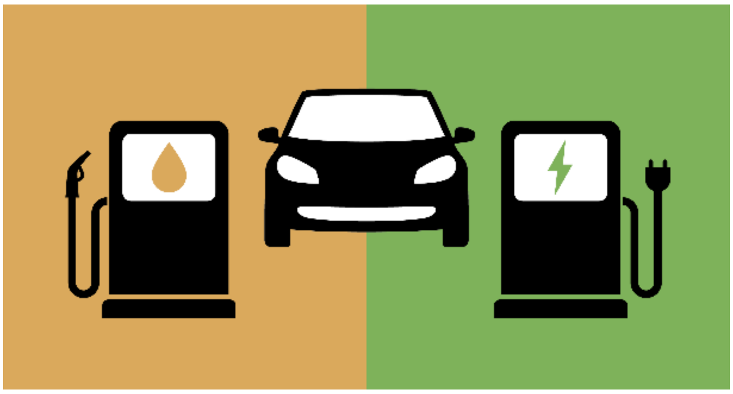
Energy Systems 2020/2021

Mobility

Professor Miguel Brito



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Every person that lives on the island travels an average of 20 km/day. This mobility is done either by motor vehicles, such as cars and buses, by bicycle or by foot. These options are mutually exclusive, meaning that if someone travels by car, then they do not use the bus or a bike.

The propulsion of motorized vehicles is provided by an engine (or motor), which can be an internal combustion engine, an electric motor, or a combination of the two, otherwise known as hybrids. The former runs on fuel, either fossil or renewable (also called biofuel), while electrical motors, as the name would suggest, are powered by electrical energy. Since the island is located on a very isolated area of the globe it must be as self-sufficient as possible, with all the energy on the island coming from local renewable sources due to its lack of crude oil reserves. As a result, the motor vehicles on the island can only run on biofuel, or electricity, whichever is more energetically efficient.

Biofuels are divided into bioethanol and biodiesel, with the best type of plantation for each being sugarcane (1.4 m^2/l) and sunflower (5.7 m^2/l), respectively. The best option for the island is the one with the smallest area requirements per litre of fuel produced, which is sugarcane. While renewable fuels help decrease CO_2 emissions when compared to fossil fuels, they also have disadvantages, such as the competition with food production for land and water resources and the loss of organic soil productivity due to intensive monoculture cultivation.

Electric vehicles (EV) are quieter than their internal combustion counterparts and are also better for the environment because they have zero exhaust emissions, thus reducing noise and air pollution and health problems related to each. They are also beneficial for the network if charged when there is a production surplus, helping the electricity network flatten the demand profile over a typical 24-hour period while allowing owners to avoid higher-cost charging periods.

All motor vehicles produce life cycle emissions of harmful pollutants and GHGs. These emissions encompass not only the use of the vehicle, but also its production, processing, distribution, and recycling/disposal. For a gasoline vehicle, emissions are produced during the extraction and refining of petroleum, in the distribution to stations, and in the exhaust emissions. Electric vehicles may not have exhaust emissions, but they usually have higher embodied energy, which is the sum of all the energy required to produce a product, including the extraction of raw materials, the assembly, and the transportation of the product. The majority of embodied emissions for electric vehicles concerns the production of batteries as well as other components. In fact, CO_2 emissions related to materials and assembly are higher for EVs than for traditional cars. However, EV life cycle emissions are much lower than conventional vehicles because most emissions are lower for electricity generation than burning gasoline or diesel, especially if the electrical energy comes from renewable sources, which is the case on the island. It must be noted that while EVs are more eco-friendly than internal combustion vehicles, they are still in need of innovation especially in regard to lowering their embodied energy.

In order to determine the annual energy demand, two different scenarios of mobility were studied: one in which a vast majority of transportation is done on individual motor vehicles and another where most of the population uses public transport, with the share of bike users/pedestrians being the same in both cases. It should be noted that since bicycles do not have a motor, they do not contribute to the energy demand, hence why they will not be taken into account in the following calculations.

Table 1 - Fraction of the population that exclusively uses the car, the bus or walks/rides a bike.

