CLEAN ENERGY FOR EU ISLANDS

Decarbonising road transport

Off-grid Scottish Islands

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Date: 24/03/2020

CLEAN ENERGY FOR EU ISLANDS

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List of Abbreviations

BEV	Battery Electric Vehicle
CNG	Compressed Natural Gas
EV	Electric Vehicle
GHG	Greenhouse Gas
GWP	Global Warming Potential
ICE	Internal Combustion Engine
LCA	Life Cycle Assessment
LFP	Lithium Iron Phosphate
LMO	Lithium Manganese Oxide
MOT	Ministry of Transport
NCM	Lithium Nickel Manganese Cobalt Oxide
NEDC	New European Driving Cycle
PHEV	Plug-in Hybrid Electric Vehicle
TTW	Tank to Wheel
WTT	Well to Tank
WTW	Well to Wheel

The Clean Energy for EU Islands Secretariat

Who we are

The launch of the Clean Energy for EU Islands Initiative in May 2017 underlines the European Union's intent to accelerate the clean energy transition on Europe's more than 1,400 inhabited islands. The initiative aims to reduce the dependency of European islands on energy imports by making better use of their own renewable energy sources and embracing modern and innovative energy systems. As a support to the launch of the initiative, the Clean Energy for EU Islands Secretariat was set up to act as a platform of exchange for island stakeholders and to provide dedicated capacity building and technical advisory services.

The Clean Energy for EU Islands Secretariat supports islands in their clean energy transition in the following ways:

• It provides technical and methodological support to islands to develop clean energy strategies and individual clean energy projects.

• It co-organises workshops and webinars to build capacity in island communities on financing, renewable technologies, community engagement, etc. to empower them in their transition process.

• It creates a network at a European level in which islands can share their stories, learn from each other, and build a European island movement.

The Clean Energy for EU Islands Secretariat provides a link between the clean energy transition stories of EU islands and the wider European community, in particular the European Commission.

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1. Introduction

The road transport sector accounted for 19% of total EU-28 greenhouse gas emissions in 2017, with 8.5% coming from passenger cars (1). Within Europe, the Off-grid Scottish islands are a peculiar case due to their rather limited size and car admittance policy. None of the eight island have more than eight kilometres of road, which makes the number of kilometres driven by each car per annum quite low, with the highest estimate of an island only ranging up to 1600km. Additionally, MOT (Ministry of Transport) failures, which are cars that did not pass the technical inspection on the mainland, are allowed to drive on the islands and can be purchased by islanders at lower prices than the market value for second-hand cars. These two factors, the fact that island cars have a very low mileage compared to mainland cars and that MOT failures can be used – effectively extending the life of most cars, make the Off-Grid Scottish Islands a unique case.

This report therefore addresses the situation in the Off-grid Scottish Islands, offering information on what type of vehicle is better from a decarbonisation point of view. This report does not function as a mobility plan nor advocates for the use of cars. It simply answers to the question of what type of vehicle would entail the least lifetime CO_2 emissions if a car is required as such.

Two scenarios are discussed in this report:

1. Buying a new electric vehicle, which could be either a Battery Electric Vehicle (BEV) or a Plug-in Hybrid Electric Vehicle (PHEV).
2. Buying a second-hand conventional vehicle, extending its life beyond what is possible on the mainland. The studied conventional vehicles are a biofuel engine vehicle and a conventional petrol engine vehicle.

These four vehicle technologies and their respective buying methods (new versus second-hand), are investigated in order to quantitatively determine which is best suited for the Off-grid Scottish Islands from an environmental perspective.

2. The local context

The Off-grid Scottish Islands consist of eight islands, six to the West of Scotland and two to the North. This report focuses on the island of Foula as a case study. The island has an area of around 12.7 square kilometres and is inhabited by about 38 people. There are currently three small cars, four medium-sized cars, six large cars, seven 4x4 and three vans. The cars run mostly on diesel, because this makes getting fuel appreciably easier. Cars are always bought second-hand, usually when they're 10-12 years old and have done about 150,000 km. Due to the age of these imported vehicles and the fact that there is no mechanic on the island, cars usually only last about six months to two years. During that time, they travel around 600 km per year, which is significantly lower than mainland cars.

Regarding electricity production on the island, 40% is generated by renewables sources while the other 60% is produced by a diesel-generator. The current plans on the island are to increase the renewable electricity generation to 60% and decrease diesel use to 40%. In total, this adds up to 30 kW of electrical capacity, with the potential for expansion to accommodate for electrification of transport and other services.

FOULA

POPULATION

38

AREA

12.7km²

ENERGY

40% Diesel generation

60% Renewables

CARS

3 small cars

4 medium cars

6 large cars

7 4x4

3 vans

Second-hand cars

10-12 years old

150 000 km

Mostly run on diesel

Last 6 months to 2 years

600 km per year

3. Methodology

This section first explains what is meant by environmental impact. Second, the method for quantifying the environmental impact is discussed. Lastly, the four vehicle types under study are reiterated and clarified.

What is environmental impact?

Environmental impact can be subdivided into two broad categories:

- impacts upon the environment (notably including contribution to climate change), and
- impacts upon human health and well-being (2).

As this report focuses on decarbonising road transport on the Off-grid Scottish islands, only the Global Warming Potential (GWP) is considered as a measure for the environmental impact. GWP is a measure of how much heat is trapped in the atmosphere due to Greenhouse Gases (GHG). Greenhouse gases — of which carbon dioxide is the most abundant and best-known — are a range of gaseous compounds that absorb and re-emit infrared radiation. The GWP of any given gas is described in terms of the equivalent quantity of carbon dioxide (CO_2e), which facilitates the comparison of the relative impacts of various gases released into the atmosphere.

Quantifying the environmental impact

A Life Cycle Assessment (LCA) is a methodology that allows estimating the environmental impact of a product over its entire journey. This journey can be subdivided into four stages: production, importation, operation, and end of life (2), as illustrated in Figure 1.

