate a maximal charge deficit of one daily energy demand which roughly equals 20% of total capacity and limit charging power to 3.3 kW per vehicle.

To better utilise battery capacity a vehicle-to-grid concept (V2G) is examined. This allows the batteries to be partially discharged while grid connected. 100% utilisation of the car batteries for V2G would leave them fully drained at times. Because a minimum state-of-charge (SoC) has to be guaranteed we consider scenarios for V2G utilisation of up to 50% in accordance with Engel [10]. An example of energy flows for V2G is shown in figure 3.

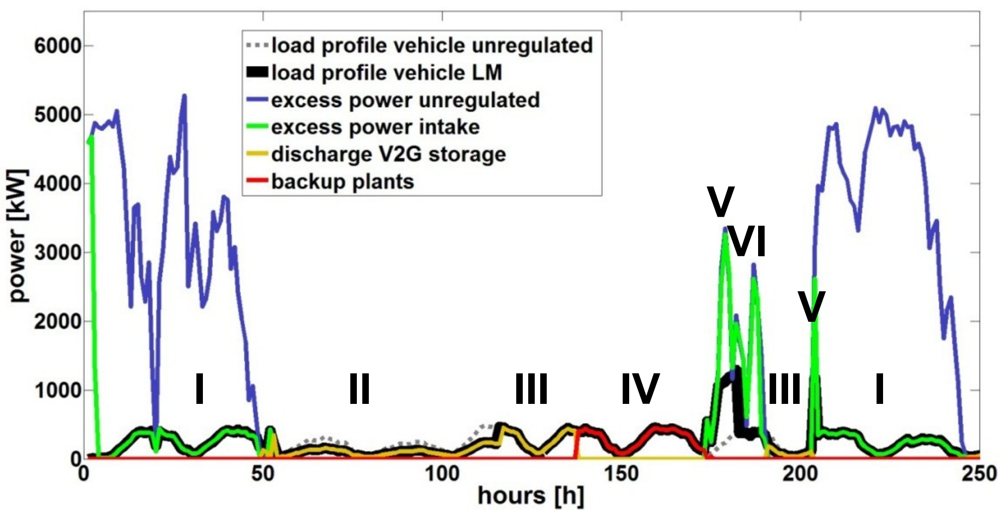

Figure 3: Charging concept including V2G and LM showing the relevant levels of power flows for a period of about ten days. Phase I: Excess energy is sufficient, V2G and LM inactive. Phase II: No excess energy. LM reduces load. V2G in discharging mode: Average SoC drops while batteries with high SoC transfer energy to emptier ones. Phase III: No excess energy. LM has reached deficit limit. V2G in discharging mode. Phase IV: No excess energy. LM and V2G at deficit limit. BEV batteries have to be charged by diesel generated

electricity. Phase V: Excess energy available. LM increases load. V2G in charging mode. Phase VI: Excess power available. LM deficit compensated, no adjustment of load. V2G still in charging mode.

Energy origin for all mobility scenarios is shown in figure 4 with the corresponding BEV scenario parameters listed in table 1.

Table 1: Parameters for BEV scenarios considered in figures 4 to 6: Percentage of total vehicle fleet battery capacity used for vehicle-to-grid (V2G) scheme and percentage of load reduction for load management (LM).

Scenario name	Parameters
BEV 1	no V2G, no LM
BEV 2	10% V2G, no LM
BEV 3	30% V2G, no LM
BEV 4	50% V2G, no LM
BEV 5	no V2G, 20% LM
BEV 6	no V2G, 40% LM
BEV 7	50% V2G, 40% LM

Renewable Power Methane Fuelled Internal Combustion Engines

In these scenarios excess power is used to produce methane. Excess gas is stored in a tank near the filling station. Scenarios differ in the size of gas storage as shown in table 2. Energy origin data for RPM 1 to 4 is shown in figure 4.

Table 2: Size of gas storage for renewable power methane (RPM) based scenarios considered in figures 4 to 6. The last scenario features bivalent methane-petrol flex fuel vehicles (FFV).

Scenario name	Storage size
RPM 1	2.600 Nm³
RPM 2	7.700 Nm³
RPM 3	12.800 Nm³
RPM 4	95.000 Nm³
RPM FFV	95.000 Nm³

Diesel Internal Combustion Engine

The European emission limit of 120 g_{CO2}/km valid from 2015 onwards is taken as a guideline for fuel consumption. This translates to annual energy demand of 4.7 GWh_{th}. Here we only consider the consumption by vehicles (tank-to-wheel) and exclude emissions occurring in the supply chain.

Energy consumption

Figure 4 shows the energy consumption of all different mobility concepts. Two different energy source categories are distinguished: Renewable excess energy from the island-wide grid and imported fossil fuel. The corresponding scenario parameters are listed in tables 1 and 2.