Mobility	**Scenario 1**	**Scenario 2**
Car	85%	15%
Bus	10%	80%
Bicycle/walking	5%	5%

We expect to have lower energy demand for scenario 2 in which there is a public transport majority. The reason for this is that a larger number of people can travel in the same the bus instead of each taking their own car, so while the energy consumption per vehicle is certainly much higher for the bus, its energy consumption per passenger is way lower than for a car (even if the bus is not filled to maximum occupation, which is often the case).

Nonetheless, to be able to compare the scenarios, we need the energy demand for the case in which all vehicles are powered by biofuel or by electricity. However, we must first calculate the number of vehicles if the entire population travelled either by car or by bus. This was done according to the equations below, keeping in mind that there are 50 000 inhabitants on the island, 0.5 cars per person, and that each bus has a maximum occupation of 30 passengers.

$$N_{car} = 0.5 \left[\frac{car}{person}\right] \times 50000\ [person] \qquad N_{bus} = \frac{50000\ [person]}{30\ [person/bus]}$$

Table 2 - Number of cars and buses on the island if all mobility was done on either kind of vehicle.

Number of cars	Number of buses
25 000	1667

The biofuel consumption for cars is 10 litres/100 km and 40 litres/100 km for buses. Knowing this, we calculated the fuel required for a 20 km ride (average daily travel per person) on each kind of vehicle. Multiplying the daily fuel consumption per vehicle by the number of vehicles gives us the daily fuel consumption for all vehicles of that kind on the island. The daily consumption on the island times 365 days of the year is equal to the annual fuel consumption for that type of vehicle.

$$E_{car/day} \left[\frac{l}{day}\right] = \frac{10\ [l]}{100\ [km]} \times 20 \left[\frac{km}{day}\right] \qquad E_{bus/day} \left[\frac{l}{day}\right] = \frac{40\ [l]}{100\ [km]} \times 20 \left[\frac{km}{day}\right]$$

$$E_{day} \left[\frac{l}{day}\right] = N_{vehicle} \cdot E_{vehicle/day} \left[\frac{l}{day}\right]$$

$$E_{year} \left[\frac{l}{year}\right] = 365 \left[\frac{day}{year}\right] \cdot E_{day} \left[\frac{l}{day}\right]$$

Table 3 - Daily and annual energy consumption for biofuel cars and for buses.

Type of vehicle	Car	Bus
Daily consumption per vehicle [l/20km/day/vehicle]	2	8
Daily consumption for all vehicles [l/20km/day]	50 000	13 336
Annual consumption [l/year]	18 250 000	4 867 640

We shall now analyse the energy demand if all cars and buses were electric (characteristics in table 4). A less radical approach with varying degrees of electric and biofuel penetration would not be feasible due to the cost of installing infrastructure for both types of vehicles.

Table 4 - Characteristics of the electric vehicles.

Type of vehicle	Car	Bus
Battery capacity [kWh]	40	88
Range [km]	270	210
Slow charge (2.3 kW AC) [h]	18.5	-
Normal charge (22 kW AC) [h]	1.8	4
Fast charge (50 kW DC, 20% to 80%) [min]	40	55
Price [€]	25 000	-

The vehicle's energy consumption (also called efficiency) is calculated by dividing the battery capacity by the range, as can be seen on the equation below. The rest of the procedure used for the electric vehicles was the same as for biofuel, using electricity consumption per kilometre instead of litres of fuel.

$$E_{vehicle} \left[\frac{kWh}{km}\right] = \frac{B_{vehicle}\ [kWh]}{R_{vehicle}\ [km]}$$

Table 5 – Vehicle efficiency. Daily and annual energy consumption for electric cars and for buses.

Type of vehicle	Car	Bus
Energy consumption [kWh/km]	0.148	0.419
Daily consumption per vehicle [kWh/20 km/day/vehicle]	3.0	8.4
Daily consumption for all vehicles [kWh/20km/day]	74 000	13 969
Annual consumption [kWh/day]	27 010 000	5 098 853

Considering a fixed electricity tariff of 0.05 €/kWh and a lifespan of 10 years, we can also determine the embodied energy of an electric car and how many kilometres a day it would have to do in that decade in order to match the energy used in its production. The embodied energy of the car is given by:

$$E_{embodied}\ [kWh] = \frac{Price\ [€]}{Tariff\ [€/kWh]}$$

The annual energy consumption of each electric car is found by dividing the annual energy consumption of all cars by the number of cars on the island. Its consumption throughout its lifetime of 10 years is 10 times the annual consumption. The ratio between the lifetime and embodied energy consumptions is found by dividing the former by the latter.