The production stage refers to the production of the base vehicle (tyres, body chassis, etc.), as well as the powertrain and battery manufacturing, which differs between electric and conventional vehicles. The emissions corresponding with this stage are generally higher for electric vehicles than conventional vehicles, since the battery components are resource intensive to make.

The importing stage is quite similar as all vehicles are transported by the same ship over the same distance to the island. A note could be made that EVs in fact have to traverse a longer distance since they come straight from the manufacturer, which might be located abroad and further away, while a suitable second-hand conventional vehicle probably must travel shorter distances. In contrast, a conventional vehicle might break down more quickly, so multiple conventional vehicles would have to be imported during the same lifetime as an electric vehicle.

The operation stage refers to the maintenance and fuel requirements of the vehicles. The maintenance of an electric vehicle is generally lower because it has fewer moving parts, but the real difference lies in the fuel requirements. EVs use electricity, which is clean at the time of consumption but has corresponding emissions at the time of production depending on the production technique, while conventional vehicles mainly have emissions at the time of consumption.

The end of life stage includes the recycling and disposing of the various vehicle components, which still poses uncertainties for EVs as batteries are recycled to a different degree depending on the location.

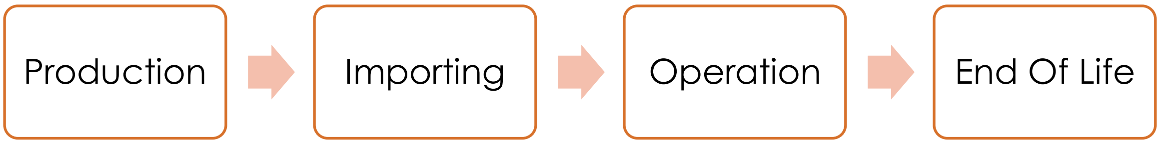

Figure 1 Stages of the LCA

This report draws on aggregated data from a multitude of LCA studies done on electric and conventional vehicles and adapts these to fit the Foula island context. In doing so, the report increases in robustness as specific LCA results are highly dependent on (1) variations in systems boundaries, (2) differences in electricity mixes and (3) the usage of the New European Driving Cycle (NEDC), which is the official laboratory test for fuel consumption and CO_2 tailpipe emissions, versus the real-life monitored tailpipe emissions for comparisons, (4) the assumptions of the lifetime of the vehicle (choosing a shorter lifetime - e.g. 150,000 instead of 200,000 - increases the relative importance of the vehicle production stage), and (5) the assumptions of the battery (choosing the lifetime of the battery is of key importance together with the battery chemistry) (3). This report thus bundles the results of previous LCA studies instead of doing a detailed, but narrow study. This results in a range of values for each LCA stage (dependent on the specific study assumptions), which is used as a sensitivity analysis.

The four vehicle types

The four vehicle technologies and their respective buying method considered in the report are

1. New Battery Electric Vehicle (BEV)
2. New Plug-in Hybrid Electric Vehicle (PHEV)
3. Second-hand conventional engine vehicle running on biofuel
4. Second-hand conventional engine vehicle running on petrol

When it comes to the conventional vehicles--based on information provided from the Off-grid Scottish Islands-- it is assumed that they are bought second-hand. Thus, especially for the MOT failure cases, their life can be extended beyond its expected lifetime. In this sense, the production stage is not considered or only up to certain percentage of its original value as the conventional vehicle would be demolished otherwise, as elaborated upon in Section 5. The importing, operation, and end-of-life stages are fully considered for conventional vehicles. The following paragraphs shortly clarify what is meant with each vehicle technology as a barrage of different names have sprung up in the automobility market nowadays.

Conventional vehicles

Conventional vehicles run on liquid fuel such as petrol, diesel or biofuel and are commonly seen on the roads nowadays. Typically, they have an engine, a fuel tank, an exhaust system, and various other components associated with their operation (including a battery and electric motors), but they do not use an electric motor or battery for propulsion (2).

Electric vehicles

Electric vehicle refers to both the Battery Electric Vehicle (BEV) and the Plug-in Hybrid Electric Vehicle (PHEV). A BEV runs solely on electricity originating from an external source (e.g. the electricity grid, standalone generators, etc.). It has fewer mechanical parts than a conventional vehicle, e.g. no combustion engine or fuel tank. Simply, a BEV is propelled by a motor that runs off the energy stored in an on-board battery. To charge this battery, the car must be plugged into an electrical socket connected to an off-board power source. Once the battery is flat, the car cannot be anymore driven until it has been charged again by plugging it in (2). PHEVs have, like a BEV, an electric motor for propulsion that is supplied from an on-board battery that can be plugged into an external source to be recharged. What sets PHEVs apart from BEVs is that they also have an on-board fuel tank and internal combustion engine (ICE) to supplement the operation of the electric motor, either when more power is required or (more typically) to extend the vehicle's range when the energy stored in the battery is depleted. A PHEV typically runs for a certain number of kilometres using the electricity stored in its on-board battery and, once that energy is depleted, it then begins to use its internal combustion engine. To achieve more electrified travel, the battery will need to be recharged by plugging in. However, if the PHEV is recharged before use of the ICE is required, the use of this "range extender" function (the fuel tank/engine etc.) can be avoided, thus operating on battery power alone (2).