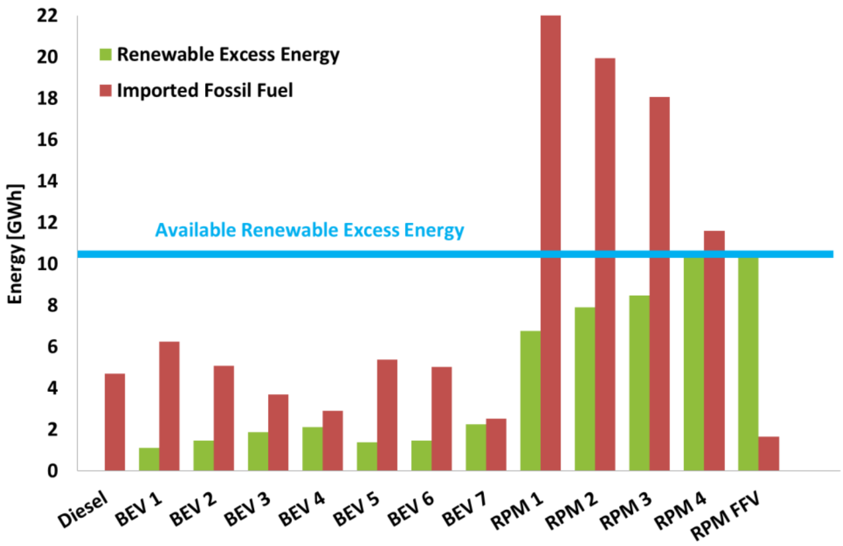

Figure 4: Energy origin for all mobility scenarios. In BEV 1 only a small part of demand can be satisfied by excess energy. Increasing V2G usage (scenarios BEV 2 to 4 and BEV7) can significantly reduce diesel need while LM (scenarios BEV 5 to 6) cannot contribute as much. Energy need for RPM is large due to the low efficiency methane production path but it can absorb a large share of excess energy. Scenarios RPM 1 to 4 demand large amounts of diesel owed to the wasteful transformation of diesel to methane. The last two RPM scenarios make use of all excess energy. RPM FFV uses imported petrol to fill the energy gap instead of methane production from diesel.

The demand for backup fuel in the first BEV scenarios is large as most of the time there is no excess energy available. With increasing use of load management and especially V2G the need for diesel generated electricity drops to about half the value of the Diesel scenario.

The RPM scenarios exhibit a large proportion of diesel contribution. Due to the insufficient size of the gas storage or the unavailability of excess power it may run dry from time to time inducing the need to produce methane by running diesel generators producing electricity for the electrolysis, a process clearly inefficient and not preferred. The RPM FFV (Flex Fuel Vehicles) scenario resolves this issue by using bivalent cars able to consume methane or petrol. Deficit energy is now imported as petrol avoiding the inefficient transformation of diesel to methane.

Costs

Input parameters used for the cost model mentioned above are as following: 10% return on equity, 5% debt interest rate, equity-to-debt ratio of 20:80 leading to WACC of 6.0%, vehicle lifetime of 10 years, infrastructure lifetime of 20 years and annual nominal increase in oil price of 7%. Costs for vehicles and infrastructure have been derived from NPE [7] and Wietschel and Bünger [8]. Figure 5 shows modelling results.

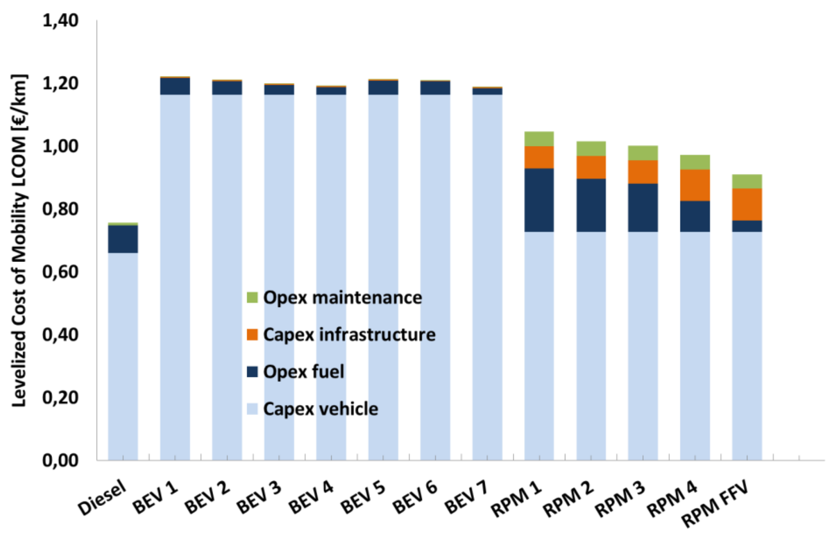

Figure 5: Levelized cost of mobility (LCOM) for all scenarios composed of capital expenditures for vehicle fleet (Capex vehicle) and infrastructure establishment (Capex infrastructure), fuel (Opex fuel) and operational expenditures for maintenance (Opex maintenance).