$$E_{year/car}\left[\frac{kWh/year}{car}\right] = \frac{E_{year}[kWh/year]}{N_{car}\ [car]}$$

$$E_{lifetime/car}\left[\frac{kWh}{car}\right] = 10\left[\frac{year}{car}\right] \times E_{year/car}\left[\frac{kWh/year}{car}\right]$$

Dividing the embodied energy by the car's efficiency we get the distance the car would need to travel in its lifetime in order to equal the embodied energy. Dividing this by the 10 years, we get the distance per year. And finally, dividing by 365 (days in a year) we get the number of kilometres the cars would need to do per day in its lifetime to match the energy used in its production.

$$D_{lifetime}\ [km] = \frac{E_{embodied}[kWh]}{E_{vehicle}\ [kWh/km]}$$

$$D_{year}\left[\frac{km}{year}\right] = \frac{D_{lifetime}\ [km]}{10\ [year]}$$

$$D_{day}\left[\frac{km}{day}\right] = \frac{D_{year}\ [km/year]}{365\ [day/year]}$$

Table 6 - Embodied energy of an electric car and distance it would have to travel in its lifetime in order to match it.

Embodied energy [kWh]	500 000
Annual energy consumption per car [kWh/year/car]	1080
Lifetime energy consumption per car [kWh/car]	10 800
Ratio between lifetime and embodied energy [%]	2.2
Distance travelled in the car's lifetime [km]	3 378 378
Distance travelled per year [km/year]	337 838
Distance travelled per day [km/day]	926

Now the only thing that is left in order to compare the scenarios for biofuels (in litres) and electricity (in kWh) is to determine the island's energy demand, which is the sum of the energy consumed by the cars and the buses in each scenario. The annual energy consumption of each type of vehicle times the fraction of the population that uses that kind of vehicle in a given scenario (see table 1). Another way of comparing scenarios is by determining the consumption per person, which is done by dividing the energy demand by its population.

Biofuel	Electricity
$\boldsymbol{E_{vehicle/scenario}\left[\frac{l}{year}\right] = f_{vehicle}\ [\%] \cdot E_{vehicle}\left[\frac{l}{year}\right]}$	$E_{vehicle/scenario}\left[\frac{kWh}{year}\right] = f_{vehicle}\ [\%] \cdot E_{vehicle}\left[\frac{kWh}{year}\right]$
$\boldsymbol{E_{island}\left[\frac{l}{year}\right] = E_{car}\left[\frac{l}{year}\right] + E_{bus}\left[\frac{l}{year}\right]}$	$E_{island}\left[\frac{kWh}{year}\right] = E_{car}\left[\frac{kWh}{year}\right] + E_{bus}\left[\frac{kWh}{year}\right]$
$\boldsymbol{E_{island/person}\left[\frac{l/year}{person}\right] = \frac{E_{island}[l/year]}{50\ 000\ [person]}}$	$E_{island/person}\left[\frac{kWh/year}{person}\right] = \frac{E_{island}[kWh/year]}{50\ 000\ [person]}$

Table 7 - Annual energy consumption for biofuel and electricity in both scenarios.

Annual energy consumption	Biofuel [l/year]		Electricity [kWh/year]	
	Car majority	Bus majority	Car majority	Bus majority
Cars	15 512 500	2 737 500	22 959 500	4 051 500
Buses	486 764	3 894 112	509 885	4 079 082
Island (cars + buses)	15 999 264	6 631 612	23 468 385	8 130 582
Island per capita [/person]	320	133	469	163

Since bioethanol and electricity are, respectively, primary and final energy, they are not directly comparable, and as such we must find variables they have in common and compare those in order to find out which is the better option for the island. The chosen variables were area required for energy production and its cost. For electricity, we had to pick one of many renewable energy sources available on the island and settled on photovoltaic.

