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Exploiting the opportunities of constrained generation in islands.

Case study: exploiting wind curtailed electricity in Orkney

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Introduction

Insular electricity networks are characterised by a more fragile structure than the mainland ones. This is caused by several aspects such as absence or insufficient interconnections with the mainland electricity network, lower inertia due to the lower amount of generation grid-connected facilities etc. The recent direction toward the introduction of renewable energy (such as wind, solar and tidal energy) based generation units, in the insular generation mix, within this fragile structure brings new serious additional challenges and, on the other hand, considerable opportunities.

Orkney islands community relies on an aged and weakly connected electricity distribution network. The only connection with the mainland Scotland consists in two 33 kV subsea cables.

Since renewable installed generation in Orkney have growth significantly in the last decade, electricity imports via the subsea cables have decreased to a point where in both 2013 and 2014 Orkney was a net exporter of electricity. Furthermore, due to the unique and weak connection with the mainland electricity network, it is not so rare that over the year situations in which combination of the extremely high power generation from the wind turbines and lower electricity demand occur simultaneously: in such circumstance the subsea cables are not able to export the whole amount of electricity in excess and the only solution are curtailments experienced by the wind turbines.

This project aims to explore possible solutions in order to avoid these curtailments and to examine their feasibility, starting from the 2013 wind power generation and electricity demand databases for Orkney.

1. Insular power system analysis

1.1. Overview of an insular power system

The term island essentially is referred to a land that is surrounded by water, its basical feature is a total physical insularity (which allude to isolation and/or dispersion) from the mainland. It was stated in the Treaty of Amsterdam that “insular regions suffer from structural handicaps linked the their islands status, the permanence of which impairs their economic and social developement” [1]. Specifically, insular areas are characterised by intrinsic limitations that require to be determined. “Limited resources, distance from the mainland, climatic conditions, frequent seasonal change of population (due to tourism), inability to achieve economies of scale are examples of such constraints” [2]. These limitations bring to several negative issues, such as overseas trade dependency, economic weakness, and the need of oversizing infrastructures such as power system [3].

In a physical point of view, the impossibility of an archipelago or an island, due to smallness and/or remoteness, to interconnect itself with other electricity production units and consumers grids located in the mainland through a wider transmission line describes an insular energy system. Thus, insular power grids correspond to electric power grid structures in physically isolated geographical areas, mainly islands in the above sense. As a result, the isolated region cannot take advantage of the more efficient and cheaper bordering electricity markets. Commonly, small islands or in mainland countries where the costs for constructing infrastructure for power transmission purposes are prohibitively high, are characterised by this type of energy system, or in cases where a country may be isolated due to political issues [4].

Typically diesel and heavy fuel oil are the major energy sources for insular energy systems. The massive use of fossil fuels for electricity production is even encouraged by the absence or scarcity of local energy resources, the limited energy delivery infrastructure, the lack of storage and the flexibility of the power generators to meet seasonal demand. Insular energy systems typically consist only in a few independent power facilities and a limited range of power generation technologies (basically thermal power plants or smaller Diesel generator). Furthermore, there is lack of attractive support schemes or incentives for the progression of the system from fossil fuels to renewable and low-carbon energy sources. “At the same time, their efforts to meet international or European obligations often fail and are normally also costly” [5].

Archipelagos represent a particular case of energy insular systems. Where possible, the local autonomous power stations' operation can be replaced by interconnections between islands. In addition interconnections between island, may allow the absorption of large amounts of renewable energy without causing the instability effects noticed in autonomous grids [4]. On the other hand, such an electricity production strategy has to deal with the significant technological problems related to the undersea electricity transportation, the rather high first installation cost (approx. € 3 million per km of transportation grid), and the strong opposition of local societies claiming important environmental impacts [5].

Generally the energy generation asset of insular systems is extremely expensive and unsecure. The fossil fuels (gasoline, oil, and liquefied petroleum gas) required for conventional energy sources are generally carried to island by tankers. This creates both an inefficient service model especially during peak times and a problematic strategy from an environmental point of view. The great dependency of insular energy systems on imported energy sources for electricity generation and their associated high transportation and shipping costs are reflected in the electricity pricing [6]. In addition, the production and consumption capacities is bounded by the limited sizes of these systems, and the establishment and growth of significant internal markets is restricted by this aspect [7]. Finally, the reduction of GHG emissions is another great challenge for insular energy systems, given that most of their electricity production is based on fossil fuels.

Hence, concerning isolated islands environment, the crucial purpose of many energy policies, especially of the ones emitted during the last decade, consists in exploiting as much as possible the local renewable resources. On the other hand, power-quality issues such as frequency and voltage deviations are more likely to occur in insular grids, especially if the penetration level of RESs is high.

According to Foikades et al. [8], the transition to smart insular grid systems can be achieved through a variety of measures and policies including:

- The promotion of energy efficiency measures;
- The utilization of renewable energy technologies;
- The installation of large storage systems;
- The establishment of smart grids.

However, every action should preliminarily take into consideration the local conditions of the energy system, as well as the economic feasibility.

The reduction of the level of energy imports of insular energy systems can be achieved exploiting renewable energy sources, with positive impacts for the balance of trade and security of supply. However, before RES penetrates the insular energy systems, there are technological, economical and practical problems that need to be overcome. Renewable energy technologies are less reliable than conventional technologies due to the fact that the energy production is variable and weather conditions dependant and thus additional technologies such as energy storage are required. Monopolistic power sectors also prevent the development of smaller scale renewable electricity generation that would be more efficient and cost-competitive and put conventional technologies in a preferential position due to the earlier profit resulting from the lower capital costs.

1.2. Analysis of typical insular grid structures

1.2.1. System size and typical infrastructure

According to their peak power demand (MW) and annual energy consumption (GWh), Erdnic et al. [2] propose a classification of insular area power systems:

- Very small islands (< 1 MW and < 2 GWh);
- Small islands (1-5 MW and 2-15 GWh);
- Medium islands (5-35 MW and 15-100 GWh);
- Big islands (> 35MW and > 100 GWh).

Typically, a single or a few and mostly conventional fuel-based generators are sufficient to fulfil electricity demand in insular areas. Therefore, the number of generating units is generally very low. Hence, the inertia of an insular energy system is significantly low, and due to possible blackouts or fuel shortages, considering such a small number of generating options, actual insular power systems are considered unreliable and likely to be subject to failures. In addition, the majority of the electricity generators, as well as electric cables and other infrastructure are old: for this reason technical losses in isolated insular networks are considered to have higher influence when compared to mainland electricity grids. This is an issue that reduce both reliability and economic sustainability. Thus, the global power system operating efficiency is significantly lower compared to that in mainland.

1.2.2. Economical framework of insular power system operation

The organization and regulation of electricity sector has substantially changed in many countries around the world over the last decades: typically vertically integrated systems and monopolies have been or have being replaced by competition and market structures. Nonetheless, the electricity grids of islands pose challenges toward the implementation of market structures and competition because of their peculiarity. According to Catalão et al., the main barriers are as follows [9]:

- "In contrast with continental grid, a generator in islands cannot have significant capacity due to system security reasons;
- More reserve capacity is required than in the mainland networks on account of absence of interconnections;
- Limited space, public opposition, and local factors do not allow vast investment in conventional power plants;
- RESs are alternative candidates for electricity production, promising economic efficiency and sustainability. Nevertheless, network security and the intermittent nature of such resources limit the RES share".

1.2.3. The need for sustainability

Many islands do not have the technical possibility to have a direct interconnection with the mainland, or more in general this is economically unsuitable. This evidence forces the insular community to fulfil the whole electricity demand by producing it on site. Typically fossil fuels consist in the main energy source in which insular electricity systems rely. Electricity is produced in conventional power plants (thermoelectric power plants for bigger islands or Diesel generators). Since the fuel is imported via sea, its higher cost affects strongly the cost of the produced electric energy, which is clearly higher than in the mainland. Other major reason for the electricity cost difference include the increasing percentage of maintenance within total costs and the decreasing efficiency of the used equipment, especially engines and turbines, both caused by aging of electricity production facilities in islands. This issue obstructs the economic sustainability of electricity market in insular areas. In addition, the use of oil and other fossil fuels also significantly contributes to the environmental pollution. It is important to remark that the climate changes issues related to global warming will have a greater impact on insular regions compared to the mainland. In place like islands, where end users are inevitably closer to the electricity production plants, greenhouse gasses emission can affect life quality to a greater extent. Furthermore, rise in sea level, natural disasters and drought are likely to be real dangers in the future and especially to have more impact on insular areas.

Is therefore important to analyse in depth both economic and environmental impacts that fossil fuel utilization in insular area can lead to, aiming to improve the sustainability of insular life.

1.2.4. Reliability requirements

The fact that insular power systems depend on a few conventional fuel fired generators, besides the stability, puts also at risk the security of the system: generators size tends to be very large in comparison with the whole system size. Especially during off-peak hours, a single generator may represent a significant share of the system's total generation installed power. It is then evident that the sudden service disruption of this unit will cause significant frequency deviations or, at worst shortages in electricity supply. Given the economic and social aspects that usage of electricity involves, measures have to been taken in order to guarantee the uninterrupted and quality operation of power system.

Power stability can be defined as the "ability of an electric power system, for a given initial operating condition, to regain a state of operating equilibrium after being subjected to a physical disturbance, with most system variables bounded so that practically the entire system remains intact" [10]. Three types of stability have been identified: rotor angles, frequency and voltage [11].

The rotor angle stability indicates "the ability of the interconnected synchronous machines of the power system to remain synchronized under severe or small disturbances. Transient stability (the ability to withstand severe disturbances) depends on both system properties and the type of fault." [2].

"Frequency should be maintained within acceptable limits around the nominal value. Off-nominal frequency has negative and potential-hazardous results such as resonance in rotating machines that tear them because of mechanical vibration, changes in the speed of the asynchronous machines, overheating of transformers and machines" [2]. To maintain frequency at its nominal value, a balance between production and retention of active power should be performed. In order to achieve this, an amount of active power is rendered available in order to control frequency through its variation.

According to Erdinc et al., the control of power system's voltage can be organized into three levels. "Primary voltage is local automatic control that maintains the appropriate voltage level at every bus. This task can be performed by the automatic voltage regulators of the generating units or by static devices such as static voltage compensators. Then, a rare level of voltage control is the centralized secondary voltage control that regulates the local reactive power injections. Finally, the manually tertiary voltage control re-establishes the reactive power flow through the power system".

1.3. Challenges and opportunities for insular power systems under high RES penetration

Modern approaches are required in order to deal with the economic and environmental issues that have briefly been analysed in the previous section and new policies should guarantee a sustainable growth in insular regions. The increase of renewable share in the energy production mix is certainly one of the leading solutions to partly overcome the supply, environmental and political pressures on the insular environment.

Many islands around the world have a good RES potential [7]. Wind resource is the most important available resource for many insular areas, followed by solar energy for island located at a proper latitude. Besides, hydro, biomass (also bio-fuels for transportation), geothermal, oceanic energy (wave or tidal) also have found application areas in specific islands. However, the major concern for small grid structures such as insular areas is established by intermittency and the unpredictability of renewable energy sources. One of the most common solution in order to deal with these issues is the attempt in integrating RES production with proper energy storage systems. In conclusion, the major challenge for insular energy systems, especially the ones in which an increasing RES penetration is taking place, is the stability of the grid in terms of frequency and voltage control, active and reactive power supply.

1.3.1. Smart islands electricity system prerequisites

According to Foikades et al., the prerequisites for the development of an intelligent energy region are the following:

- "The existence or the potential of developing the necessary energy distribution and storage infrastructure in terms of smart grids;

- The existence of advanced renewable energy sources (RES) applications as well as the required renewable energy potential for the diversification of the energy mix;

- The existence of indigenous energy sources and their contribution toward reducing the cost of energy; the potential of an energy system to be upgraded into a smart one greatly depends on the availability of indigenous energy sources;

- The existence of political obligations such as those imposed under European directives or other policy initiatives such as the Kyoto Protocol" [8].

The economic potential and the RES availability is essential to build the required infrastructure for developing a smart energy region. “This potential can be defined through financial vectors such as the country’s gross domestic product (GDP) and its economic growth rate. One more significant parameter that defines the potential of achieving smart energy systems is the political or other obligations, which commit the countries to the promotion of relevant policies” (Foikades et al.).

1.3.2. Generation side

Renewable energy sources are seen as a way of augmenting the self-sufficiency of insular power systems: they also compensate the negative economic and environmental effects of conventional energy source dependence (i.e. fossil fuels). Depending on the specific necessity and characteristics of each insular energy system, there are many local energy sources that can be used.

In the last decade the deployment of RES has been encouraged by many countries and organisations, following the increasing interest in reducing greenhouse gas emissions.

Wind Energy

A considerable amount of the islands located in remote locations are characterised by exploitable on-shore and especially off shore wind potential. “In fact, there are many examples of relevant investments in islands of different sizes across the globe. In the Greek island of Rhodes, approximately 6% of the energy production comes from the 11.7 MW installed wind power. The biggest Greek island, Crete, has an installed wind capacity of 105 MW which accounts for 12.5% of the total capacity and the twelve wind farms may instantaneously provide up to 39% of the total generated power. However, the total licensed capacity exceeds 200 MW” [12]. “In 1998 Samso Island was chosen by the Danish Government as a demonstration of a 100% RES electricity production island. As an evidence of this successful effort, Samso Island currently has 23MW of offshore wind power generation and 11 MW of onshore wind power generation while all its demand needs are produced by RES. The Spanish El Hierro Island is also subject to an ambitious target of becoming a 100% renewable energy island and currently wind power penetration reaches 30%” [13]. “The South Korean Jeju Island is also an example of high wind power generation penetration. There is the goal of installing 250 MW of wind power and in 2010 88 MW of wind power generation was already installed” [2].

While planning to utilize wind energy to produce electricity it is fundamental to deal with the fact that wind energy is intermittent and variable, especially in insular and isolated environments. “Intermittency is referred to the unavailability of wind for a considerably long period while volatility describes the smaller, hourly oscillations of wind velocity” (Erdinc et al.). The absence of planning and control over the wind energy production, may cause serious issues frequency and voltage of the electricity grid.

Ocean Energy

Compared with wind and solar energy, the ocean energy is characterized by less volatility and better predictability; nevertheless the existing ocean energy utilization is still in the early development and demonstration stages.

"Wave energy is consistently more reliable than solar and wind power because of its energy density (typically 2–3 kW/m^2 compared to 0.4–0.6 kW/m^2 of wind and 0.1–0.2 kW/m^2 of solar potential). In addition, wave energy is characterised by several advantages with respect to other RES. First of all, waves are able to travel long distances without losing much of their energy and as a result wave energy converters can generate up to 90% of time compared to 20–30% for wind and solar converters. This fact renders wave energy a credible and reliable energy source" [2].

Regarding this work's aim, certainly the utilization of wave energy and ocean thermal energy conversion (OTEC) devices has received more attention in insular environments. "There are some demonstration projects to utilize ocean energy for electricity supply, such as a 10 MW OTEC power plant in Reunion, a 1.5 MW wave energy system in Micronesia, and a seawater air conditioning project under construction in Oahu Island" [14]. With the development of energy conversion technologies, ocean power generation will have a promising and attractive prospect in the future.

Furthermore, there are also specific advantages that make it an appealing choice for the electrification of insular power systems. Firstly, the resource is available in multiple locations (from shoreline to deep waters). Secondly, the correlation of demand and resource (distance between generation and load) is higher in islands. Finally, this type of renewable resource has lower environmental impacts than other alternatives. This is particularly relevant for islands with limited space, especially for islands the economy of which relies on tourism.