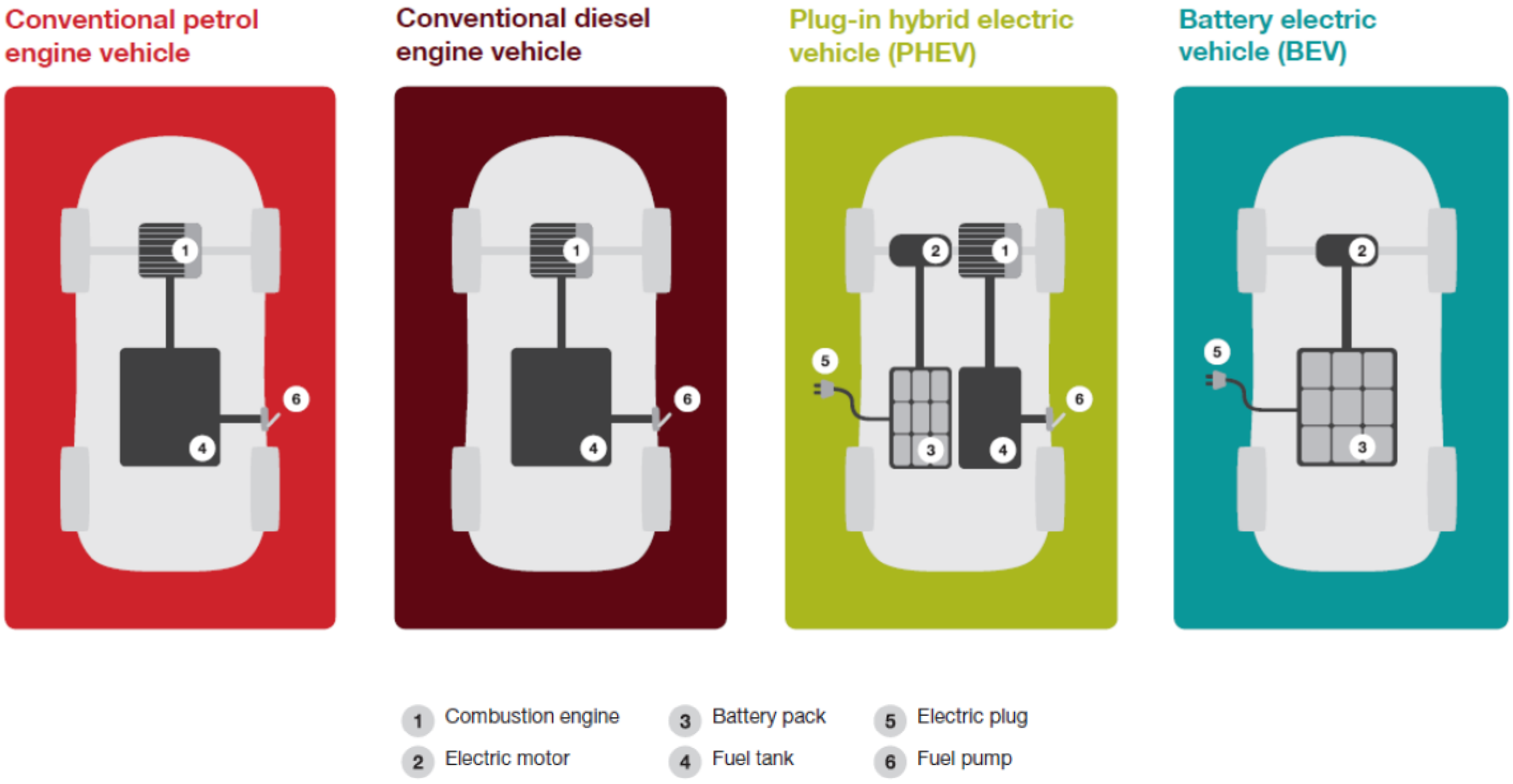

Figure 2 Key components of differing vehicle technologies. Data source: (2)

4. Data

The data were collected by carrying out a thorough review of LCA studies on electric and conventional vehicles. It is Important to note is that these studies can quite drastically differ in their figures due to different system boundaries, modelling assumptions and the geography of study, as mentioned before. The lowest and highest values found in literature are taken in order to check the sensitivity of the results. First the production stage is discussed, followed by the importing, operational and end of life stage.

Production

The lowest and highest values for climate change impact of the production of BEVs, PHEVs, and conventional cars are shown in Table 1. When it comes to electric vehicles, the estimates vary quite significantly. As a matter of fact, the lowest possible value, 6,890 kg CO_2e as found by Notter (4), is almost half of the highest value, 12,075 kg CO_2e, which corresponds to the highest estimate by Hawkins (5). This difference can be partly explained by the choice of battery chemistry: Notter uses a Lithium Manganese Oxide (LMO) chemistry while Hawkins takes a Lithium Nickel Manganese Cobalt Oxide (NCM) and Lithium Iron Phosphate (LFP) chemistry.

Peters (6) performed a review of previous LCA studies on battery production that helps understanding the impact of the type of batteries in the EVs production emissions. The results of his work are shown in Figure 3, which presents the various lithium-ion battery chemistries on the x-axis and the Global Warming Potential (GWP), expressed in kg CO_2 per Wh battery capacity, for all reviewed studies on the y-axis. The figure shows that the mean value of LMO is 0.055 while LFP and NCM are 0.160, a value three times as high. Additionally, the difference in the impact of battery production is also partly explained by the fact that Hawkins based his work on a study by Majeau-Bettez (7), who uses a top-down approach to estimate the energy required to produce battery components. Notter, on the other hand, uses a more detailed process level approach, which according to Dunn (8) who analysed both types of studies, is more accurate. Furthermore, Hawkins utilises the base of a Mercedes A class model, while Notter uses the base of a smaller VW golf. The values for the production of PHEVs are taken from Samaras and are subdivided in PHEVs with a driving range of 30 km, 60 km and 90 km (9). The values for the conventional vehicles are, like the BEV, taken from Hawkins and Notter.