For the biofuel scenarios, the area required to fulfil the island's energetic demand must also be determined. It is known from the biofuel project that to produce 1 litre of biofuel it is required 1.4 m^2 of sugarcane plantation. The plantation area needed in a given scenario can be determined according to the equation below:

$$A_{BF}\ [m^2] = 1.4 \left[\frac{m^2}{l}\right] \times E_{island,BF}\ [l]$$

According to the biofuel project, the cost per litre of bioethanol produced is 0.23 €/l, which means that the total for the island's energy demand is:

$$C_{BF}\ [€] = 0.23 \left[\frac{€}{l}\right] \times E_{island,BF} \left[\frac{l}{year}\right]$$

For electricity, the annual energy density is 265.89 kWh/m^2 (obtained from PV project). Therefore, the area required for electricity production in a certain scenario can be found by:

$$A_E\ [m^2] = \frac{E_{island}\ [kWh]}{265.89\ [kWh/m^2]}$$

According to the PV project, the cost per kWh produced by a photovoltaic system is 0.07 €/kWh, which means that the total for the island's energy demand is:

$$C_E\ [€] = 0.07 \left[\frac{€}{kWh}\right] \times E_{island,E} \left[\frac{kWh}{year}\right]$$

Table 8 - Area and cost requirements for biofuel and electricity in both scenarios.

	Biofuel		Electricity	
	Car majority	**Bus majority**	**Car majority**	**Bus majority**
Area required for energy production [km^2]	22.4	9.3	0.09	0.03
Ratio of area for production and island area [%]	4.5	1.9	0.018	0.006
Cost [€]	3 679 830.72	1 525 270.76	1 642 786.97	569 140.76

According to the previous table, the most area and cost efficient scenario is the one in which all vehicles are electric and, as expected, where there is a public transport majority (scenario 2). More public transport means less traffic and a decrease in the emissions of air pollutants. The latter, however, is not very relevant for the case study since it has already been determined that all the vehicles will be electric and, therefore, have zero exhaust emissions.

Now that we settled on the types of vehicle (electric) and transport (public), we must graph the corresponding load diagram to see how it will impact the electricity network on a daily basis. To do so, we need to know how often and at what time the electric vehicles will be charging.

Electric vehicles charge when they are not being used. According to the following graph, they are not being used the majority of the time, given that at any moment at least 90% of the individual cars are parked. This means that their charging times can be adjusted to be most beneficial for the energy grid, which is when maximum production from non-dispatchable sources occurs (around midday for photovoltaic and during the night for wind energy).

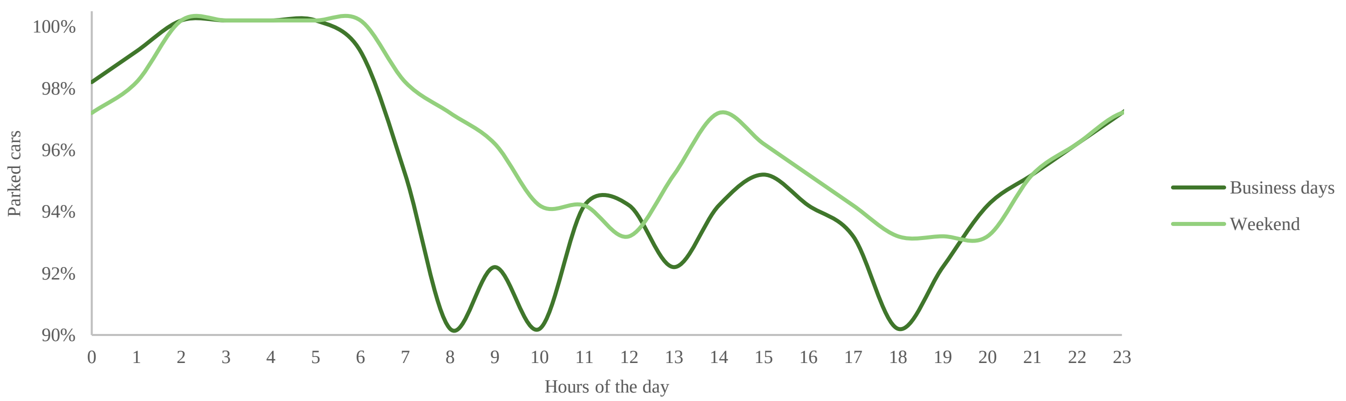

Figure 1 - Fraction of parked cars throughout the day.