The main challenge towards the large-scale integration of wave energy is the infant phase of technologies. To provide high quality power to the grid, frequency and voltage have to be of appropriate levels. Together with the fact that the wave power is uncertain, special storage systems are needed to support the output of such plants.

Electricity Energy Storage Systems

Electricity Energy Storage (EES) is chiefly considered as the leading technology to overcome technical problems intrinsically linked to the massive renewable production. EES technologies show the potential of solving many issues concerning the renewables integration issue, as well as most of grid support services carried out by conventional generation. EES technologies vary in design, cost and technological maturity, thus it is inappropriate to state which is the best EES technology but there are many and each with its own worthy characteristics: there are differences in energy and power capabilities. The purpose of storage applications can be categorised based on the nature and duration of events that take place in the grid. Fast storage units that offer short duration (seconds, minutes) storage option can be used for power quality sustaining including frequency regulation, etc. while middle duration (hours) storage systems can be used for load levelling, peak shaving, etc. actions for load pattern reshaping. On the other hand, storage units offering long duration (days) of storage are generally used for providing autonomy to the system also by levelling output of intermittent RES with a considerable penetration within the relevant grid structure.

As discussed in the previous sections, the main concern in an insular energy system is related to power balance mismatches, as well as frequency and voltage issues. The role of energy storage systems in insular power grids is progressively gaining more importance especially since RES investments have become more important towards reducing dependence on imported fuels to ensure sustainable growth of insular areas. Since RES are highly dependent on the conditions of nature, the energy produced by these resources can significantly vary monthly, daily, or even instantly. This leads to the fact the produced energy may not exactly match with the energy demand. In order to meet the current load demand in every condition, energy storage units offer a cost-effective solution show great potential. Additionally, the surplus energy can be stored in high generation periods, where it can be released when the output of the generator drops due to a fall in wind speed or caused by the passage of clouds. When RESs generate electricity in excess, is transferred to energy storage units, and this stored energy is used to supply the load demand when the main sources are non-existent or are not sufficient. "Besides, the rapid unavailability of RES units especially during high RES penetration may in any case force the conventional units to reduce their power ratings below an allowable lower limit. Here, storage systems can effectively be employed to meet this discrepancy in production and consumption to ensure safe operation of main power units. This issue is especially significant for small systems like insular areas where the number of available generators is tightly limited that offers nearly zero flexibility. Energy storage units with different characteristics come into action at this point to add different levels of flexibility in required points of the low inertia insular power system" (Erdinc et al.).

Power quality issues can be attenuate with the bi-directional power flow characteristics of EES devices. This property has the possibility to boost the integration of renewables. It could also permit the peak shifting, by storing energy during high generation periods and discharging it during peak load periods. “It becomes clear that there is a growing consensus among insular system operators regarding the potential benefits of transferring such services to EES systems. Certainly it would only make sense if the EES system meets the energy and power requirements, which are determined by the type of application, charge/discharge frequency and discharge time duration” (Rodrigues et al.).

Regardless of all potential positive benefits discussed, EES still obliges to careful analysis on the costs and benefits issues. The introduction of EES as a grid code requirement should be done in order to give freedom of choice to the power plant owners or the grid operator as regards to the technology that matches the desired application [11].

At the present time, EES technologies display some drawbacks such as limited life-cycle and being too expensive on a level needed for helping large-scale penetration of solar and wind power. Consequently, in the upcoming years high costs will prevent the adoption of EES as a requirement for insular grid codes.

Hydrogen Energy Storage

Hydrogen Energy Storage (HES) deserves a particular mention. Hydrogen as an energy storage medium can increase the penetration of renewable energy sources in the energy mix of the islands weak electricity grids.

“Compared with CAES, super-capacitors energy storage, and flywheel energy storage, the HES with high energy density can respond rapidly to balance power supply and demand, improve frequency quality, and smooth the power output of renewable energy” (Krajačić et al.). HES has some interesting characteristics, and the production, storage and usage of hydrogen are mutually independent [15]. In case of lack of a proper energy storage system, typically in small islands, only a low share of power output from RES sources (especially from wind turbines) can be utilized. Through the hydrogen storage technique, the utilization rate of wind power can be improved up to 100% [16]. As an example, an isolated power system with HES has been designed and implemented in Milos Island, in Aegean Sea, and further comparative analysis indicates that the system can increase the penetration level of renewable energy from 0.13 to 0.85, thus reducing 50% of fossil fuel consumption and electricity costs [17].

Furthermore, possibility for using hydrogen as an energy vector (intended as a way to allow to make energy available for use at a distance of time and space from the source) in the islands’ energy supply is not a modern idea. Hydrogen, as an energy vector, has been applied to the islands of Mljet-Croatia, Porto Santo-Madeira, Terceira-Azores, and Malta [15].

Electric Vehicles

Also, a new type of load that can act as a means of energy storage integration, namely the Electric Vehicle (EV), is considered a factor of flexibility in power systems, especially in insular or isolated ones.

Electric drive technology exists for more than a century but it was not a viable transport option due to limited range and production costs when compared with the internal combustion engine technology. Only recently with battery technology development, radical innovation in electric vehicles caused profound changes in the way automakers develop their products and electric cars came into scene again.

A small insular environment is perfectly suited for EV use because the majority of daily trips are expected to be less than 100 km, so the range limitation problem almost does not exists in small islands.

EVs could provide a good opportunity to reduce CO_2 emissions from transport activities if the electricity used in providing the load EVs is produced by renewable sources.

Many studies have been done to evaluate the potential social, environmental and economic impacts of electric vehicles (EV) and plug-in hybrid electric vehicles (PHEV) in many OECD (Organization for Economic Co-operation and Development) countries. The Samsoe Island (Denmark) case study is very interesting as the island is characterised by a 100% renewable electricity production and so the EV could be considered a well-to-wheels zero emissions vehicle reducing fossil fuel use and imports in the island [18].

In recent years an interest in V2G (Vehicle-to-Grid) technology has increased, several studies have studied that by adding vehicle to grid capability where the vehicle can discharge as well as charge, an additional potential storage capacity can be added to the network offering regulation and peak power control services with possible revenues for vehicles owners.

One of the main advantages that could derive from a massive penetration of EVs is that they could be charged during off-peak hours and thus they are able to augment overnight electricity demand so that more renewable energy sources can be installed in the power system, together with the greenhouse gases emission reduction.

1.4. Operation and system planning aspects

As discussed in previous sections, the most widely spread RES technologies such as wind and solar are intrinsically characterised by variability due to their volatile nature, in the integration process of such large shares of non-dispatchable resources in small sized energy systems is necessary to deal with operational and economic issues. “The magnitude of the problem depends on the specific grade of penetration of the specific RES technology in the specific electricity generation mix, while its mitigation is reflected on the “flexibility” of the power system” (Erdinc et al.).

Instantaneous, seasonal and yearly fluctuations of solar irradiation and wind speed values strongly affect the generation output. Fluctuating RES production influences also the normal operation of traditional fossil fuels based generators [19]. Under high penetration conventional units are likely to operate in inefficient conditions. Fluctuation of RES output power leads to cycling of conventional units and shortens the life of their turbines, while causing increased generation costs.

The accurate modelling of uncertainty factors using advanced forecasting and scenario generation techniques is an indispensable tool in the decision-making process for in insular power systems. Precise forecasting may improve the results of power plants effort and reduce as much as possible the operational costs. Besides, sophisticated scheduling tools can be used in order to take into account uncertainty variables at different time steps.

For instance, HOMER (Hybrid Optimization Model for Electric Renewables) software is a powerful appliance, developed by National Renewable Energy Laboratory (NREL), for designing, sizing and planning of hybrid renewable energy system in order to determine optimal size of its components through carrying out the techno-economic analysis. Many resources such as wind turbines, PV panels, fuel cells, small hydropower, biomass, converter, batteries, and conventional generators are modelled in HOMER. It works based on the model inputs, which are used to simulate different configurations and combinations of components and generate results that will list the feasible configurations. This allows for comparisons to be made and the best option to be decided upon. HOMER can also be used to identify which factors have the greatest impact on the design and operation of the power system [20].

Another viable and cost effective solution in order to increase the flexibility of insular energy systems consists in demand-side management. A more flexible power system can allow a more efficient utilization of the RES production while an inflexible one may show curtailments in renewable generation in order to maintain the generation-demand balance (or to bypass overloaded transmission lines). Therefore, the more the system is flexible, the more is able to exploit the environmental and economic potential of RES production.

In conclusion, according to Catalão, when planning the integration of RES in insular power systems, system operators should consider the following aspects [9]:

- “RES based power plants may reduce or increase the transmission line capacity requirements (and subsequently active power losses) according to their location and their distance from the load;
- Voltage quality may be improved because of the capability of several RES technologies (such as doubly-fed induction generators (DFIG) wind turbines) to control their reactive power. As a result, connecting RES to weak parts of a power system may contribute to the voltage stability of the system;
- The RES installations should be as much geographically dispersed as possible in order to avoid further requirements in transmission capacity;
- Demand of loads that contribute to peaks (such as air-conditioning) may be correlated with the peak production of several RES (such as solar energy). This is a fact that should be recognized during the sizing and connection procedure”.

1.5. Reliability

The intrinsic structure of insular power systems together with the increasing penetration of RES result in issues regarding the reliability of the networks. “As mentioned before, insular power grids are characterised by very low system inertia and hence, are highly sensitive to frequency deviations” (Erdinc et al.). Another big issue that is caused by increasing RES share within the typical insular power system is represented by the technical impossibility of traditional generators to reduce their output when non-dispatchable RES production is high. Typically, diesel-fired generators have a minimum output limit of 30% of their installed capacity. Forcing a load-following unit to shut-down in order to retain the generation and demand balance may compromise the longer-term reliability of the power system. In order to avoid such deficit in system's inertia, RES generation is normally curtailed in order to avoid switching off synchronous generators at the expense of economic losses [9].

In addition, also voltage stability can be affected by penetration of RES into insular energy systems. This can happen because power sources such as “fixed-speed induction wind turbines and PV converters have limited reactive power control. Apart from frequency regulation, load-forecasting error, sudden changes (ramps) in the production of RES units, equipment forced or scheduled outages need also to be confronted” (Erdinc et al.). To deal with these issues adequate generation or demand-side capacity should be kept. According to Erding et al., in order to improve frequency and voltage stability several measures can be taken:

- “The reduced inertia in isolated power systems with inverter interfaced RES can be replenished by energy storage that keeps the power balance. Grid code changes have been proposed and many different applications of energy storage systems in island systems already exist;
- Demand-side management resources can be used in order to provide frequency stabilization reserves. Either there can be continuous control if the load is supplied by power electronics based power supply, or the loads can be switched on and off for specific periods of time;
- A relatively new concept that may prove indispensable is the inertial-control of wind turbines. “Virtual” wind inertia is created through utilizing the kinetic energy stored in the rotating mass of wind turbines in order to respond to frequency drops. Variable speed wind turbines may accept wide speed variations and as a result the inertial response of wind turbines is greater (more kinetic energy can be transformed to electrical energy) than of the regular synchronous generators given the same inertia value. Power control of wind farms with respect to frequency can complement the frequency control schemes of the insular power system;
- Solar and wind power plants have the ability of controlling their reactive power. Doubly-fed induction generator (DFIG) and permanent magnet (PM) synchronous generators are capable of injecting or consuming reactive power. Power electronics that interface solar power plants have the same ability. Therefore, regulating voltage at the common connection point is possible. Connecting wind-farms and solar power plants to weak network points can thus improve the overall stability of the system” [2].

Conclusively, several recent studies denote that a degree of penetration of RES not higher than 40% does not seem to have strong effects on transient stability [9]. Besides, given a specific insular network one could suggest a maximum penetration limit for RES in order to avoid affecting transient stability.

2. Orkney Islands background

2.1. Orkney Islands geophysical information

Orkney is an archipelago in the Northern Isles of Scotland, situated 16 kilometres north of the northeast coast of Great Britain. Orkney lies between 58°41’ and 59°24’ North, and 2°22’ and 3°26’ West, measuring 80 kilometres from northeast to southwest and 47 kilometres from east to west, and covers 975 square kilometres [21]. Orkney comprises approximately 70 islands, of which 20 are inhabited [22]. According to National Records of Scotland, Orkney has a population of 21,314 and a population density of 21 persons per square kilometre [23].

The largest island, Mainland has an area are kilometres, making it the sixth-largest Scottish island and the tenth-largest island in the British isles. Both of Orkney’s burghs, Kirkwall and Stromness are on this island, which is also the heart of Orkney’s transportation system, with ferry and air connection to the other islands and to the outside world. Seventy-five per cent of Orkney population live on Mainland, which is more densely populated than the other islands of the archipelago. Mainland population was recorded in 2011 as 17,162 an increase of just over 12% on the 2001 population of 15,315 [22]. The Mainland is split into areas called East and West Mainland. These areas are determined by whether they lie East or West of Kirkwall. The bulk of the mainland lies West of Kirkwall, with comparatively little land lying East of Kirkwall.

The two main settlements on Orkney, both located on Mainland, in order of magnitude are Kirkwall and Stromness. Kirkwall, with approximately 10,000 inhabitants is the capital of the islands. Kirkwall is located on the isthmus between west Mainland and east Mainland, which historically enabled it to have highly active harbours facing in two directions for the southern and the northern Orkney islands. Kirkwall is a port with ferry services to Aberdeen and Lerwick, as well as the principal north islands in the group.

After expensive work on harbour facilities, the town has become a popular cruise ship stop, with several ships arriving each week in the season. This has added to the prosperity of the town and allowed a thriving sector of independently owned shops. Each year now, 140 cruise ships visit Kirkwall and Stromness [24].

Mainland contains the vast majority of the island’s roads, and is also connected to those on the main southeast islands.

Orkney has a cool temperate climate that is remarkably mild and steady for such a northern latitude, due to the influence of Gulf Stream. The average temperature for year is 8°C; for winter 4°C and for summer 12°C. The average annual rainfall varies from 850 millimetres to 940 millimetres. Winds are a key feature of the climate and even in summer there are almost constant breezes. In winter, there are frequent strong winds, with an average of 52 hours of gales being recorded annually.

2.2. Orkney Islands economy

The soil of Orkney is generally very fertile and most of the land is taken by the farms, agriculture being by far the most important sector of the economy and providing employment for a quarter of the workforce.

Today, the traditional sectors of the economy export beef, cheese, whisky, beer, fish and other seafood. In recent years there has been growth in other areas including tourism, food and beverage manufacture, jewellery, knitwear, and other crafts production, construction and oil transportation through the Flotta oil terminal. Retailing accounts for 13% of total employment, and public services also play a significant role, employing a third of the islands' workforce [25].

2.3. Orkney energy audit

Since the early 2000s, there has been a significant shift in the way energy is sourced. There has been a large increase in power generated from renewables and from wind in particular, which has increased almost four fold since 2003 [26].

Concerning petroleum products, the total road fuel usage has stayed fairly constant since 1990: road diesel has seen a general increase in use whereas petrol has continually decreased in demand year on year. Not general trends are apparent for red diesel and kerosene consumption.

Petrol and diesel usage (GWh)	Red diesel (GWh)	Kerosene (GWh)
104.37	113.43	84.44

Table 1: petroleum products usage (2012). Source: OREF

Regarding solid fuels, the general national trend of falling coal consumption has also been seen in Orkney over the past two decades. However, coke continues to be used at the Highland Park distillery as part of the whisky manufacturing process. 2013 coal usage was about 7.67 GWh. Also for peat the main demand comes from Highland Park distillery which approximately uses 1.43 GWh per year.

It is generally acknowledged that Orkney's natural environment offers significant potential for the generation of electricity from renewable sources, particularly wind, wave and tidal stream. In recognising Orkney's potential, a significant new industry has begun to emerge within the county.