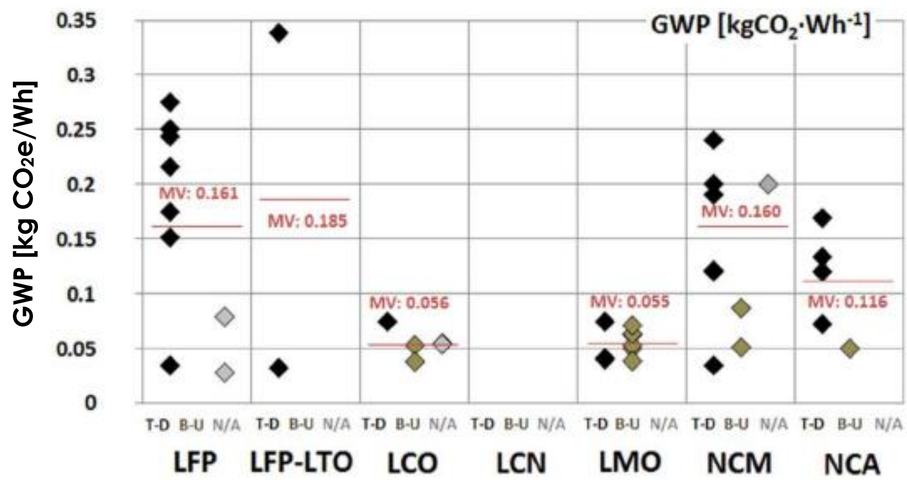

Figure 3 NCM and LFP lithium-ion batteries are more polluting than LMO batteries. Data source: (6)

In order to compare the total CO_2e emissions to produce a BEV, a PHEV, and a conventional vehicle, the results of different authors are shown in Table 1. Producing a PHEV with an electric range of 30 km results in 6,810 kg CO_2e, one with an electric range of 60 km results in 7,610 kg CO_2e, and one with a range of 90 km corresponds to 8,420 kg CO_2e. No distinction was made between the base of the vehicle and the powertrain components, instead one value is given (see Table 1). The numbers were based on the low-carbon electricity scenario of 200g CO_2/kWh in the study since this nicely resembles the current UK situation (10).

The estimates of the production impact of conventional vehicles of Notter and Hawkins are more similar than their electric vehicle counterpart, ranging from 5200 kg CO_2 to 6525 CO_2. The difference is because Hawkins uses as reference the base of a Mercedes A class model, while Notter uses the base of a smaller VW golf, as mentioned above. Important to note is that conventional vehicles emit significantly less during the production stage compared to their electric counterparts.

Table 1 Electric vehicles emit more CO_2e during production than conventional vehicles

Production	**BEV**			**PHEV**			**ICEV**	
Author	Notter (4)	Hawkins (5,11)		Samaras (9)			Notter (4)	Hawkins (5,11)
Total kg CO_2e	**6890**	**10,875**	**12,075**	**6810**	**7610**	**8420**	**5200**	**6525**
Base vehicle	3740	5100	5100	6000	6000	6000	3740	5100
Powertrain	1350	1125	1125				1460	1425
Battery	1800	4650	5850	810	1610	2420	/	/
Chemistry/range /fuel	LMO	NCM	LFP	PHEV 30	PHEV 60	PHEV 90	Petrol	Petrol

Importing

All vehicles, whether a BEV, a PHEV or a second-hand conventional vehicle need to be imported to the island, with corresponding emissions. Importing any of these types of vehicles to the island has a similar environmental impact. However, if conventional vehicles have a drastically shorter lifetime because they are second hand, they may need to be imported more often which increases the climate change impact of importing conventional vehicles. On the other hand, the EVs probably must traverse a longer distance to the island since they come straight from the manufacturer, which might be located abroad and further away, while a suitable second-hand conventional vehicle probably must travel less far. An LCA study on electric and conventional vehicles in New-Zealand found that the shipping distance of 9,500 km from Tokyo to Wellington had a global warming potential of less than 0.1% compared to the total CO_2 emissions (2). This indicates that the environmental effect of importing, compared to the other Life Cycle Assessment stages, is in fact negligible. Therefore, the importing stage will be neglected for the purpose of this report.

Operation

The emissions corresponding to the operation of BEVs depend on the carbon-intensity of the electricity production. The electricity-mix on Foula is based on 40% oil-fired and 60% renewable production, for which the range of CO_2 emissions per kilometre is given in Figure 4 along with different types of electricity production and fuels. The emissions for the Foula electricity-mix are significantly lower than the reference petrol vehicle, and lower than the bioethanol vehicle, indicating that a BEV emits less CO_2 during its operation on Foula than the reference conventional vehicle. If electricity is produced from a coal-fired plant, a BEV emits more than a reference petrol car. Electricity based on oil sources emits similar amounts of CO_2 compared to the reference petrol car, while CNG-based electricity production has a lower environmental impact. If renewable sources are utilised to produce electricity, a BEV has barely any emissions during its operation.

The emissions of the PHEV are based on an electric driving range of 30 km and the Foula electricity mix of 60% renewables and 40% oil-fired production.

The CO_2 emissions of the reference petrol vehicle are based on the Well-To-Wheel (WTW) value. This takes into consideration the extraction and transportation of fuels, also referred to as Well-To-Tank (WTT) and the internal efficiency losses of the combustion engine, also specified as Tank-To-Wheel (TTW). According to research by the European Environmental Agency (EEA) for 2015, the TTW value rests around 120 g CO_2/km (12). However, this has been subject of controversy as the NEDC has been critiqued for not properly reflecting actual driving conditions. In fact, the difference between laboratory and actual driving measurements were found to be in the range of 30% to 40% (12). Based on these figures, in this study the TTW number has been increased by 35% (which corresponds to the maximum value in Figure 4) to properly reflect actual driving conditions. The WTT rests around 23 g CO_2e/km (13), which is a value for the general European context. For the specific Foula context, this value could become bigger since fuel needs to be transported to the island instead of more easily reached cities and hubs. This effect is rather small as the WTT is considerably lower than the TTW and thus only a fraction of the total WTW value. Hence, the fact that Foula is an island is assumed as negligible on the total WTW value for the purposes of this work.