We divided the battery capacity of cars and buses by their daily energy consumption to know how many days they could go without charging.

$$N\ [day] = \frac{B_{vehicle}\ [kWh]}{E_{day/vehicle}\ [kWh/day]}$$

To extend the battery life, fast charging and complete discharge should be avoided, as well as too much time at 100% (like leaving it charging all night every night). For this reason, we established that each vehicle would only charge once a week and then we determined how much energy and how long it would take to charge the battery up to 100% in order to outline charging periods for each type of vehicle.

$$E_{charge}\ [kWh] = B_{vehicle}\ [kWh] - 7\ \left[\frac{day}{week}\right] \times E_{day/vehicle}\ [kWh]$$

Table 9 - Relevant data regarding vehicle charge and discharge.

Type of vehicle	Car	Bus
Time vehicle could go without charging [days]	13	10
Charge after 7 days [kWh]	19.3	29.3
Charging required to reach 100% [kWh]	20.7	58.7

As we already mentioned, there is a lot of flexibility regarding charging times for electric vehicles, which means that the days and periods we used for the load diagram are just one of many options. We considered that the cars charge in normal charging stations during business days while people are at work and that the buses can charge any day of the week during the night at bus stations, all of them at 22 kW. We also assumed that the number of vehicles in the chosen scenario would be evenly distributed throughout the days and the periods when they would be able to charge.

Car	Bus
$N_{car/scenario\,2}\ [car] = f_{car/scenario\,2}\ [\%] \cdot N_{car}\ [car]$	$N_{bus/scenario\,2}\ [car] = f_{bus/scenario\,2}\ [\%] \cdot N_{bus}\ [car]$
$N_{car/day}\ \left[\frac{car}{day}\right] = \frac{N_{car/scenario\,2}\ [car]}{5\ [day/week]}$	$N_{bus/day}\ \left[\frac{car}{day}\right] = \frac{N_{bus/scenario\,2}\ [car]}{7\ [day/week]}$
$N_{car/charging\ period}\ \left[\frac{car}{period}\right] = \frac{N_{car/day}\ [car/day]}{4\ [period/day]}$	$N_{bus/charging\ period}\ \left[\frac{bus}{period}\right] = \frac{N_{bus/day}\ [bus/day]}{1\ [period/day]}$

With this information we were able to determine the load for every hour of the day and make the corresponding diagram.

$$Load\ [kW] = 22\ [kW] \times N_{vehicles/charging\ period}$$

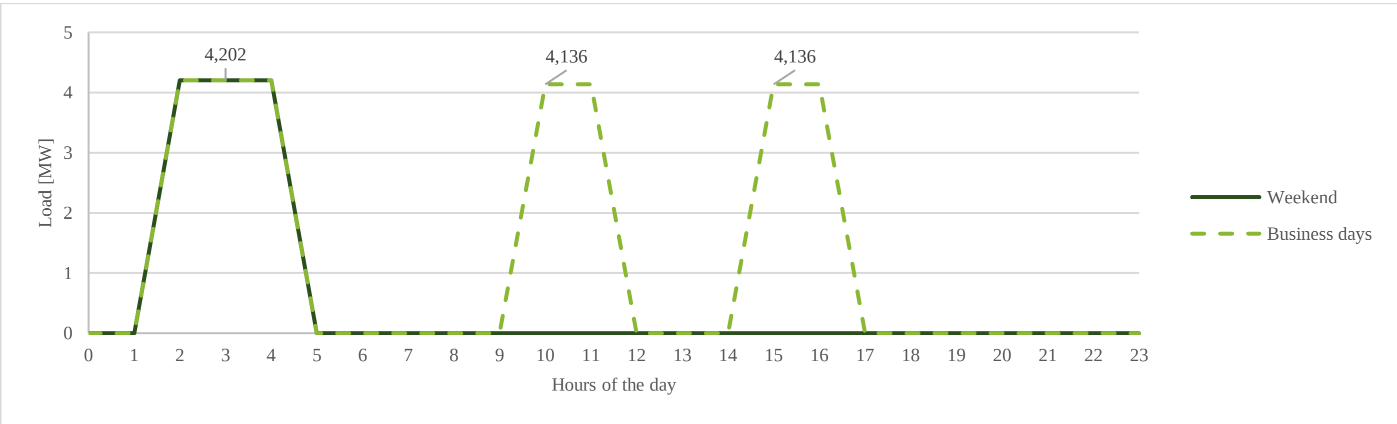

Figure 2 - Load diagram of the mobility on the island.

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