2.4. Orkney's energy resources

At first sight, it may seem exceptional that a very small group of islands represents the forefront of renewable energy development and implementation in the UK. Situated between the Atlantic and the North Sea, some of the most energy-rich waters in Europe find home in the sea surrounding the archipelago, as well as some of the strongest winds. These factors are even emphasized by a community that have embraced the 'green' potential of the islands eagerly.

Orkney's extraordinary wave and tidal resources made it an obvious site for EMEC, the European Marine Energy Centre, where new wave and tidal energy converter technologies are tested in challenging wave and tidal conditions. EMEC has put Orkney at the very cutting edge of marine energy technology worldwide, with an incredible record of more grid-connected ocean energy devices tested in Orkney than at any other single site in the world [27].

The first time new renewable technology has been pioneered in Orkney dates back to 1950s, with the very first test of a grid connected wind turbine in the archipelago. Nowadays, Orkney is home to circa 500 domestic turbines, more than any other county in the UK, together with many larger scale wind farms and several wind turbines owned by the community. One in twelve Orcadian households is generating electricity from renewable sources: Orkney has the highest proportion of households making their own electricity of anywhere in the UK [27]. Orkney can thus be considered as an avant-garde of a decentralised energy system that is still just being talked about in the rest of the UK.

2.5. Orkney Islands electricity System

Orkney electricity system serves approximately 11,500 customers. The only connection with mainland Scotland consists in two 33 kV subsea cables installed respectively in 1982 and 1998 respectively between Rackwick Bay on Hoy, and Murkle Bay near Thurso. These cables have a total capacity of 40 MW and the current connected embedded generation in Orkney exceeds all the available export capacity in the existing 33 kV cables and no further generation can connect to the system at this time. The existing network is a distribution network operating at 33 kV or below. Demand on the Islands varies between 7 MW in the summer and 46 MW[1] in the winter, and is

[1] Although, according to SHEPD, winter peak demand in 2017-2018 has been 35.7 MW.

secured in the event of a network fault with the assistance of a stand-by generator installed in Kirkwall.

Figure 1 displays the demand trend compared with the constrained generation[2] trend for December, the month with the lowest number of sunshine hours and one of the coldest, together with January and February. Demand fluctuates between 28 MW and 12 MW, while constrained generation peak is slightly higher than 35 MW.

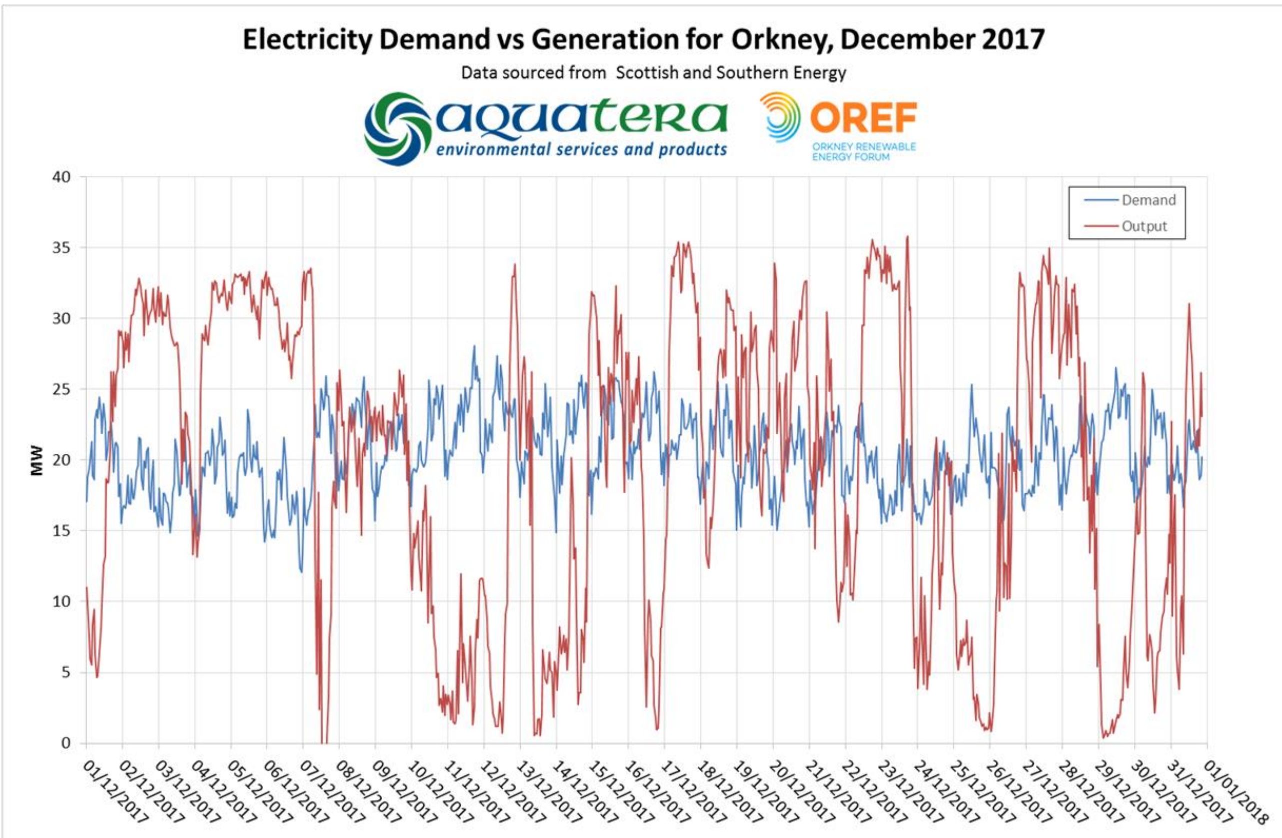

Figure 1: Electricity demand vs constrained generation in Orkney, December 2017. Source: aquatera, OREF

According to National Records of Scotland, electric central heating was the most common type (41% of the households), due to the absence of main gas supply [28]. Therefore, winter period can be identified as the most electricity requiring.

There is no additional capacity in the existing network and consequently any increase in the connected generation on Orkney will require a reinforcement of the existing network [29].

According to Scottish and Southern Energy Power Distribution (SSPED), in 2014 Orkney average summer demand was 6 MVA, average winter demand was 34 MVA. Total connected generation capacity was equal to 74.4 MW (57.10 MW of which renewable) [30], excluding the 15.5 MW of

[2] Wind curtailed electricity has not been included in the graph

emergency standby Diesel generator.

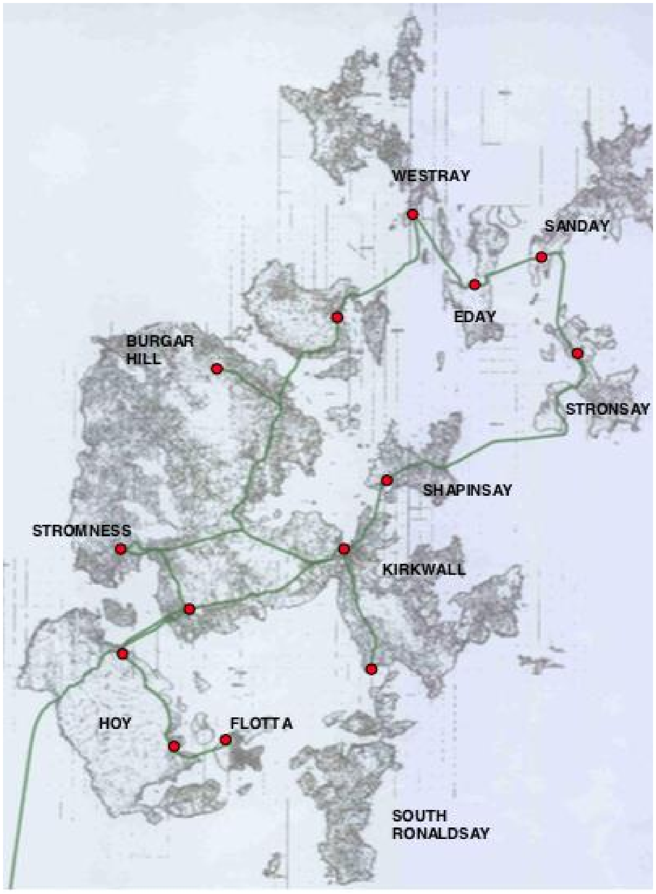

Figure 2: Orkney electricity grid. Source: Scottish and Southern Energy Power Distribution

In 2003-04 the electrical power required to meet local demand was sourced from mainland Scotland via the subsea cables, the Flotta gas turbine, the Kirkwall Power Station and also a small amount from renewable sources.

Table 2 below shows how the amount of energy imported via subsea cables experienced a peak in the early 2000's in the period when both subsea cables were in operation. The Kirkwall Power Station was only used for standby purposes and before substantial renewable generation took off.

year	1990	1995	2002-03	2009	2010	2011	2012	2013	2014
Export (GWh)	unknown	unknown	unknown	7	10	24	17	45	48
Import (GWh)	91	73	102	55	70	46	54	44	37

Table 2: import & export of electricity via subsea cables. Source: OREF [26]

The current generation mix is strongly dominated by wind energy, with small contributes from wave and tidal power and gas. More recently, as renewable generation has grown, imports via the subsea cables have decreased to a point where in both 2013 and 2014 Orkney became a net exporter of electricity. However, the cables remain a vital link to mainland Scotland in meeting demand when there is insufficient wind and exporting power to the mainland.

In 2013, Orkney total electricity demand was produced through RES, increasing this figure to 104% in 2014 [27]. Nonetheless, the local grid infrastructure has not kept up with this growth in generation, and the lack of definite future connection opportunities is hindering the growth of renewable energy within the county.

At present, the current level of contracted generation between National Grid (the system operator) and developers is for a minimum of 180MW of new generation by 2022.

To connect this level of generation, a transmission connection is needed between Orkney and the Scottish Mainland.

2.6. On-going projects in Orkney

As a response to the limitations of insufficient grid capacity, Orkney is currently also home to various innovative schemes.

2.6.1. Active Network Management

In the early 2000s, network operator Scottish and Southern Energy Power Distribution (SSEPD) teamed up with the University of Strathclyde, because of the higher cost of traditional grid reinforcement, decided to design another solution to Orkney's grid capacity constraints. Work on the 'smart grid' idea began in 2004 and the stakeholders developed an innovative new Active Network Management (ANM) approach to make better use of the current network by controlling generator output, in real time, to match the available network capacity.

After 5 years, in 2009, the UK's first 'smart grid' project was deployed in Orkney and started work at full operation. The smart grid uses an Active Network Management (ANM) approach to better utilise the existing network, giving coded guidelines to generators in order to control their output, in real time, to match the available network capacity, optimizing power flows. The smart grid has permitted the same amount of renewable generation to be connected to Orkney's electricity distribution network as would have been made possible by conventional network reinforcement with mainland Scotland [31]. ANM is therefore a mean to bypass the insular status of Orkney islands and the limitation imposed by the low network capacity, compared with the renewable production potential.

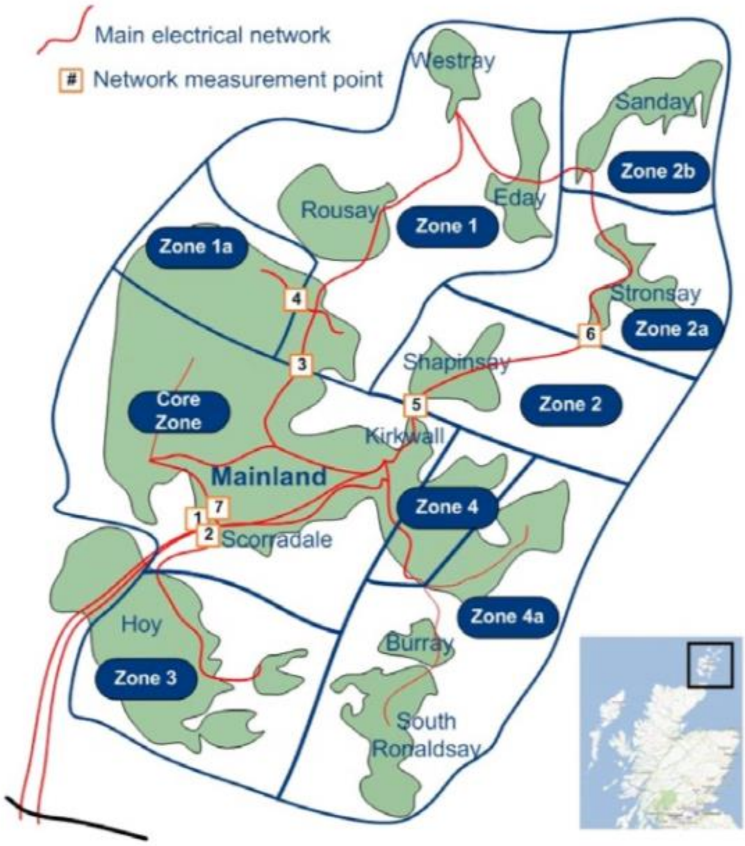

Figure 3: Active Network Management operation scheme. Source: SSEPD

"In detail, the ANM system allowed the connection of an additional 20 wind power generators with a combined maximum output of 24.2 MW. The Orkney Isles now have over 72 MW of distributed generation connected in addition to a further 5 MW of micro-generation. With over 77 MW of grid-connected generation, the Orkney Isles became a net exporter of electricity in 2013 with 103% of demand met by renewable generation. Of this, over 40% was managed by the ANM system, delivering over £ 4 millions of benefit to the local economy" [32].

After its success on Orkney, other isolated communities characterised by grid constrained energy systems, such as Shetlands, Outer Hebrides and the Isle of Wight are investing effort and resources in order to replicate this pioneering ANM system.

2.6.2. Storage battery

Additionally, in 2013 a 2 MW battery was installed in Kirkwall as forefront study about how large-capacity batteries could play an important role in fixing the issue of RES volatility and in general, the resolution of frequency and power stability problems. The 2 MW lithium ion battery, was installed by Scottish Hydro Electric Power Distribution (SHEPD) at Kirkwall Power Station, and connected it to Orkney's electricity distribution network [32]. The same model of the battery deployed, provided by Mitsubishi, has already been tested for two years in Japan. The battery should facilitate to smooth out intermittent power generation from renewable sources by allowing the operator to store clean energy and release it when required. The installation of the battery has not yet given an immediate solution to grid constraints issues on the Orkney distribution grid: however it is believed that the outcomes of the study will help show that batteries could provide a cost effective solution of releasing capacity on the network.

Other options for energy storage or large-scale increase in demand are under study to bypass grid constraints. As it will be discussed later, EVs' deployment can offer a serious, advantageous and feasible solution. Today Orkney has a record of nearly 4 times the national average of electric vehicles per capita.

2.6.3. Surf 'n' Turf

The Surf 'n' Turf initiative was the first on its kind in Europe. Surf 'n' Turf attracted £1.46 millions of support from Local Energy Scotland and the Scottish Government's Local Energy Challenge Fund. The project is led and managed by Community Energy Scotland, alongside partners EMEC, Orkney Island Council, Eday Renewable Energy and ITM Power [33]. Surf 'n' Turf project has been officially launched on September 29th 2017.

The project has been involved in the initial investment in the infrastructure required in developing a hydrogen economy in Orkney and aims to establish whether it is replicable in other locations around the world. The central idea behind Surf 'n' Turf project is gather together renewable energy from tidal energy converter and the curtailed wind energy generated in Eday to produce hydrogen on Eday itself [34]. In practise, surplus electricity coming from tidal power devices located at the European Marine Energy Centre test site at the Fall of Warness, in the sea just west of the island of Eday, and from the Eday Renewable Energy community-owned onshore wind turbine, is used to feed a 0.5 MW electrolyser, provided by ITM energy which generates hydrogen by splitting water.