The use of biofuel has the potential to decrease emissions, but care must be taken with the biological source of this type of fuel. Biodiesel, which takes almost 70% of the EU biofuel market, leads to total emissions that are around 80% higher than the fossil fuels they aim to replace (14). This is largely because the plant-based sources of biodiesel are often grown in the tropics, which can lead to unwanted land use change due to tropical deforestation and associated peatland drainage. Palm and soy, which make up around 32% of the EU biofuel market, are two of the four major drivers of tropical deforestation–together with beef and wood. This makes their corresponding emissions up to three times higher than fossil fuels (14).

Bioethanol, on the other hand, can decrease the emissions compared to fossil fuels by around 30% on average, but only accounts for 22% of the EU biofuel market. Large variations between plant-based sources do exist though. Barley and wheat lead to emissions that are slightly higher or similar to fossil fuels, whereas maize and sugar-based bioethanol leads to 50% less emissions (14). The minimum for bioethanol in Figure 4 thus corresponds to a reduction of 50% of the TTW value of the convention petrol vehicle while the maximum corresponds to a 30% reduction of the NEDC adjusted TTW value of the petrol vehicle. Not all conventional vehicles can run on bioethanol, often referred to as E85 (85% is bioethanol and 15% is fossil fuel). Instead, a flexible-fuel vehicle is required which can burn any proportion bioethanol as fuel injection and spark timing are adjusted to the actual blend in the combustion chamber. Additionally, many conversion kits exist nowadays, which allow conventional cars to use bioethanol as well (15).

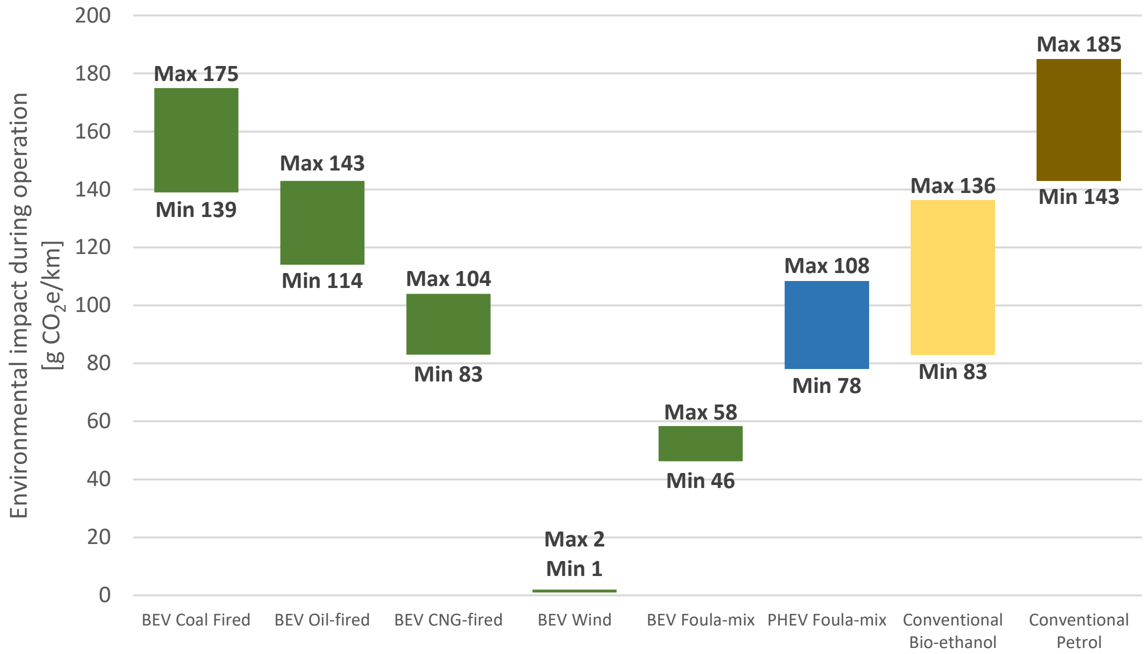

Figure 4 The Foula electricity mix emits less than conventional vehicles. Graph adapted from (3,14)

End of life

The end of life includes the treatment and disposal of the vehicle and batteries. This is mostly the same for each type of vehicle as disposing of the vehicle's base is the same for all. The need to dispose the batteries of a BEV adds additional CO_2 emissions, but these are generally in the range of only 1-2% over the entire lifetime (2,5,13) and hence negligible compared to the production and operation stage.

5. Results & Discussion

The following section presents the results for the life cycle assessment of a new BEV and PHEV compared to buying a second-hand petrol or bioethanol conventional vehicle, effectively extending its expected life. The results in this study account for impacts during the production and operation stages of the life cycle assessment. The importing and end of life stage were found to be negligible and hence were not considered in the analysis. As the goal of this report is to inform the off-grid Scottish Islands on how to decarbonise their road transport, the environmental impact discussed in this report is restricted to the global warming potential (GWP, see Section 3), expressed in CO_2e.

Three different scenarios are discussed, ranging from least to most beneficial for the electric vehicles:

- Scenario 1 uses the Foula electricity mix, which consists of 60% renewables and 40% oil-fired sources, and assumes that the life of the second-hand conventional vehicle is extended beyond its expected life as otherwise the vehicle would be demolished.

- Scenario 2 also uses the Foula electricity mix but loosens the restriction that second-hand vehicles need to be MOT failure vehicles or fully depreciated. In fact, most second-hand vehicles on Foula are 10-12 years old while the lifespan of a car is assumed to be 15-20 years old. The remaining lifetime of the average Foula car therefore ranges between 50% and 20%. In fact, this means that 20% to 50%of the production stage of the LCA is still attributable to the total CO_2 emissions.

- Scenario 3 uses a 100% renewable electricity mix, as is the case on some Off-grid Scottish Island and, as for Scenario 2, assumes a remaining expected life between 20% and 50%.

Scenario 1

The environmental impact of each vehicle type is laid out over the distance driven on the island, as illustrated in Figure 5. When the vehicles get to the island (0 km driven in Figure 5) the emissions correspond only to the production stage. The conventional vehicles have no emissions at this point since the production stage has already been fully depreciated: it is assumed that these vehicles would be demolished otherwise; therefore, their use on the island means extending their lifetime. The production stage of the BEV and PHEV on the other hand, has not been depreciated. Only the lower impacts of producing the BEV and PHEV are shown because these are more accurate, as mentioned in Section 4, and because these vehicles serve as the challenger to the conventional vehicles.