Largest share is in all cases the Capex for the vehicles. Estimated low annual mileage of 5000 km [3, 4] inflates this value. The currently increased cost of BEVs compared to combustion engine vehicles dominates their LCOM. Infrastructure cost is only noticeable in the RPM scenarios, the large gas tank producing a significant share in RPM 4 and FFV. Opex fuel includes current Portuguese fuel taxes for scenarios Diesel and RPM FFV.

Integrating RPM into the mobility sector broadens the set of options for renewables based mobility concepts on an attractive LCOM level. Similar results are obtained by transforming the global power supply towards a hybrid PV-Wind-RPM based system [11].

CO_2 Emissions

Specific CO_2 emissions for all mobility scenarios are indicated in figure 6. Carbon emissions from diesel-electric generation only have been considered while neglecting emissions during vehicle manufacture. As excess energy is used for BEV, no CO_2 emissions are considered for this share of consumed energy.

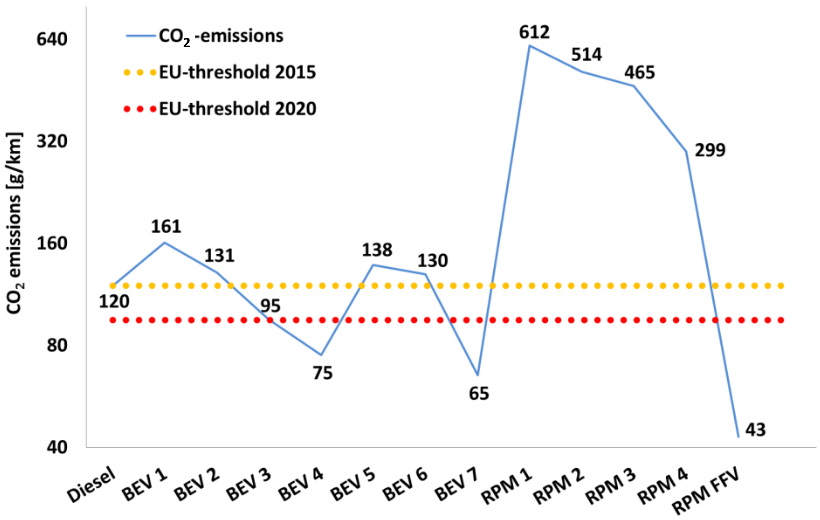

Figure 6: Specific CO_2 emissions for all mobility scenarios. Curve shape is similar to the one for fuel usage in figure 4. The EU defines a limit of 120 g_{CO2}/km from 2015 onwards and 95 g_{CO2}/km after 2020 for tank-to-wheel emissions, the 2015 threshold being used as value for the Diesel scenario. Only BEV scenarios with high V2G usages (BEV 4 and 7) achieve low emissions. The low efficiency of converting diesel to methane causes skyrocketing emissions for RPM 1 to 4. Scenario RPM FFV has lowest emissions due to small share and efficient use of imported fuel.

The Diesel scenario is assumed to be the 120 g_{CO2}/km EU limit of 2015. BEV 1 has relatively high emissions which decrease by increased V2G usage and in a smaller scope by using LM. Scenarios with high V2G usage reach reasonably low emissions with BEV 4 and 7 even being below the EU tank-to-wheel threshold for 2020. The other BEV scenarios need to generate a significant amount of electricity from diesel. Emissions for RPM 1 to 4 are extraordinarily high due to the conversion of diesel to methane with a total efficiency of about 15%.

RPM FFV exhibits lowest emissions as here about 75% of fuel demand can be satisfied by methane from renewable excess energy and only about a quarter is covered by imported fuel. This can be achieved differently: Either by a fleet of bivalent vehicles running on methane most of the time but being able to use petrol in the summer months of low excess energy availability or by splitting the fleet into methane vehicles and those consuming other fuels. In the latter case storage facilities need to be enlarged to guarantee availability over the course of the year. Alternatively methane could be imported as LNG but this might not be suitable for an island of this size.

CONCLUSION

Mobility concepts using renewable excess energy involving battery-electric and renewable power methane fuelled vehicles have been examined. Considering LCOM, the baseline Diesel scenario is the most appealing achieving about 0.76 €/km with assumed CO_2 emissions of 120 g/km. BEVs using vehicle-to-grid schemes in a large scale can cut CO_2 emissions and the need for imported fuel by about half but their high cost of about 1.20 €/km is still an inhibiting factor. Renewable power methane powered vehicles can absorb up to 100% of excess energy and can reduce imported fuel demand by more than 60% with only a moderate cost increase resulting in about 0.97 €/km and CO_2 emissions of 43 g/km. To achieve this suitable fuel has to be imported to bridge the times of low excess energy availability.

6th International Renewable Energy Storage Conference and Exhibition (IRES 2011), Berlin 2011, November 26-27, Oral Presentation, O. Arnhold: “Mobility Concepts Using Excess Power from Proposed Renewable Energy Supply System on Graciosa Island, Azores Archipelago”

This paper focussed on only using excess energy. Optimising the whole energy system, especially considering synergies between the stationary battery and V2G and possibly increasing renewable electricity generation capacities will provide further advantages and is highlighted in another paper [12].

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