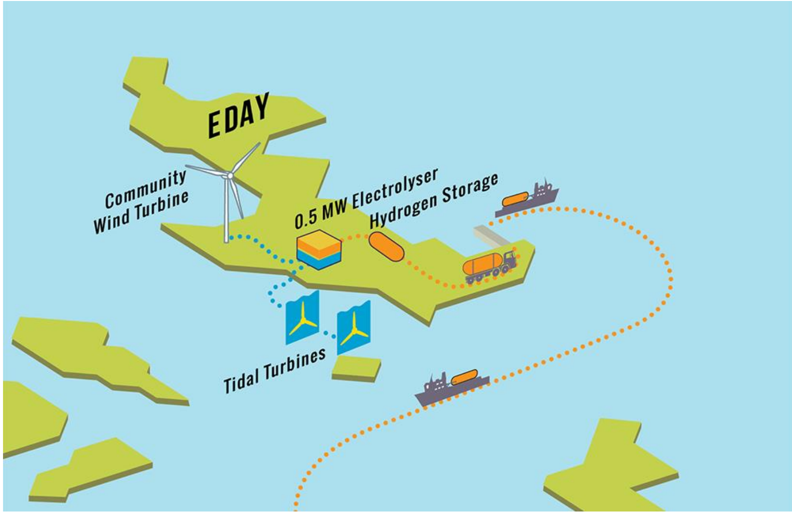

Figure 4: Surf 'n' Turf operation scheme. Source: surfnturf.org.uk

The hydrogen is stored as compressed gas then transported on a trailer by road and sea to Kirkwall. There it powers a fuel cell to generate clean electricity when required by network needs.

The next fundamental phase of this pioneering project consists in establishing proper end uses for the hydrogen produced in creating a healthy hydrogen economy on Orkney. The encouraging results of Surf ’n’ Turf project opened the way for additional funding for analysing more in depth hydrogen feasibility plans to continue in Orkney by means of BIG HIT project.

2.6.4. BIG HIT

BIG HIT (Building Innovative Green Hydrogen systems in an Isolated Territory), based on foundations left by the Orkney Surf ‘n’ Turf project, plans the hydrogen production on the islands of Eday and Shapinsay using wind and tidal energy. In a similar way of Surf’n’ Turf initiative, renewable electricity generated in these islands is used by electrolysers to produce hydrogen by electrolysis of water. This hydrogen is then stored as high pressure gas in tube trailers, which can be transported to mainland Orkney.

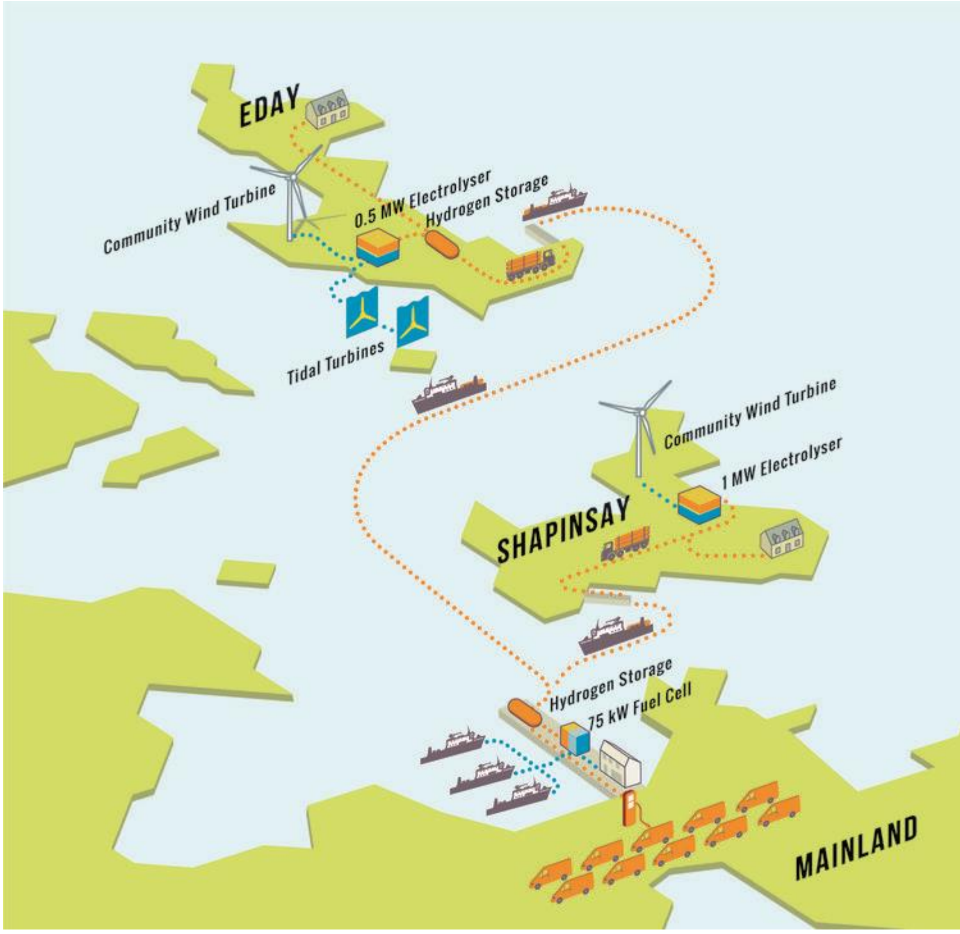

Figure 5: BIG HIT project scheme. Source: bighit.eu

"BIG HIT uses two state-of-the-art proton exchange membrane (PEM) electrolysers. The Shapinsay electrolyser is 1 MW and Eday electrolysers is 0.5 MW capacity" [35], both located close to the renewable generation assets. The innovation point of BIG HIT lays in the final use foreseen for the produced hydrogen: it acts as an energy-storage medium, which can later be converted back into heat and power for buildings and ships in Kirkwall harbour, as well as the fuel for the operation of zero-emission hydrogen vehicles in and around Kirkwall.

2.6.5. Electricity network reinforcement proposals

In February 2014, Scottish and Southern Energy Power Distribution (SSEPD) undertook a stakeholder consultation to hear what stakeholders views were on the next steps for electricity network reinforcement in Orkney [29].

The Consultation presented three development options, these were:

- *"Option 1- Transmission[3] reinforcement"*: "Scottish Hydro Electric Transmission (SHE Transmission) has developed proposals for a 220 kV AC 180 MW subsea cable connection

[3] Transmission lines work at higher voltage and can transport more electricity than distribution lines

between Dounreay and Bay of Skaill; new substations at Bay of Skaill Finstown, Crook and Newark Bay; and interconnecting 132kV circuits incorporating a mix of overhead line and underground / subsea cable. This option has been developed to meet the needs of the contracted marine generation".

- *"Option 2– Distribution reinforcement": "*the Consultation included an indicative cost for distribution reinforcement – circa £30m for a single 30MW 33kV subsea connection – and recognised the volume of contracted generation exceeded the capability of a single reinforcement".
- *"Option 3- Making best use of the existing network*": "if, for whatever reason, network reinforcement is not possible at this time consideration should be given to how best to use the existing network. SSEPD is already seeking ways of amending the ANM to help address these issues, however, it would require agreement from all currently connected parties".

Whilst the majority of respondents felt that transmission reinforcement was the best solution, a number of responders indicated that they wanted a two-phase approach, with a distribution solution first followed by a transmission connection at a future date. However it was also recognised that distribution reinforcement was unlikely to provide sufficient capacity and would likely be uneconomic for developers.

In the latest years, generation has continued to seek connection in Orkney and at present there are five contracted connection agreement between National Grid and developers totalling 181 MW of new generation on Orkney- split 80% of onshore wind and 20% of marine.
Consequently transmission network development and reinforcement will be needed to accommodate this volume of new installed generation.

In February/ March 2017, Scottish and Southern Electricity Networks (SSEN) held a round of public consultation events to seek early feedback from the local community and other stakeholders on a number of options for the transmission reinforcement.

SHE Transmission is developing proposals to provide a transmission connection from the Scottish mainland to Orkney and to develop transmission infrastructure on Orkney including new 132kV overhead lines, subsea cables and a number of new substations. It is intended that a single 220kV AC cable would be installed to connect the Orkney Islands with the Caithness county. The initial assessment considered the Caithness transmission network for the connection of generation from Orkney. A number of potential subsea cable landfall areas in Orkney and Caithness were identified, as well as marine corridors which could potentially accommodate a subsea cable link between

Orkney and Caithness.

The Orkney to Caithness connection options produced by the above exercise were ranked using a multi criteria assessment methodology and the most favourable were used to further develop options for the infrastructure development on Orkney.

An additional evaluation of the remaining options was carried out using relevant criteria including technical challenge of installation, environmental impact, cost and consenting risks as well as potential impact on designated areas and features.

The existing substation at Dounreay, and the planned new substation at Gills Bay, have both been identified as possible connection points between Orkney and the national electricity transmission system.

As a result of the option selection process, three options have been identified as being potentially suitable for transmission network development to accommodate new generation schemes in and around Orkney. There are a number of key differences with the options presented, although the same configuration of substation locations and developer connections is included in each option.

In November 2017 SSEN has published its proposed subsea and land cable route, as well as its proposed substation location.

SSEN’s proposal would see a new indoor substation located at Finstown with an underground cable installed to connect this to Warebeth/Billia Croo to the west of Stromness on the Orkney mainland. This would then connect to a subsea cable, connecting to Dounreay in Caithness, allowing electricity from Orkney to be transmitted to areas of demand across the main GB transmission system [36].

The new link would provide an additional 180MW of capacity. The main elements of the projects are as follows [37]:

- A new substation at Finstown;
- An underground cable linking Finstown substation to a cable landing site west of Stromness;
- A marine cable linking Mainland Orkney and Caithness;
- A new cable route between the Dounreay marine cable landing point and the new substation at Dounreay;
- Construction of a new substation at Dounreay.

The project construction commence is planned for 2020.

3. Modelling part

3.1. Project purpose

Since renewable installed generation in Orkney Islands have growth in the last years, electricity imports via the subsea cables have decreased to a point where in both 2013 and 2014 Orkney was a net exporter of electricity. Furthermore, since the only connection with the mainland grid only consists in two 33kV subsea cables it is not so rare that over the year situations in which combination with two event such as the extremely high power generation from the wind turbines and lower electricity demand occur simultaneously: in such circumstance the subsea cables are not able to export the whole amount of electricity in excess and the only solution are curtailments experienced by the wind turbines.

This work aims to explore possible solutions in order to avoid these curtailments and examine their feasibility, starting from the 2013 wind power generation and electricity demand databases for Orkney. More in detail, this dissertation will try to prove that is theoretically feasible, from the energy balances point of view, to develop a completely carbon-free passenger transport system in Orkney, considering private body-type car and bus public transport.

The realisation of this project, besides following the same pathway of Sustainable Orkney Energy Strategy for 2017-2025, could lead to important results from environmental point of view, such as achievement of ambitious carbon reduction targets and reduction of fuel poverty. Furthermore, this project would contribute to positioning Orkney as a globally recognised region for developing original and innovative solutions for the world's energy system challenges.

Electric vehicles and hydrogen (both as an energy storage vector and as a road fuel) are great opportunities for achieving a low carbon transport and heat. The model hereby proposed is indeed extreme and in a certain way utopian, but electric vehicles have a higher rate of adoption in Orkney that other parts of UK. Further development and potential integration with local Smart Grid present opportunities for a more integrated energy system approach. Moreover, smart transport options link innovation with efficiency. This also leads to reduce carbon emissions by supporting use of carbon-free public transport (FCEV buses) and low carbon technologies (EVs) [38].

Therefore, the intent is to build a model that uses wind curtailed electricity:

- Directly, for electric vehicles charging purposes;

- Indirectly, for hydrogen production purposes: produced hydrogen will feed Fuel Cell buses.

3.2. Modelling preparation

3.2.1. My Electric Avenue data analysis

My Electric Avenue was a pioneering three-year Ofgem[4]-funded project (2012-2015) that has been carrying out trials to discover the impact that charging clusters of electric vehicles (EVs) might have on local electricity network at peaks time. It undertook trials with over 200 customers.
My Electric Avenue has been hosted by Scottish and Southern Energy Power Distribution and lead by EA Technology [39]. It has been funded through Ofgem's Low Carbon Network Fund, with in-kind contribution from key partners. The project has analysed the various kinds of low voltage networks in the UK and four types are expected to experience issue due to the uptake of EVs at different penetration levels.

By recruiting clusters of neighbours around United Kingdom who drove Nissan LEAF electric cars for 18 months, the project teams aimed to mimic a future scenario where many people in an area choose to use a pure electric vehicle or a plug-in hybrid electric vehicle (PHEV). The project analysed the data about people's charging habits and the impact on the local electricity networks [39].

Whilst there's plenty of capacity to deliver power for EV charging across the UK, if the charging requirements are concentrated in a small area and during peak demand, local feeders can become overloaded. Therefore, clusters of EVs have been "created". To encourage customer participation, neighbours were offered a "group" deal, where they were given a very low rental price for an EV for 18 months, if they all signed up. In return, participants allowed they EV chargers to be controlled and their EV data to be collected, and they provided feedback of their experience. Recorded data includes the times of day they charge their EV, and how far they drive between charging. Experience has been captured using surveys [40].

Since this project aims to study exclusively the feasibility of sustaining electric vehicles introduction with wind curtailed electricity rather than assess the impact of EVs deployment on Orkney electricity grid, MEA database has been used only to extract EVs belonging to Orkney cluster and study their performances over the trial period.

MEA project data include [41]:

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[4] Office of Gas and Electricity Markets

- My Electric Avenue participants: trial participants have been anonymised, and are identified by a 'Participant ID', this is used to link participants with collected data. The participants' geographic locations have been indicated using the first half of their postcode. This allowed to collect solely data regarding electric vehicles used in Orkney Islands.
- EVs driving data: the trial participants' driving behaviour was recorded using the EVs' telematic systems. The distance, times, power consumption and odometer reading for each EV journey is recorded.
- EVs charging data: the trial participants' charging behaviour was recorded using EVs' telematic systems. The system recorded times and state of charge (expressed as a number between 0 and 12) each time the EV was charged.

Additionally, other information, regarding grid-stability issues but not useful for our purpose, were recorded:

- feeder measurements: the demand on each phase of the LV feeders was monitored for each technical trial cluster using a monitor controller device.
- Intelligent Control Box measurements: each technical trial participant had an Intelligent Control Box (ICB) installed with their EV charger. This device was used to restrict EV charging and also to record measurements of voltage and current associated with the EV charger.
- Switching measurements: the monitor controller instructed ICBs to switch throughout the trials. A record of each change in switch state (from ON to OFF and vice-versa) is recorded in this data set.

From the MEA participants analysis, EV trials in Orkney result to be eight. As Table 3 shows, all EV trials in Orkney began in the first half of 2014 and ended in the second half of 2015.