The total CO_2 emissions increase linearly with the number of kilometres driven on the island during the operation stage, as shown in Figure 5. The impact of this operation stage is strongly influenced by the type of fuel or the source of electricity. In the case of Foula, the electricity mix corresponds to 60% renewables and 40% oil. Each fuel type or electricity source has a lower and upper emissions value per kilometre, as shown in Figure 4. In order to assess whether the challengers (BEV and PHEV) in their best-case scenario can beat the conventional vehicles in their worst-case scenario, the lower value is chosen for the BEV and PHEV while the higher value is taken for the conventional vehicles.

Combining the production and operation stage illustrates that the BEV only becomes environmentally better than the regular petrol vehicle once about 50,000 km are driven (see

Figure 5). However, the average number of kilometres per year on the island of Foula is 600 km, so it would take almost 85 years until the BEV outcompetes the conventional petrol vehicle from an environmental point of view in Scenario 1.

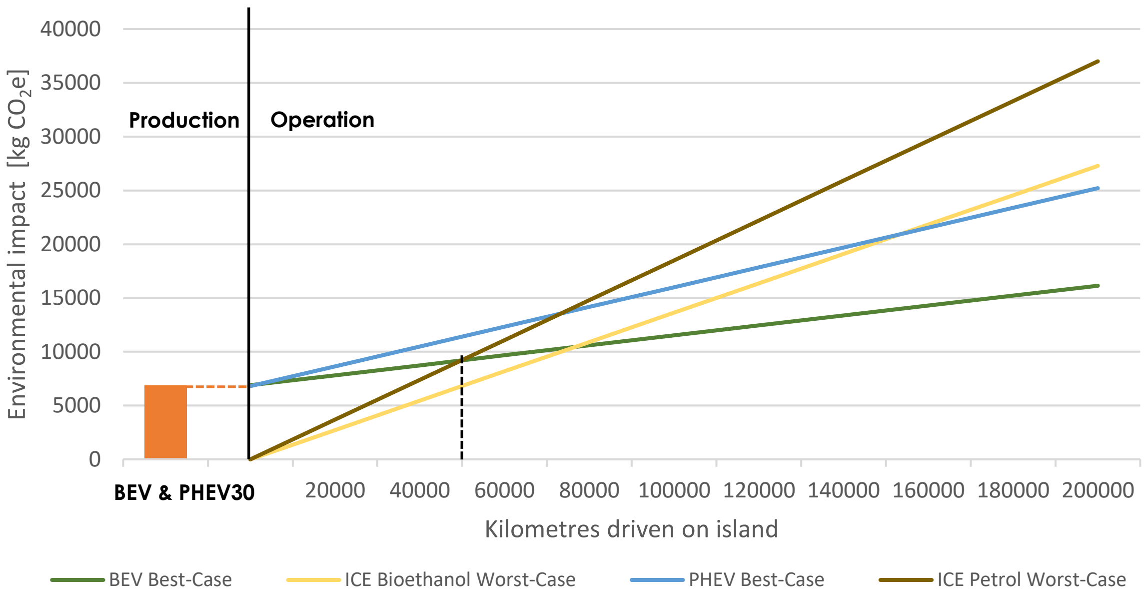

Figure 5 MOT failure petrol and bioethanol conventional vehicles emit less over their lifetime if less than 50,000 and 76,000 km are driven on the island, respectively.

Scenario 2

The environmental impact of each vehicle type is, as for Scenario 1, laid out over the distance driven on the island in Figure 6. When the vehicles get to the island (0 km driven) the emissions correspond only to the production stage. In this case, however, the conventional vehicles still have 20% to 50% of their expected life and therefore of their production stage emissions left. The emissions corresponding to the lower impacts of producing the BEV and PHEV are at 100%, as was the case in Scenario 1. Both the CO_2 emissions corresponding to the operation stage and the Foula electricity mix are the same as in Scenario 1.

Combining the production and operation stage illustrates that if the petrol vehicle still has 50% of its expected life, the BEV only becomes environmentally better once about 26,000 km are driven. left. However, if the conventional vehicle only has 20% expected life left, it takes about 40,000 km for the BEV to outcompete the conventional car. Since the average number of kilometres per year on Foula is still 600 km, it would take 43 years for 50% expected life and 67 years for 20% expected life until the BEV outcompetes the conventional petrol vehicle from an environmental point of view in Scenario 2. Only if the conventional vehicle has more than 86% of its expected life left when buying second-hand, does the BEV outcompete the conventional vehicle in a sensible 15 years in this scenario.