Participant ID	EV lease beginning	EV lease end	Location
ST1001	19th Jan 2014	27th Aug 2015	KW17
ST1007	23rd Jan 2014	27th Aug 2015	KW17
ST1013	15th Jan 2014	12nd Aug 2015	KW17
ST1030	17th May 2014	27th Aug 2015	KW17
ST1042	27th Jun 2014	9th Nov 2015	KW16
ST1048	13th Feb 2014	24th Aug 2015	KW15
ST1060	21st Jul 2014	6th Nov 2015	KW17
ST1068	7th Aug 2014	29th Nov 2015	KW17

Table 3: MEA electric vehicles trials in Orkney

Table 4 displays the results of MEA project data elaboration: total distance traveled per EV and total power consumption per EV values allowed to calculated the average power consumption of electric vehicles in Orkney, expressed in Kwh/km.

participant ID	trial days number	trips number	tot distance traveled [km]	tot power consumption [kWh]	km per day	km per trip	power consumption [kWh/km]
ST1001	585	2468	25373,1	4190,8	43,4	10,3	0,1652
ST1007	581	1627	17940,8	3145,8	30,9	11,0	0,1753
ST1013	574	1406	21252,2	4259,6	37,0	15,1	0,2004
ST1030	467	1674	19133,9	2862,8	41,0	11,4	0,1496
ST1042	500	2273	32769,8	5505,1	65,5	14,4	0,1680
ST1048	557	2357	17792,8	3566,8	31,9	7,5	0,2005
ST1060	473	1826	20852,4	3614,9	44,1	11,4	0,1734
ST1068	479	2308	14378,5	2437,2	30,0	6,2	0,1695
average	527	1992	21186,7	3697,9	40,5	10,9	0,1752

Table 4: trial EVs in Orkney data elaboration

Table 5 below reports same Table 3 information normalised on a yearly basis.

Participant ID	power consumption [kWh/km]	trips number	tot distance [km]	tot power consumption [kWh]	Hourly charge progression	power consumption [kWh/km]
ST1001	0,1652	1539,9	15831,1	2614,7	8,44%	0,1652
ST1007	0,1753	1022,1	11270,9	1976,3	9,70%	0,1753
ST1013	0,2004	894,1	13514,0	2708,6	9,73%	0,2004
ST1030	0,1496	1308,4	14954,7	2237,5	19,51%	0,1496
ST1042	0,1680	1659,3	23922,0	4018,7	10,01%	0,1680
ST1048	0,2005	1544,5	11659,6	2337,3	8,15%	0,2005
ST1060	0,1734	1409,1	16091,2	2789,5	8,92%	0,1734
ST1068	0,1695	1758,7	10956,5	1857,2	14,64%	0,1695
average	0,1752	1392	14775,0	2567,5	11,14%	**0,1752**

Table 5: trial EVs in Orkney data elaboration normalised on yearly basis

The number of EV trials in Orkney, compared with the total number of body-type car in Orkney, is too low for using collected data with the purpose of building a yearly traffic model in Orkney. Nonetheless, since electric vehicles operation is strongly influenced by local climate and weather conditions [42],[43], this data set is useful to assess EVs performances in Orkney.

Therefore, the most valuable information obtained from MEA project data consists in the average power consumption: it is equal to 0.1752 kWh/km.

3.2.2. Orkney Renewable Energy Forum data analysis

According to Orkney Renewable Energy Forum (OREF), as of November 2017, over 160 electric vehicles and plug-in hybrid electric vehicles are present in Orkney. Furthermore, in December 2017 OREF published draft strategy to get the county ready for the planned 1000 EVs expected on Orkney's road in the next five years. Orkney already has the highest proportion of its vehicles being electric of any county in Scotland, with around 1.5% of the approximately 11200 cars being run on clean green, locally generated electricity.

In January 2016 OREF has started up a database for EV drivers in the area. The database captures information on the number of electric miles travelled per day and per month, and the subsequent saving in CO_2 emissions and easing effect on Orkney's grid [44]. However, consumption data of electric vehicles (expressed both in kWh/day/vehicle and in kWh/month) are available only since January 2017 [45]. The number of registered electric vehicles varies from 16 in January 2016 to 52 in October 2017. Furthermore, according to OREF, in October 2017, the total mileage by the vehicles in the database travelled is 1,290,820 miles and 438 car years of experience have been gained.

From the analysis and elaboration of the OREF electric vehicles database, the average EV consumption, expressed in kWh/km, has been calculated. It is remarkable to mention that its value-0.170 kWh is really close to the average consumption value calculated from My Electric Avenue database.

3.2.3. Wind curtailed electricity dataset analysis

For the estimation of the curtailed wind electricity profile, theoretical wind generation in Orkney data for 2013, calculated by dr. Andrew Peacock, Research Associate at Heriot Watt Univerity, have been used. The calculation of theoretical wind generation in Orkney has been performed starting from an hourly weather dataset for 2013 in Orkney and from the Orkney installed wind capacity.

Turbine type	Number	Turbine cap [MW]	Total cap [MW]	Hub Height [m]
Enercon 44	26	0,9	23,4	45
Nordex N60	1	1,3	1,3	76
Neg Micon n92	1	2,75	2,75	116
Neg Micon 1.5MW	1	1,5	1,5	76
Neg Micon 2.3MW	3	2,3	6,9	76
Windflow 500	4	0,5	2	40
Vestas V80	5	2	10	70

Table 6: wind installed capacity in Orkney. Source: Peacock A.D., (2018) private communication.

The total installed wind capacity in Orkney in 2013 was equal to 47.85 MW.

In order to calculate theoretical wind generation, hourly measured wind speed has been reported to the wind turbine hub height, with the logarithmic wind profile law.

$$u_2 = u_1 \cdot \frac{\ln\left({}^{h_2}/_{z}\right)}{\ln\left({}^{h_1}/_{z}\right)}$$

Where u_2 is the corrected wind speed at the hub height, u_1 is the measured wind at the height h_1, h_2 is the hub height of the wind turbine and z is the roughness length.

Combining the polynomial power curves and cut in, cut out and maximum output of the various types of wind turbine (empirically derived) with the corrected hourly wind speed at the hub height the hourly theoretical wind generation for each wind turbine is obtained.

Hourly wind curtailments profile in Orkney in 2013 has been estimated comparing theoretical wind generation with actual wind generation[5], at an hourly time step.

It is worth highlighting that the actual wind generation dataset is incomplete: it covers only the 85.8% of the whole year. Table 7 below displays the time intervals for which there are not wind generated data.

Interval start	Interval end	No. of 'NO DATA'time steps
2013-01-28-08:00	2013-02-04-15:00	176
2013-04-05-00:00	2013-04-08-23:00:00	96
2013-08-27-12:00	2013-08-30-15:00	76
2013-08-30-19:00	2013-08-31-03:00	9
2013-09-03-13:00	2013-09-04-10:00	22
2013-09-04-23:00	2013-10-08-09:00	803
2013-11-04-05:00	2013-11-04-13:00	9
2013-11-13-10:00	2013-11-13-18:00	9
2013-11-17-13:00	2013-11-17-14:00	1
2013-11-18-01:00	2013-11-18-02:00	1
2013-12-17-01:00	2013-12-17-09:00	9
2013-12-19-05:00	2013-12-19-11:00	7
2013-12-31-02:00	2013-12-31-23:00	22

Table 7: 'NO DATA' time steps identification and characterization

The longest time intervals occur between January 1st and February 4th, April 5th and April 9th, August 27th and August 30th, and mainly September 4th and October 8th. The overall number of

[5] Source: Peacock A.D., private communication (2018)

time steps for whose there are no recorded data for actual wind generation is 1220: the majority of these are allocated in September.

Table 8 highlights more clearly how the dataset incompleteness is allocated over the whole year.

Dataset month coverage	
January	88,2%
Febraury	86,9%
March	100,0%
April	86,7%
May	100,0%
June	100,0%
July	100,0%
August	88,6%
September	10,1%
October	76,1%
November	97,2%
December	95,8%

Table 8: actual wind generation dataset coverage per month

Every month except September and October is characterised by data coverage higher than 85%. In particular, for the month of September, data are available only between Setepmber 1^{st} and 4^{th}.

average hourly curtailment (MWh)	
August	3,44
June	3,74
October	4,01
July	4,02
May	4,50
February	4,92
April	4,98
January	5,64
March	5,92
November	7,20
September	9,28
December	11,20

Table 9: average hourly wind curtailments per month

For these reasons, wind curtailment electricity has been calculated only for the time step for whose actual wind generation data are available. Therefore, the temporal domain successively used in the simulation is not the whole year 2013, but specifically it consists only in the 7520 time steps for whose there are actual wind generation data.

For each time step of the temporal domain, if the current theoretical generation is higher than the actual generation, wind curtailed electricity has been calculated as the difference between theoretical and actual generation, otherwise curtailed electricity has been set equal to zero.

Some wind turbines in Orkney experience curtailments both due to low electricity demand in periods of high wind production and to non-firm grid connections.

Figure 6 shows the wind curtailed electricity trend over the temporal domain.

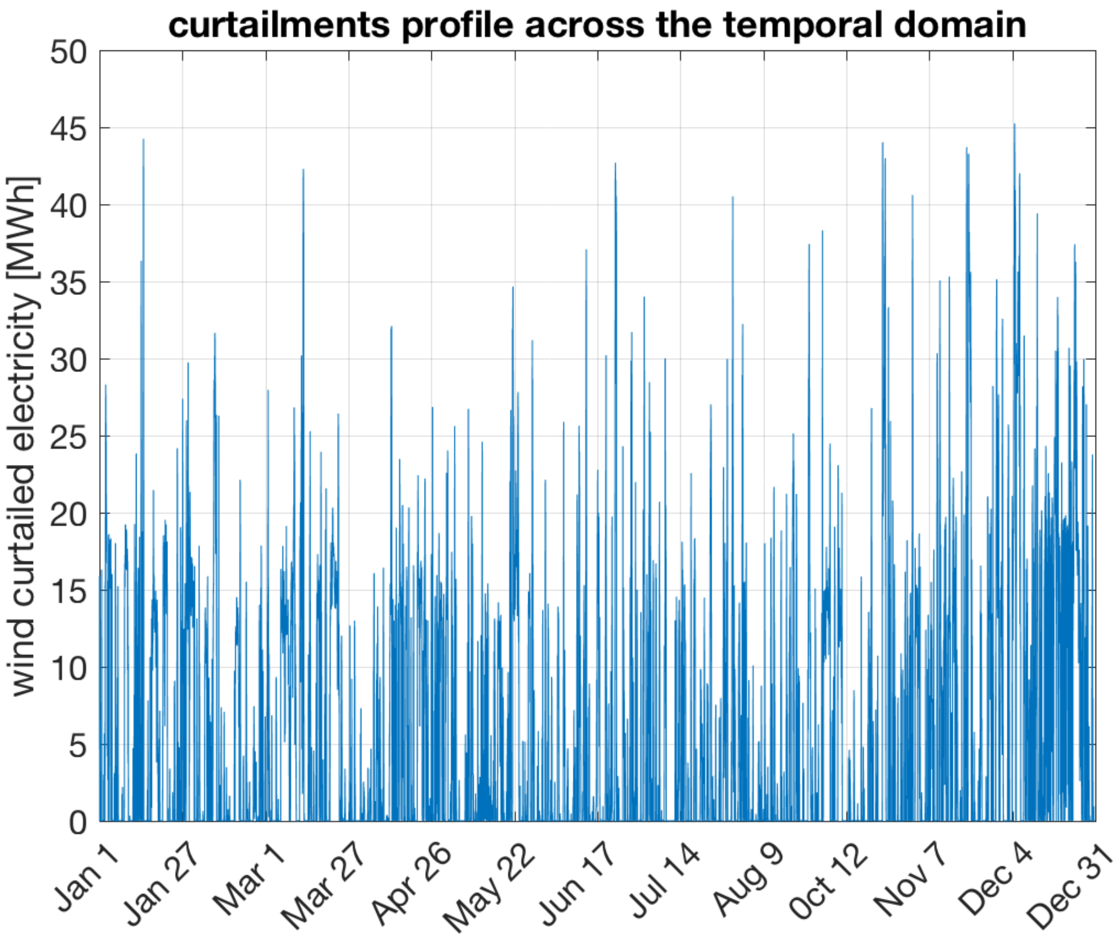

Figure 6: wind curtailed electricity trend

For 54.2% of the temporal domain there are no curtailments in wind generation in Orkney.
For the remaining part, wind turbines experience curtailments. The wind curtailed electricity amount varies between zero and the maximum installed capacity as figure 7 displays.

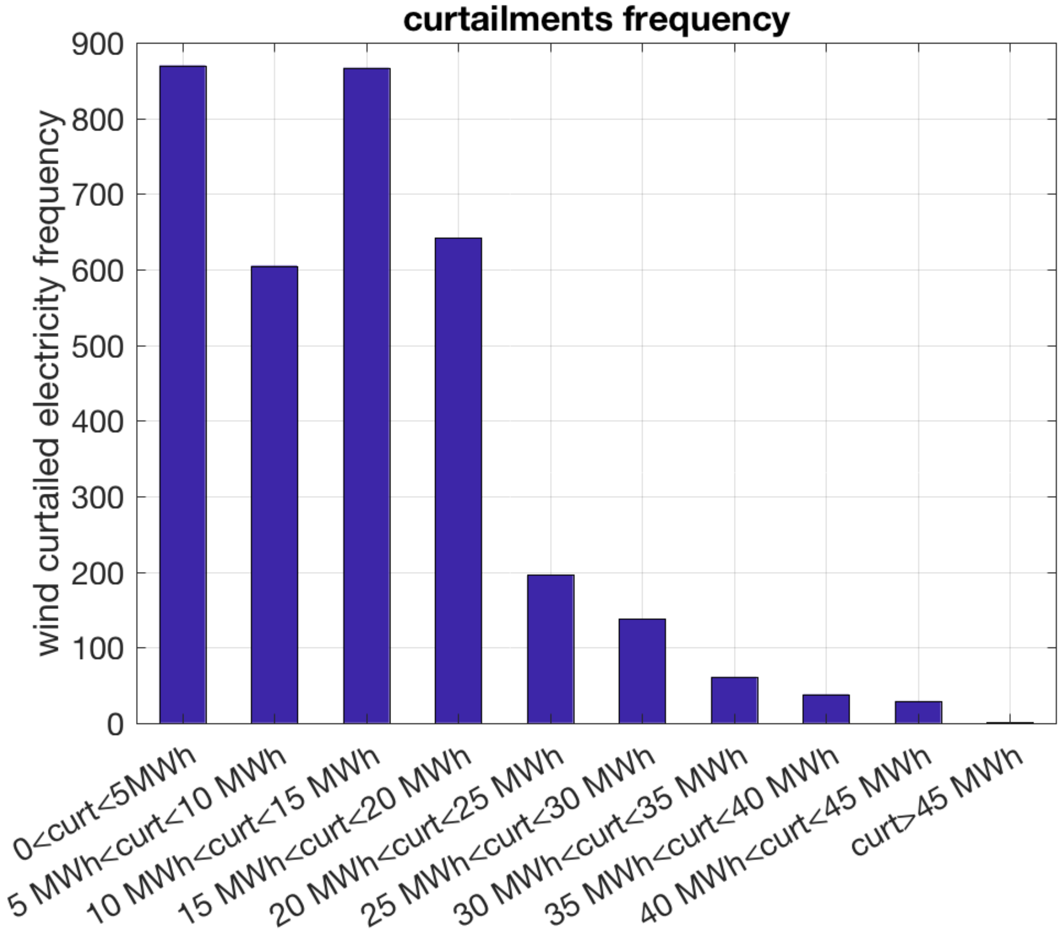

Figure 7: curtailments frequency

Despite the total installed capacity is 47.85 MW, the maximum of hourly wind curtailed electricity is equal to 45.3 MWh: this means that occasionally, due to extremely low electricity demand, almost the entire amount of wind-produced electricity is curtailed. However, hourly curtailments are higher than 20 MWh only 13.4% of cases in which curtailments are registered. The average curtailed wind electricity value is equal to 3.45 MWh.

3.3. Models characteristics

In order to find an optimal strategy for exploiting wind curtailed electricity in Orkney, two models have been used.

In this section, the two adopted models will be described. The first one, the "Traffic Model" is realised on Microsoft Excel, while the second one, the "Simulation Model" is implemented on Matlab.

The *Traffic Model* intent is to determine the traffic volume of body type cars in Orkney with a hourly time step on a annual basis; furthermore it calculates the needed amount of electricity, time step per time step, if a set percentage of the body-type cars existent in Orkney were electric. This model is characterised by a stochastic essence, as will be discussed in the following.

The *Simulation Model* target is to explore the potentials of exploiting curtailed wind electricity, This model takes as input data the results of the *Traffic Model*; on the contrary, it is important to remark that this model has not a statistic nature. The inputs are elaborated and processed from a mathematical perspective.

3.4. Traffic Model

The preparation of this model consists in gathering together the following preliminary data:

- Orkney population information, including demographic data, age breakdown, employment and occupation, households and their location across the archipelago [46], [47], [48].
- Information about road transport vehicles, road network and network and road traffic in Orkney. Very important data for the model are the number of body-type cars and the total yearly mileage [49].

The collected data are shown in the table below.

DEMOGRAPHIC INFORMATIONS	
total Orkney population	21570
population aged 0-15	3572
population aged 16-64	13508
population aged over 65	4450
households number	9945
Mainland inhabitants	17162
Kirkwall inhabitants	9295
Stromness inhabitants	2190
others	4408

Table 10: Demographic informations. Source: National Records of Scotland

OCCUPATION INFORMATIONS	
economically active population	12400
managers, directors and seniors officials	1100
professional occupation	1400
associate professional & technical	1800
administrative & secretarial	1300
skilled trades occupations	1300
caring, leisure and other	1000
sales and customers services	1100
process plant & machine operatives	900

elementary occupation	2200
unemployed	300
economic inactivity	1500
looking after family/home	350
retired	500
school population	3000

Table 11: Occupation information. Source: Highlands and Islands Enterprise.

VEHICLES, ROAD AND TRAFFIC INFORMATIONS	
cars registered per 1000 people aged 17+	495
body type cars	11200
road traffic (millions km)*	133
petrol and diesel consumption of road vehicles (thousands of tons)*	9.3
A roads (km)	161
B roads (km)	205
C roads (km)	160
unclassified (km)	458
tot (km)	984

Table 12: Vehicles, roads and traffic information. Source: Transport Scotland

*: 2013 data

The following step consist in determine the number and the categories of people likely to own a car among the total Orkney population.

Population aged 16-64 likely to own a car	**#**	**percentage**	**car number**
delivery workers	200	1,59%	178
commuter workers	2760	21,89%	2452
Kirkwall workers	6120	48,54%	5437
Stromness workers	1328	10,53%	1180
other workers	1050	8,33%	933
retired	500	3,97%	444
unemployed/looking after family	650	5,16%	577
total	12608	100,00%	11200

total students (don't have car but need a ride)	**3000**	**1500**
student (Kirkwall)	2400	1200
student (Stromness)	400	200
student (other villages)	200	100

Table 13: Population likely to own a car partition

Then, nine journey-types have been identified, considering inhabitants' jobs, duties and leisure. For each journey type, the following data have been provided: average trip distance, average trip time, number of trips per day per car, maximum number of vehicles doing the considered journey.

journey type	trip distance [km]	no of daily trips per car	average trip time (min)	no of vehicles
school run	2,41	1	10	1500
delivery[6]	40,23	4	60	178
commuter[7]	19,31	2	30	2452
workers in kirkwall	2,41	1	15	5437
workers in stromness	3,22	1	10	1180
other workers[8]	6,44	1	20	933
leisure / sport	5,63	variable	15	variable
shopping	5,63	variable	15	variable
work + school run	4,02	1	25	1500

Table 14: Main journey types characteristics for a normal weekday

The maximum number of vehicle per journey type is directly obtained from Table 4. The evaluation of the maximum number of vehicle per leisure/sport and shopping journey type is more complex and was performed under the following assumptions:

- Maximum number of circulating vehicles per leisure/sport and shopping journey type in weekdays is equal to the sum of the unemployed/looking after family, retired categories car number, plus the 40% of the other vehicle owners car number.
- Maximum number of circulating vehicles per leisure/sport and shopping journey type in Saturdays is equal to the 40% of the household number.
- Maximum number of circulating vehicles per leisure/sport and shopping journey type in festivity days–Sundays is equal to the 50% of the household number.

Obtained values are shown in Table 15 below.

	No of circulating vehicles		
journey type	festivity day-Sunday	weekday	Saturday
leisure/sport	4973	5622	3978
shopping	4973	5622	3978

Table 15: No of circulating vehicles for leisure/sport and shopping journey types according to the day-type

In addition, in order to fill the tables 13, 14 and 15, the following assumptions have been made:

[6] standard itinerary: Kirwall to Stromness via Tingwall House
[7] Kirkwall to Stromness journey
[8] related to people living in other settlements

- Student population has been arbitrarily divided into Kirkwall students, Stromness students and other settlements students categories, according to National Records of Scotland data.
- Work and school run are coupled only in the morning.
- *Unemployed/looking after famil*y and *retired* categories just do school run, leisure/sport and shopping journey types.

Subsequent phase consists in establishing six types of daily profiles, according to population habits and duties. The selected day-types are:

- Normal weekday;
- Normal Friday, in which schools have different schedules with respect to other weekdays;
- Weekday without school, in which students do not need a ride;
- Saturday;
- Sunday – festivity day.

For each of the five day-types, a daily profile at a 5 min time step has been built: the percentage of circulating cars has been stochastically set per each time step of the day and per each jorney type. This, from a mathematical point of view, gives rise to five m by n daily traffic matrices, one for each day-type, where m=288 is the number of time steps per day and n=9 is the number of journey types.

The filling process of the daily traffic matrix tries to simulate with the highest accuracy the car owners behaviour: nonetheless it is relevant to put in evidence anew that this procedure is purely stochastic. The major aspects considered are work time schedule and school time schedule. Furthermore, other studies have been considered [50].

From the *Daily traffic matrices*, using the data introduced above and the results of the analysis of My Electric Avenue (MEA) and Orkney Renewable Energy Forum (OREF) databases, the following figures have been calculated:

- Hourly mileage profile per every journey type;
- Hourly percentage of circulating cars;
- Hourly energy consumption if all the body-type cars were electric.

Next step consists in shifting from the daily scale to a yearly scale. The 2013 calendar has been built, considering school calendar and festivities. Each day of the year, according to its day-type, has been filled with the values previously calculated. Thus, the first outcome of the *Traffic Model* is here obtained: according to the model, the total 2013 yearly mileage for body-type cars solely is equal to 125.47 millions km. In order to prove the validity of the model, this data has to be compared with the Traffic on all roads 2013 data, provided by Transport Scotland (Table 12), which corresponds to 133 millions km. In this value all vehicles mileages are comprehended, including other vehicles, motorcycles and public transports. Considering that:

- Fraction of body-type vehicles in Orkney is 68,7% but they are the most common main of road transport by far;
- The remaining part, composed by other vehicles and motorcycles, consists of not very used means of transport, and characterised anyhow by shorter journeys and thus lower mileages;
- Yearly public transports mileage is slightly less than 1 million km, as it will be shown in the following;

The first outcome of the *Traffic Model* can be considered solid and reliable.

The most important step of the *Traffic Model* consists in gathering together the information about the journey types and the categories of people likely to own a car. The goal is to create a certain number of typical and credible daily route types. The seven categories of people likely to own a car have been divided in turn into twenty subcategories, each per each daily route type. The intent is to allocate and aggregate the journey types in the subcategories so that each daily route type is composed by various journey type and it is characterised by a different daily mileage profile. This process has been performed for each day type, always taking into account the limitations imposed by the daily mileage profiles calculated beforehand.

subcategories daily routes description								
people likely to owe a car	cars number	car partition	subcategory name	WEEKDAY daily route types	FRIDAY daily route types	WEEKDAY WITHOUT SCHOOL daily route types	SATURDAY daily route types	SUNDAY-FESTIVITY daily route types
delivery workers	178	178	del	delivery only	delivery only	delivery only	delivery only	non-working day
commuter workers	2452	613	com1	work run + leisure + shopping	work run + leisure + shopping	work run + leisure + shopping	work run + leisure + shopping	leisure/sport
		613	com2	work run + school run + leisure + shopping	work run + school run + leisure + shopping	work run + leisure + shopping	work run + leisure	leisure/sport
		613	com3	work+school run + work run + leisure + shopping	work+school run + work run + leisure + shopping	work run + leisure + shopping	work run + shopping	leisure/sport
		613	com4	work run + shopping	work run + shopping	work run + shopping	staying home	staying home
Kirkwall workers	5437	1359	kirk1	work run + leisure + shopping	work run + leisure + shopping	work run + leisure + shopping	work run + leisure + shopping	leisure/sport
		1359	kirk2	work run + school run + leisure + shopping	work run + school run + leisure + shopping	work run+ leisure + shopping	work run + leisure	leisure/sport
		1359	kirk3	work+school run + work run + leisure + shopping	work+school run + work run + leisure + shopping	work run + leisure + shopping	work run + shopping	leisure/sport
		1359	kirk4	work run + shopping	work run + shopping	work run + shopping	staying home	staying home
Stromness workers	1180	295	strom1	work run + shopping	work run + shopping	work run + shopping	staying home	staying home
		295	strom2	work run + leisure + shopping	work run + leisure + shopping	work run + leisure + shopping	work run + leisure + shopping	leisure/sport

		295	strom3	work run + school run + leisure + shopping	work run + school run + leisure + shopping	work run+ leisure + shopping	work run + leisure	leisure/sport
		295	strom4	work+school run + work run + leisure + shopping	work+school run + work run + leisure + shopping	work run + leisure + shopping	work run + shopping	leisure/sport
other workers	933	233	oth1	wok run + shopping	wok run + shopping	wok run + shopping	staying home	staying home
		233	ot2	work run + leisure + shopping	work run + leisure + shopping	work run + leisure + shopping	work run + leisure + shopping	leisure/sport
		233	oth3	work run + school run + leisure + shopping	work run + school run + leisure + shopping	work run + leisure + shopping	work run + leisure	leisure/sport
		233	oth4	work+school run + work run + leisure + shopping	work+school run + work run + leisure + shopping	work run + leisure + shopping	work run + shopping	leisure/sport
retired	444	444	ret	leisure/sport + shopping	leisure/sport + shopping	leisure/sport + shopping	leisure/sport + shopping	leisure/sport
unemployed / looking after family	577	289	unempl1	school run + leisure/sport + shopping	school run + leisure/sport + shopping	leisure/sport + shopping	leisure/sport + shopping	leisure/sport
		289	unempl2	leisure/sport + shopping	leisure/sport + shopping	leisure/sport + shopping	leisure/sport + shopping	leisure/sport

Table 16: subcategory daily routes description

As an example, Table 17 below shows the partition of the total amount of body-type cars in Orkney into the twenty subcategories for the *weekday* day-type.

category and car number	car partition	subcategory	tot km per subcategory	daily km per car
delivery workers 178	178	del	34847	196,1
commuter workers 2452	613	com1	36256	59,2
	613	com2	36800	60,0
	613	com3	37186	60,7
	613	com4	27382	44,7
kirkwall workers 5437	1359	kirk1	39364	29,0
	1359	kirk2	41355	30,4
	1359	kirk3	42490	31,3
	1359	kirk4	13914	10,2
stromness workers 1180	295	strom1	3505	11,9
	295	strom2	9624	32,6
	295	strom3	9926	33,7
	295	strom4	10215	34,6
other workers 933	233	oth1	2397	10,3
	233	oth2	5440	23,3
	233	oth3	5621	24,1
	233	oth4	5862	25,1
retired 444	444	ret	5747	12,9
unemployed/ looking after family 577	289	unempl1	3860	13,4
	289	unempl2	3257	11,3

Table 17: subcategories car partition for the "weekday" day-type

Table 18 below displays the hourly mileage for each of the 20 subcategories for weekday day-type.

WEEK DAY	delivery workers	commuter workers				kirkwall workers				stromness workers				other workers				retired	unemployed/ looking after family	
No of vehicles	178	613	613	613	613	1359	1359	1359	1359	295	295	295	295	233	233	233	233	444	289	289
subcat	del	com 1	com 2	com 3	com 4	Kirk 1	Kirk 2	Kirk3	Kirk4	Strom 1	Strom2	Strom3	Strom 4	oth 1	oth2	oth 3	oth 4	ret	unempl 1	unempl2
0:00	0,00	0,04	0,04	0,04	0,00	0,05	0,05	0,05	0,00	0,00	0,06	0,06	0,06	0,00	0,03	0,03	0,03	0,02	0,02	0,02
1:00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
2:00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
3:00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
4:00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
5:00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
6:00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
7:00	0,00	0,06	0,06	0,06	0,00	0,08	0,08	0,08	0,00	0,00	0,09	0,09	0,09	0,00	0,05	0,05	0,05	0,03	0,03	0,03
8:00	3,35	19,95	19,95	21,46	19,31	1,30	1,30	3,60	0,48	0,64	1,55	1,55	3,56	0,00	0,57	0,57	2,38	0,36	0,32	0,32
9:00	23,13	1,44	1,44	1,44	0,50	1,86	1,86	1,86	0,64	0,71	2,06	2,06	2,06	0,77	1,62	1,62	1,62	0,92	0,80	0,80
10:00	24,81	1,45	1,45	1,45	0,46	1,88	1,88	1,88	0,59	0,65	2,08	2,08	2,08	0,41	1,31	1,31	1,31	0,92	0,80	0,80
11:00	26,82	1,19	1,19	1,19	0,25	1,54	1,54	1,54	0,32	0,36	1,70	1,70	1,70	0,22	1,07	1,07	1,07	0,73	0,64	0,64
12:00	15,42	1,60	1,60	1,60	0,66	2,07	2,07	2,07	0,86	0,95	2,30	2,30	2,30	0,60	1,44	1,44	1,44	1,05	0,91	0,91
13:00	14,08	1,75	1,75	1,75	0,87	2,27	2,27	2,27	1,13	1,25	2,51	2,51	2,51	0,78	1,58	1,58	1,58	1,17	1,02	1,02
14:00	24,14	1,04	1,04	1,04	0,37	1,34	1,34	1,34	0,48	0,53	1,48	1,48	1,48	0,34	0,93	0,93	0,93	0,67	0,58	0,58
15:00	23,13	1,56	2,64	1,56	0,46	2,02	3,48	2,02	0,59	0,65	2,24	3,26	2,24	0,41	1,41	2,18	1,41	0,98	2,95	0,86
16:00	20,12	2,36	2,36	2,36	0,70	3,05	3,05	3,05	0,91	1,01	3,38	3,38	3,38	0,63	2,13	2,13	2,13	1,49	1,30	1,30
17:00	16,43	9,40	9,40	9,40	8,30	3,68	3,68	3,68	2,25	2,93	4,51	4,51	4,51	4,25	5,24	5,24	5,24	0,82	0,72	0,72
18:00	4,69	14,11	14,11	14,11	11,51	3,68	3,68	3,68	0,32	0,36	4,08	4,08	4,08	0,71	3,05	3,05	3,05	1,68	1,46	1,46
19:00	0,00	2,03	2,03	2,03	1,20	2,63	2,63	2,63	1,55	1,72	2,91	2,91	2,91	1,08	1,83	1,83	1,83	1,39	1,22	1,22
20:00	0,00	0,72	0,72	0,72	0,08	0,93	0,93	0,93	0,11	0,12	1,03	1,03	1,03	0,07	0,65	0,65	0,65	0,43	0,37	0,37
21:00	0,00	0,31	0,31	0,31	0,00	0,41	0,41	0,41	0,00	0,00	0,45	0,45	0,45	0,00	0,28	0,28	0,28	0,18	0,16	0,16
22:00	0,00	0,08	0,08	0,08	0,00	0,10	0,10	0,10	0,00	0,00	0,11	0,11	0,11	0,00	0,07	0,07	0,07	0,04	0,04	0,04
23:00	0,00	0,07	0,07	0,07	0,00	0,09	0,09	0,09	0,00	0,00	0,09	0,09	0,09	0,00	0,06	0,06	0,06	0,04	0,03	0,03

Table 18: hourly mileage per each subcategory for weekday day-type

With the variation of the day-type, the journey types that form the subcategories vary too. For instance, in the day-type festivity day-Sunday only leisure/sport journey types have been included; furthermore it has been considered the option “staying home”.