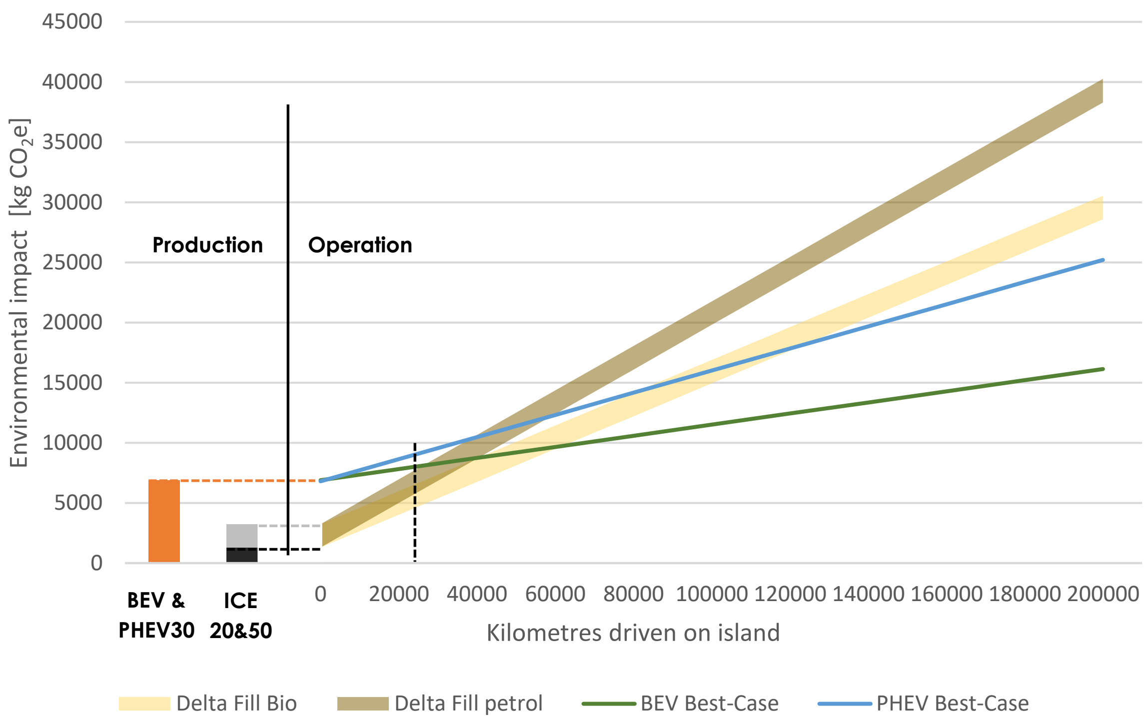

Figure 6 The petrol and bioethanol conventional vehicles emit less over their lifetime if less than 26,000 and 40,000 km are driven on the island, respectively

Scenario 3

The environmental impact of each vehicle type is once again laid out over the distance driven on the island, as illustrated in Figure 7. The emissions of the production stage are the same as in Scenario 2. The operation stage, however, differs in the sense that the BEV is assumed to get its electricity from 100% renewable energy sources, for which the lower emission value of Figure 4 is used in favour of the challenger.

Combining both stages shows that the BEV becomes environmentally better than the regular petrol vehicle once about 20,000 km are driven. Since the average number of kilometres per year on Foula is still 600 km, it would take 33 years until the BEV outcompetes the conventional petrol vehicle from an environmental point of view in this scenario.

Petrol versus bioethanol

This section zooms in on the petrol and bio-ethanol conventional vehicle. Figure 8 shows that bioethanol has less emissions during the operation stage than petrol, but the question arises of how big and significant this influence is. The bioethanol vehicle emits 136 g CO_2/km while the petrol vehicle emits 185 g CO_2/km in their worst-case scenario. Assuming 600 km per annum, as is the case on Foula, this adds up to about 30 kg CO_2 that the petrol vehicle emits more than the bioethanol vehicle, which is still quite abstract. As a reference, 2.5 kg of hard cheese has around 30 kg of CO_2e emissions (17). This makes the difference between petrol and bioethanol vehicles more interpretable and illustrates that for a low number of kilometres driven per annum, the benefit of switching to bioethanol is rather marginal.

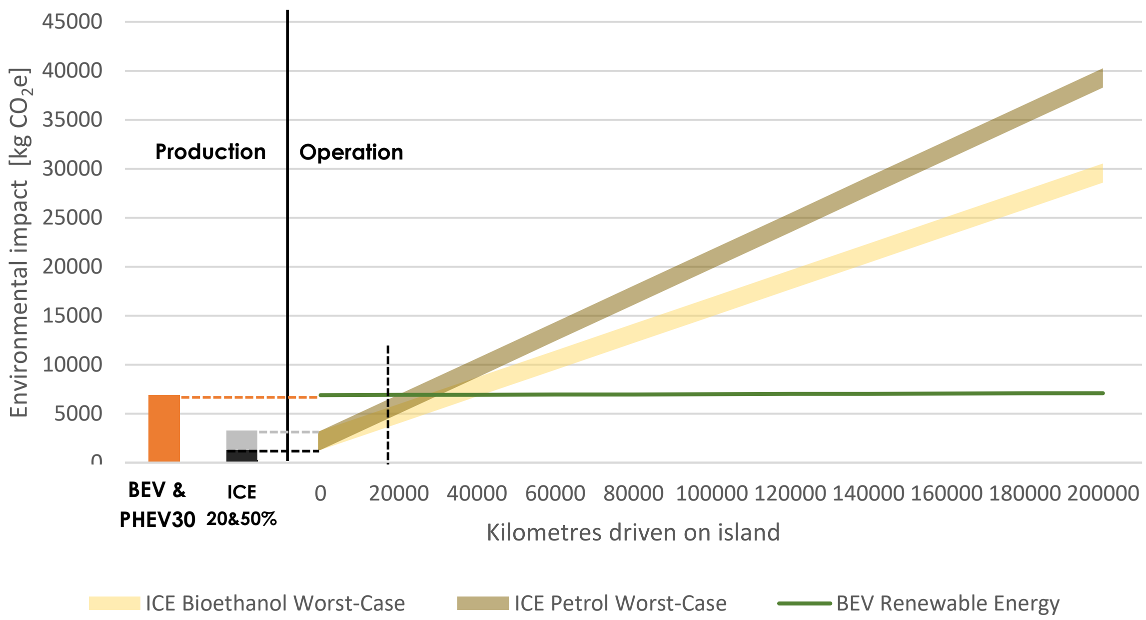

Figure 7 The petrol and bioethanol conventional vehicles emit less over their lifetime if less than 20,000 and 30,000 km are driven on the island, respectively