Finally, according to the journeys attributed to each subcategory and according to the daily mileage profiles of each single journey type, for each subcategory and for each day-type, the mileage daily profile at a hourly time step has been calculated.

Therefore, the conclusive outcome of the Traffic Model is represented by twenty different daily mileages at a hourly time step, each one per subcategory of car owner: this results are obtained per each day type.

This procedure can be explained highlighting which is the central idea of the subsequent model, namely studying the behaviour of the Electric Vehicles not at a global level, on the contrary at the single EV car level. This approach leads to a higher level of granularity in the Simulation Model and to a larger reliability and accuracy of the results.

3.5. Simulation Model

The ambitious goal of the Simulation Model is to state whether is possible to feed a hypothetical 100% Electric Vehicles environment in Orkney, only using the wind curtailed electricity, fulfilling all the constraints imposed by electric power balance, together with the necessity of meeting the electricity demand needed for charging the EVs. Furthermore, the model includes a sub model, called FC bus model, which explores the opportunity of using a fraction of the curtailed electricity for Hydrogen production purposes. The Hydrogen produced would be used to fuel new Fuel Cell buses, that would replace older and tradition bus models.

Simulation Model is intrinsically an iterative model: while in the Traffic Model outcomes were calculated only a single time per each day-type and then extended on a yearly scale, Simulation Model must establish, time step after time step, which hour of the day it is and which type of day it is, and then calculate the outputs. Thereafter, the model examines the following time step. This approach allows to compute and store the hourly required output values over the whole temporal domain, supporting the awareness of critical periods (i.e. days in which curtailments profile drops significantly) and encouraging feasible model modification.

Another important peculiarity of the Simulation Model is that it differs with the Traffic Model on the time domain: the Traffic Model performs its analysis over the whole year; on the contrary, the Simulation Model takes into account only time steps in which there are wind curtailed electricity available data. Therefore, time steps that build Simulation Model are 7520.

3.5.1. *Simulation Model* preparation: input data description

As mentioned above, the most important input for the *Simulation Model* consists in the daily mileage profiles of each subcategory car owner, depending on the day-type. In this section, the other inputs will be shortly described.

- Curtailments profile: it contains the hourly amounts of wind curtailed electricity, in kWh;
- Calendar profiles: suitable vectors that contain information useful to establish which hour of the day it is and which day-type it is;
- Body-type car number;
- Battery size: capacity of the electric car battery, fixed at 30 kWh;
- Initial state of charge (SoC) of the EVs batch, randomly generated. The minimum allowable value is 10 kWh, i.e. 30% SoC;
- Power consumption: expressed in kWh/km, is the highest value between the two power consumption values obtained from the elaboration of MEA and OREF databases. It equals to 0.1752 kWh/km;
- Vehicles classification and vehicles hourly mileages information;
- Charging units: information about amount, location and specifications of the charge points across Orkney [51]. Charge points were basically divided into two categories: the home/work chargers (slow chargers) and the public chargers (quick chargers). Slow charging units are rated 3 kW. Charging times vary on unit speed and vehicle, but a full charge for an EV will typically take 6-12 hours. Slow charging is the most common method of charging electric vehicles, used by many owners to charge at home overnight. Slow units aren't necessarily restricted to home use, with workplace and public points also able to be found. Because of the longer charging times over fast units, slow public charge points are less common. A different speech has to be done for the quick chargers: for reasons of simplicity rapid (43 and 50 kW DC) and fast (7 and 22 kW) chargers have been aggregated into the so-called "quick chargers" category, performing a weighted average between their specifications and their amount in Orkney. Since the model analyses the charging capability at a hourly time step, as it will be explained later, the two most important figures of merit are the *EV charge progression*, that expresses how much the EV battery increases its State of Charge while under charge, and the *energy consumption,* that expresses how much energy is used to allow EV battery charging process, both expressed in kWh/hour.

CHARGING UNITS SPECIFICATIONS			
size	charge progression [kWh/hour]	energy consumption [kWh/hour]	number
46.5 kW rapid	30	23,25	9
22 kW fast	20	22	21
7 kW fast	6	7	10
3 kW slow	2,86	3	11255
25 kW average quick	18,75	18,53	40

Table 19: Charging units specifications. Source: zap-map.com

- The percentage of electric vehicles available to be charged by a slow or a quick charging unit, time step per time step. The amount of EVs available to be charged by a slow charging unit is directly obtained from the percentage of non-circulating car, calculated previously in the *Traffic Model.* On the contrary, since quick chargers are mainly present in public points (shopping centres, supermarkets, etc.), the amount of EVs available to be charged by a quick charging unit is obtained from the percentage of circulating vehicles regarding the only shopping journey type.

  In the model, these two information are represented by two 7520 x 5 matrices, where the rows represent the time steps considered in the model and the columns represent the day-types.
- Hydrogen producibility information: basically they regard electrolyser efficiency in different operating conditions.
- Fuel cell buses and fuel cell electric vehicles specifications: these data will be respectively used in modelling the *FC buses model* and in the model modifications.

3.5.2. *Simulation Model* description: tasks

The model, with an hourly time step, must:

- Check and sort in ascending order the State of Charge of the vehicles. The strong hypothesis is that all body-type cars in Orkney are Electric Vehicles.
- According to the curtailed wind electricity of the current time step, charge the EVs starting from the lowest SoC. This point takes into account the opportunity of using both slow and quick chargers, according to their number and according to EVs availability of being charged in the current time step.
- If there is still residual electricity, then use it in order to produce Hydrogen, with ITM electrolysers.
- Compute all EVs mileage profiles, according to the *Traffic Model* outcomes an update again

the SoC of the EVs.

This iterative process is performed for each of the 7520 time steps that compose the model.

3.5.3. Simulation Model integration: Fuel Cell buses model

In certain periods of the simulation it can occur that the hourly curtailment is so high that, once charged electric vehicles, according to their state of charge and to the availability of charging units, there is still an amount of wind curtailed electricity that can be used for other purposes.

The Fuel Cell buses model stems from the intent of using this residual electricity that cannot be used for electric vehicles charging purposes.

The idea is to use this amount of residual electricity feeding electrolysers, producing hydrogen. This hydrogen will be used in charging new generation Fuel Cell buses, which would replace the traditional buses nowadays present in Orkney.

A fuel cell electric bus is an electric bus that includes both a hydrogen fuel cell and batteries/capacitors. In such hybrid architecture, the fuel cell provides all of the energy for the vehicle operation, whilst the batteries/capacitors are able to provide peak power to the motors to meet rapid acceleration and gradients. By using a fuel cell in conjunction with a battery, the size of each can be optimized for a given route.

The fuel cell power module on-board the bus generates electric energy through an electro-chemical reaction leaving only water and heat as by-products, thus there are no local emissions. The electric energy is used to provide direct electric traction and keep the batteries charged. The by-product heat is stored on the brake resistors and is used to maintain heating passenger comfort and considerably increase energy efficiency. The batteries also provide storage for regenerated braking energy. All the energy required for the bus to operate is provided by hydrogen stored on board.

Hydrogen offers higher energy density compared to electrical storage systems such as batteries, this enables a longer range compared to systems where the batteries are used as stores of energy.

Refuelling of the bus takes around 7 minutes for typical fill today, with designs being developed to allow less than 5 minute.

A fuel cell electric bus does not require any additional city infrastructure work or permits other than a centralized hydrogen refuelling station (HRS) at the bus depot.

Because the fuel cell generates only water as an emission it will always be a zero emission bus. Whilst most of the industrial hydrogen used in the world today is produced from fossil sources of energy (mainly natural gas) the hydrogen fuelling stations in Orkney would be based on wind energy curtailments. When fuelled by hydrogen produced via any of these routes, the fuel cell bus offers a completely zero carbon solution to public transport. The fuel cell electric bus is an all electric zero emission solution that offers an operation close to that of a diesel bus and hence is marketed as the closest like for like zero-emission option to replace Diesel [52].

The following tables describe the Orkney public bus services [53].

bus route details								
route	itinerary	km	weekday daily trips	required buses	Saturday trips	required buses	Sunday trips	required buses
2	Kirkwall to Houton ferry	33,5	6	2	5	2	0	0
3	Kirkwall to Deerness (via Tankerness)	48,6	5	2	3	1	0	0
4	Kirkwall to Kirkwall airport	11,9	27	2	20	2	10	1
5	Stromness to Houton ferry	25,4	2	1	0	0	0	0
6	Kirkwall to Tingwall ferry (Evie)	42,2	7	2	7	2	0	0
7	Kirkwall to Birsay (via Dounby)	63,1	4	2	4	2	0	0
8	Stromness academy to Guardhouse Park	5,8	1	1	0	0	0	0
8S	Kirkwall to Skara Brae	54,4	2 trips Mon and Thurs	1 on Mond and Thurs	2	1	0	0
9	Kirkwall town service	7,7	11	2	11	2	4	1
X1	St Margaret's Hope-Kirkwall-Finstown-Stromness	48,1	16	8	7	7	0	0
X1	Stromness-Finstown-Kirkwall-St Margaret's Hope	48,1	16	8	7	7	0	0
X10	Hatston ferry link to Stromness	43,8	2	1	2	1	2	1

Table 20: Orkney bus transport system main aspects (part 1). Source: Orkney.gov

Fuel Cell buses Model approach is analogous to the *Traffic Model* one. It does not analyse the mileage at the individul FC bus level. The model just considers the total daily mileage and the required buses, according to the different days of the week.

	total daily km				total daily km per bus			
route	Mon Thur	Tue Wed Fri	Saturday	Sunday	Mon Thur	Tue Wed Fri	Saturday	Sunday
2	200,8	200,8	167,4	0,0	100,4	100,4	83,7	0,0
3	243,0	243,0	145,8	0,0	121,5	121,5	145,8	0,0
4	321,5	321,5	238,2	119,1	160,8	160,8	119,1	119,1
5	50,9	50,9	0,0	0,0	50,9	50,9	0,0	0,0
6	295,2	295,2	295,2	0,0	147,6	147,6	147,6	0,0
7	252,3	252,3	252,3	0,0	126,2	126,2	126,2	0,0
8	5,8	5,8	0,0	0,0	5,8	5,8	0,0	0,0
8S	108,8	0,0	108,8	0,0	108,8	0,0	108,8	0,0
9	85,0	85,0	85,0	30,9	42,5	42,5	42,5	30,9
X1	769,9	769,9	336,8	0,0	96,2	96,2	48,1	0,0
X1	769,9	769,9	336,8	0,0	96,2	96,2	48,1	0,0
X10	87,5	87,5	87,5	87,5	87,5	87,5	87,5	87,5

Table 21: Orkney bus transport system main aspects (part 2).

Hence, the outputs of *FC buses model* are the average daily mileages per single FC bus.

day type	total mileage	circulating buses	km per bus
Monday	3190,7	32	**99,7**
Tuesday	3081,9	31	**99,4**
Wednesday	3081,9	31	**99,4**
Thursday	3190,7	32	**99,7**
Friday	3081,9	32	**96,3**
Saturday	2053,8	27	**76,1**
Sunday	237,5	3	**79,2**
festivity	0,0	0	**0,0**

Table 22: Orkney bus transport system main aspects (part 3).

Total FC buses mileage is equal to 0.907 millions kilometres.

The chosen buses for the model are manufactured by Van Hool. These buses are already under demo's project in several European cities, like London, Aberdeen (UK), Aalborg (DK), Rotterdam, Groningen (NL), Antwerp (BL), Oslo (N).

Van Hool FC buses are equipped with Ballard HD85 FC modules. They are equipped with a Siemens PEM 1DB2022-210 kW electric traction motor and with a LTO battery ACTIA 36 kWh.

Table 23 below illustrates the most important characteristics of the Van Hool Fuel Cell bus most recent model.

Van Hool FC bus specifications	
range [km]	200-550
typical range [km]	350
consumption [kg H2/100km]	10
energy storage [kWh]	37
tanks	5 x 322L
tank [kg]	38,5
tank pressure [bar]	350
electric motor [kW]	210

Table 23: Van Hool FC bus specifications

4. Results analysis and proposed modification

In this section, after the empirical validation of the model, the results obtained will be presented.

4.1. *Simulation Model results*

Primarily, it is interesting to compare the total mileage calculated by the Simulation Model with the total mileage obtained from the Traffic Model. As mentioned above, Traffic Model mileage equals to 125.47 millions of kilometres, while Simulation Model mileage amounts to 107.48 millions of kilometres. The relative error between these two quantities is 14.34%, a quite significant value. Nonetheless, this discrepancy is explained by the fact that the Traffic Model takes into account the whole year (i.e. 8760 time steps) while the Simulation Model includes exclusively time steps in which curtailments data are available (i.e. 7520 time steps). The relative difference between the two temporal domains extension is equal to 14.16%. The almost identical relative errors explain appropriately the difference in the mileage values and validate simultaneously the Simulation Model result.

Hence, from now on, all the results will be presented on adjusted time domain basis, namely considering only time steps for which curtailments data are present. From the total mileage, it is possible to directly calculate the electricity needed for support a 100% electric vehicles environment. This information is obtained by multiplying the total mileage by the power consumption of EVs in Orkney (data obtained from OREV and MEA databases elaborations, see previous chapters). The needed electricity results to be 18.83 GWh, much less than the total curtailed electricity (41.18 GWh). This first result apparently proves the feasibility of the dissertation's aim.

The second important result is the total electricity used for EVs charging, considering charging points electrical losses, if all the body-type cars were electric. The value obtained by the model is equal to 19.76 GWh.

It is worth to remark that, these two quantities, although they have similar values, represent two different physical concepts: more precisely, needed electricity is an overall data and it is computed only taking into account the total mileage of body-type cars in Orkney. The used electricity for EVs charging value instead, is calculated and updated for every time step of the model. However, at this early modelling stage, as we will see in the following pages, the model runs admitting the possibility of having in some certain time steps state of charge lower than zero. This means that the electricity used for EVs charging could be higher than the first value already calculated by the model.

On the other hand, when wind curtailed electricity is higher than the electricity needed to charge all electric vehicles available, the residual electricity is used to produce Hydrogen. Thus, the total residual electricity, that is equal to 21.52 GWh, represents the fraction of curtailments profile that cannot be used for electric vehicles charging function, due to charging unit availability, high state of charge of EVs, extremely high hourly curtailments.

Therefore, the *Simulation Model* prescribes that the curtailed electricity must always be used somehow: firstly charging as much as possible (i.e. considering limitations mentioned above) EVs, then using the residual for Hydrogen production purposes.

Total curtailments	**Total electricity used for EVS charging**	**Total residual electricity**
41.183 GWh	19.762 GWh	21.521 GWh
100%	47.9%	52.1%

Table 24: how wind curtailed electricity is used

The following graph shows the cumulative sum trends of the quantities presented above. It is worth to mention that EVs charging electricity trend is linear, because beyond the dipendace from the curtailments profile, EVs charging electricity is related to the EVs electricity consuption, quantity that is approximately constant over the days. The dashed line, which represents the sum of EVs charging electricity and residual electricity, proves that this amount corresponds exactly to the curtailments profile.