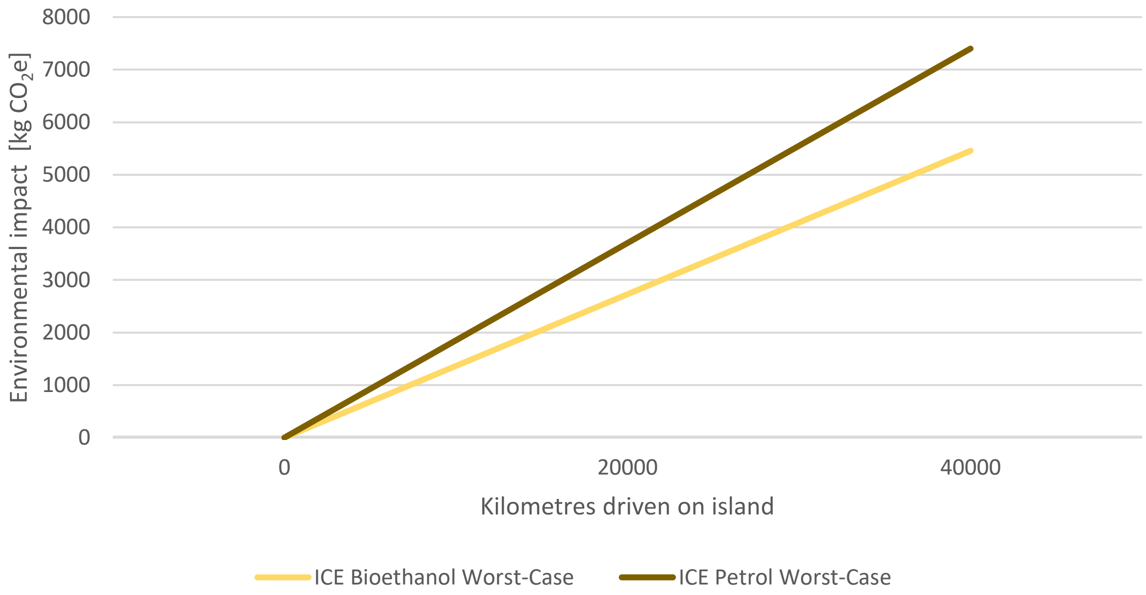

Figure 8 Bioethanol offers decent emission reductions, but only when a significant number of kilometres are driven. In the case of Foula with 600 km per annum, the benefit is only 30 kg CO_2, the equivalent of producing 2.5 kg of hard cheese.

6. Conclusion

Through analysing different scenarios, it became clear that in the specific case of the Off-grid Scottish Islands, electric vehicles have more emissions than conventional vehicles over their lifetime due the more emission intense production stage and the fact that the cars have a very low mileage per annum. In the most beneficial case for electric vehicles where conventional vehicles still have 50% of their expected life left and the off-grid Scottish island has completely renewable energy, it takes 20,000 km driven on the island before the BEV becomes better from an environmental point of view. With an average of 600 km driven per annum on the island of Foula, this corresponds to 33 years. Furthermore, the analysis was carried out with the worst-case emission values for the conventional vehicles, the best-case emission values for the electric vehicles, and the lowest emission value during production for electric vehicles. These assumptions are all in favour of the electric vehicle challenger and still neither the BEV nor the PHEV proved to have lower emissions over its lifetime for the specific case of Off-grid Scottish Islands.

These results might seem contradictory as BEVs are perceived as an environmentally benign technology due to their advantages in terms of powertrain efficiency, maintenance requirements, and zero tailpipe emissions (11). Furthermore, many authors urge society to accelerate the shift to electro-mobility since neither incremental improvements to existing vehicles nor the use of advanced biofuels are enough to reduce transport emissions by more than 90% by 2050 (16). However, the reality is more complex and requires a complete account of impacts throughout the vehicle's life cycle for the specific situation. In this sense, islands such as the Off-grid Scottish Islands cannot be evaluated to the same standards as the mainland since situations differ significantly.

The most important differences in this context are the low number of kilometres driven per annum on the island and the fact that the Off-grid Scottish Islands can use MOT failure vehicles, vehicles that would be demolished otherwise, or older vehicles that have little expected life left. Both these factors help explain why a BEV, which has less emissions during its operating stage, fails to outcompete a conventional vehicle from an environmental point of view for the specific case of the Off-grid Scottish Islands. Additionally, no repair shops are present on the island, which makes reaching the full expected life span of any vehicle logistically difficult. Lastly, a trade-off exists between rapidly disposing of conventional vehicles and the additional emissions that are released during the production process of new vehicles. A vehicle lifetime of 15-20 years is seen as optimal to minimise the emissions of the entire life cycle (16). In this sense, extending the life of conventional vehicles can in fact help reduce overall emissions in the case of the Off-grid Scottish Islands.

When considering conventional vehicles, a choice should be made between running on traditional petrol or one on biofuel. Biofuel has the potential to decrease emissions, but care must be taken with the biological source of this type of fuel. Biodiesel leads to total emissions that are higher than the fossil fuels they aim to replace because the plant-based sources are often grown in the tropics, which can lead to unwanted land use change. Bioethanol, on the other hand, can decrease the emissions during operation by 30% on average compared to fossil fuels. However, when considering the low annual mileage of vehicles on the Off-grid Scottish Islands, this effect is rather small as it only saves about 30 kg CO_2e per 600 km driven, the equivalent of producing 2.5 kg of hard cheese. A trade-off should be made between the additional emissions of procuring bioethanol versus the emission reduction of using this fuel.

The key message is that if a car is necessarily required on the Off-grid Scottish Islands, from an environmental point of view the choice should be a conventional vehicle (petrol or bioethanol) at the end of its life cycle, that would be demolished otherwise. This is assuming that, if purchasing an electric vehicle, it would be a new one: if the market for second-hand electric vehicles increases in Scotland, it would be interesting to consider this option adjusting the results obtained in this study. Given the short distances that vehicles travel in the Off-grid Scottish Islands, even if the battery range is low in a second-hand electric vehicle, it would probably suffice. In any case, the most environmental option for short distances on the Off-grid Scottish Islands is still to use active modes of transport such as walking, cycling and so forth.

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Published by the
Clean Energy for EU Islands
Secretariat