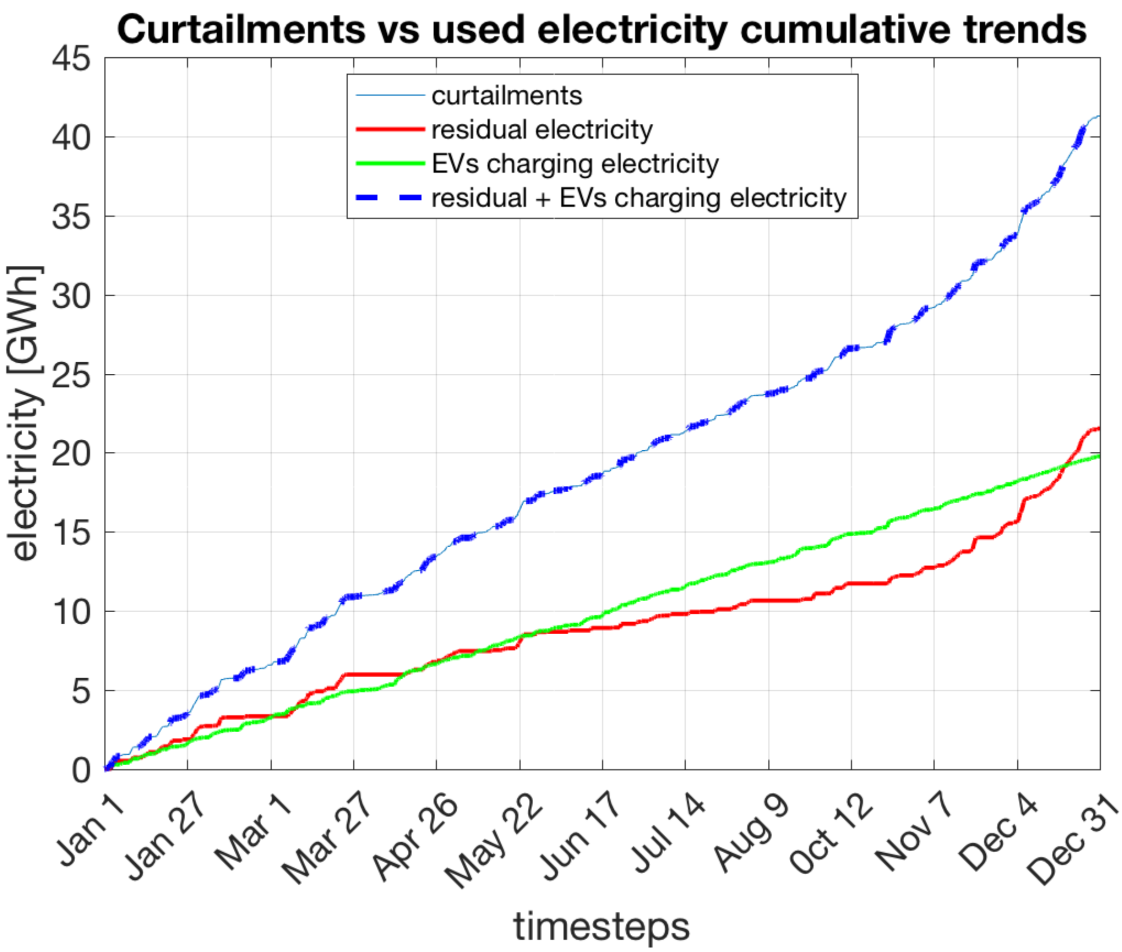

Figure 8: curtailments profile versus used electricity trends

Results shown so far prove the theoretical feasibility of the model. However, the most restrictive constraints lie in the state of charge of the single electric vehicle: it must never be less than zero.

The following graphs show the state of charge trends of the twenty subcategories: in particular, for each subcategory, it has been chosen the electric vehicle with the lowest initial SoC.

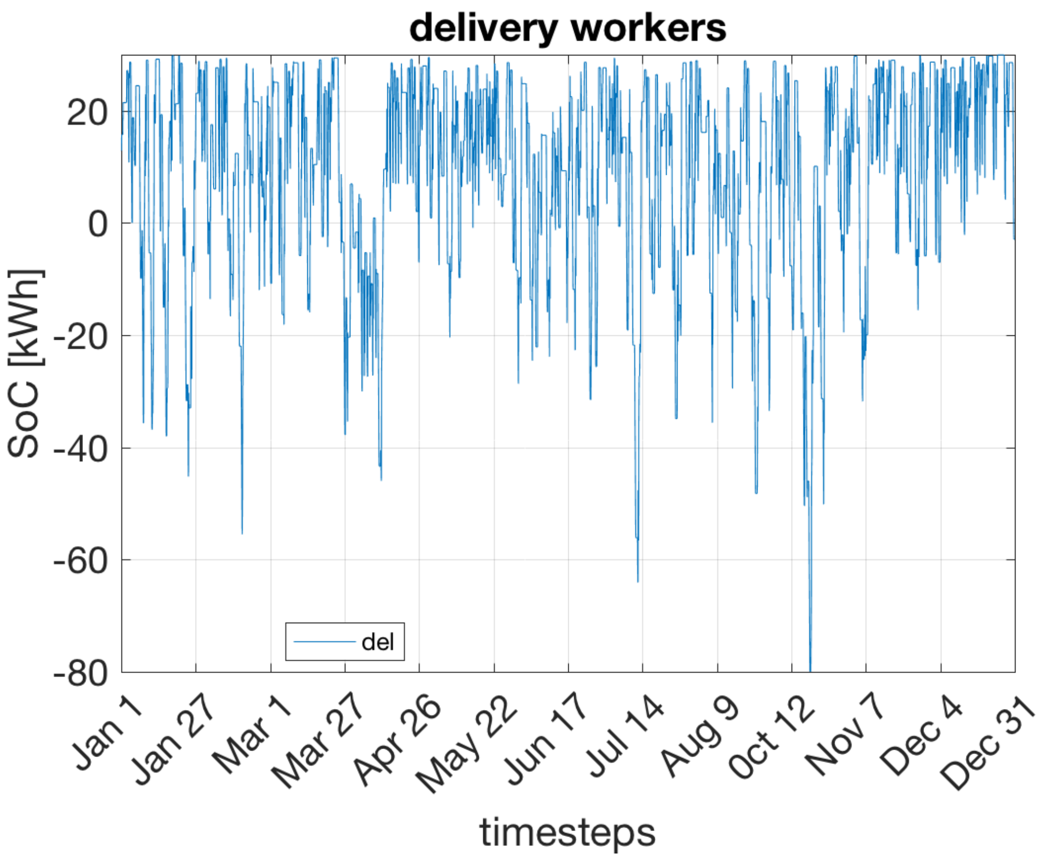

Figure 9: delivery vehicle SoC trend

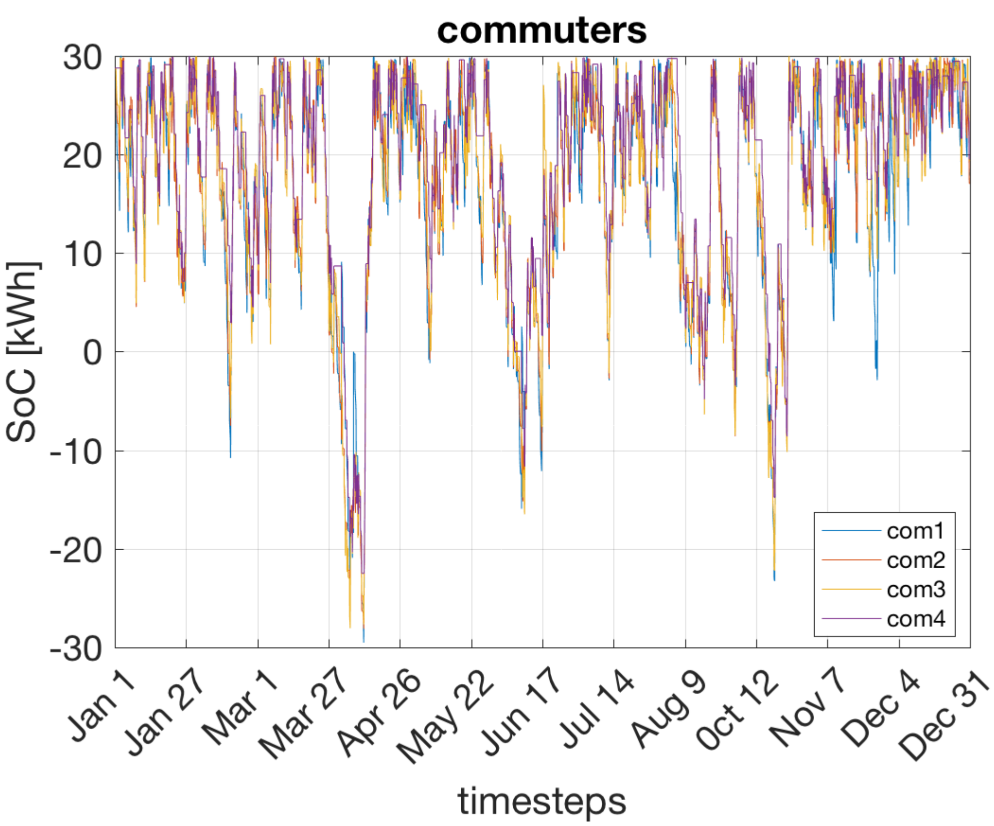

Figure 10: commuters vehicles SoC trends

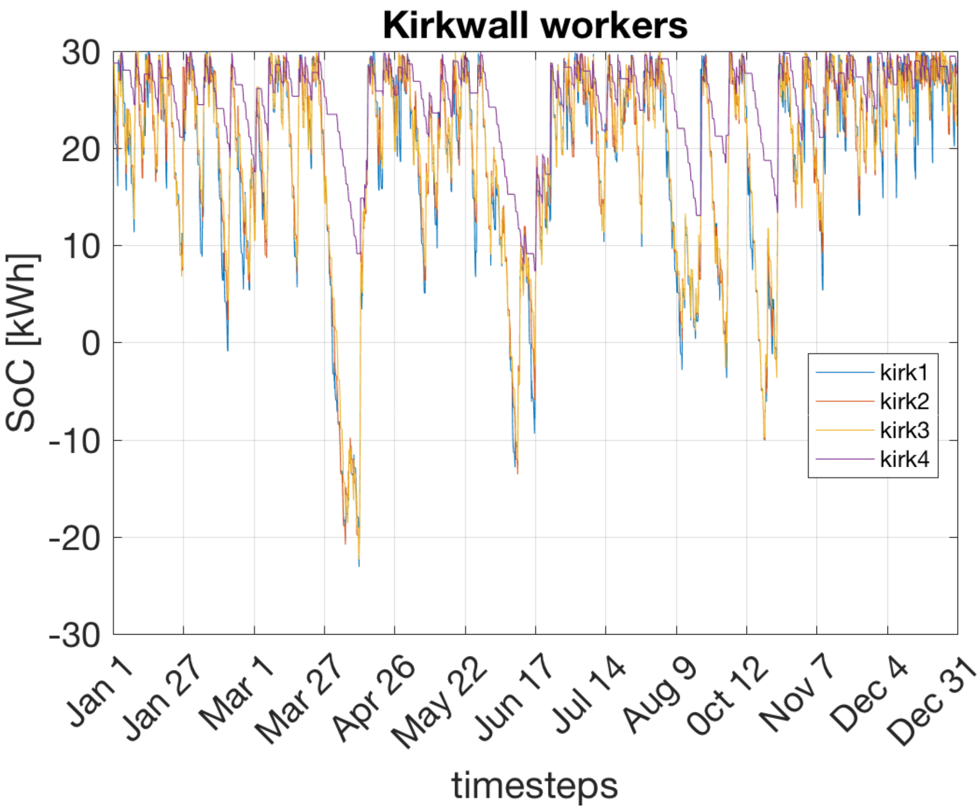

Figure 11: Kirkwall workers vehicles SoC trends

Figure 12: Stromness workers vehicles SoC trends

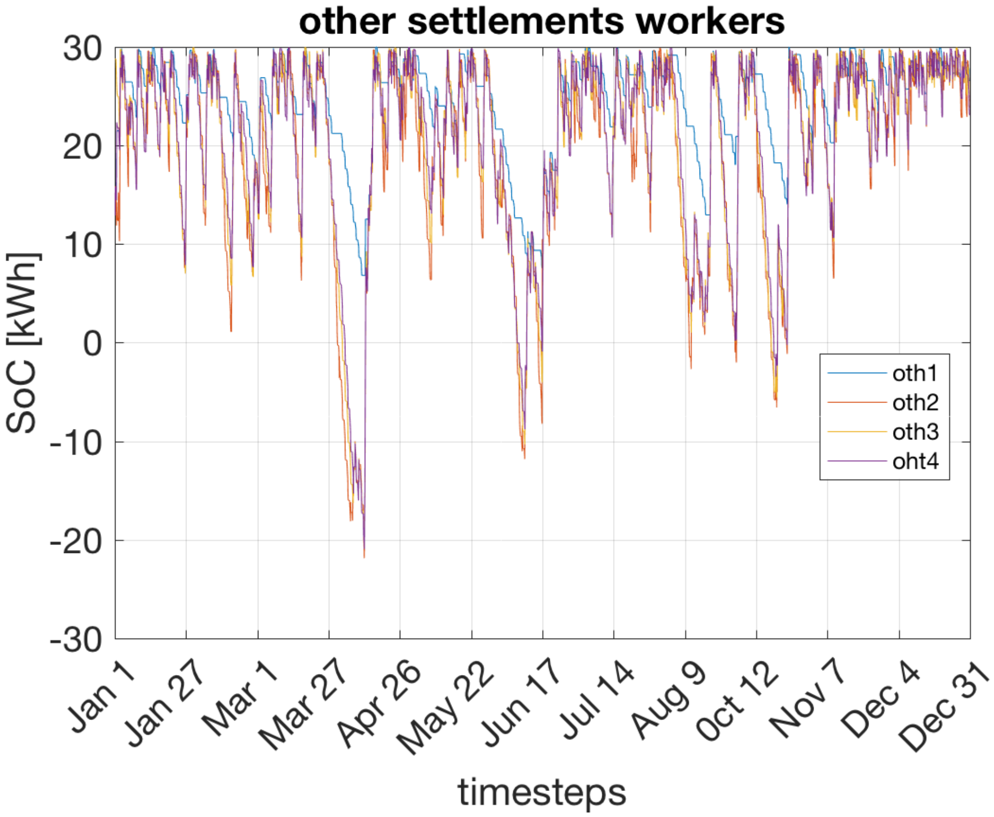

Figure 13: other settlements workers vehicles SoC trends

Figure 14: unemployed and retired vehicles SoC trends

As the graphs display, it is evident that there are some critical intervals in which, in different proportions, the present state of charge becomes lower than zero. In particular, due to its extremely high daily mileage, the delivery vehicles subcategory turns out to be the most problematic one, with negative peaks that reach approximately -70 kWh. The Traffic Model estimated the typical weekday mileage for a delivery vehicle to be around 196.1 km. This value floats around the autonomy of an electric vehicle. Therefore, it can be stated that using EVs for delivery in Orkney is too hazardous and uncertain. Hence, the decision of removing from the Simulation Model delivery subcategory has taken. Moreover, this decision could lead to more fitting SoC trends for the 19 subcategories left.

Graphs below show which are the state of charge trends, after removing delivery vehicles from the model.

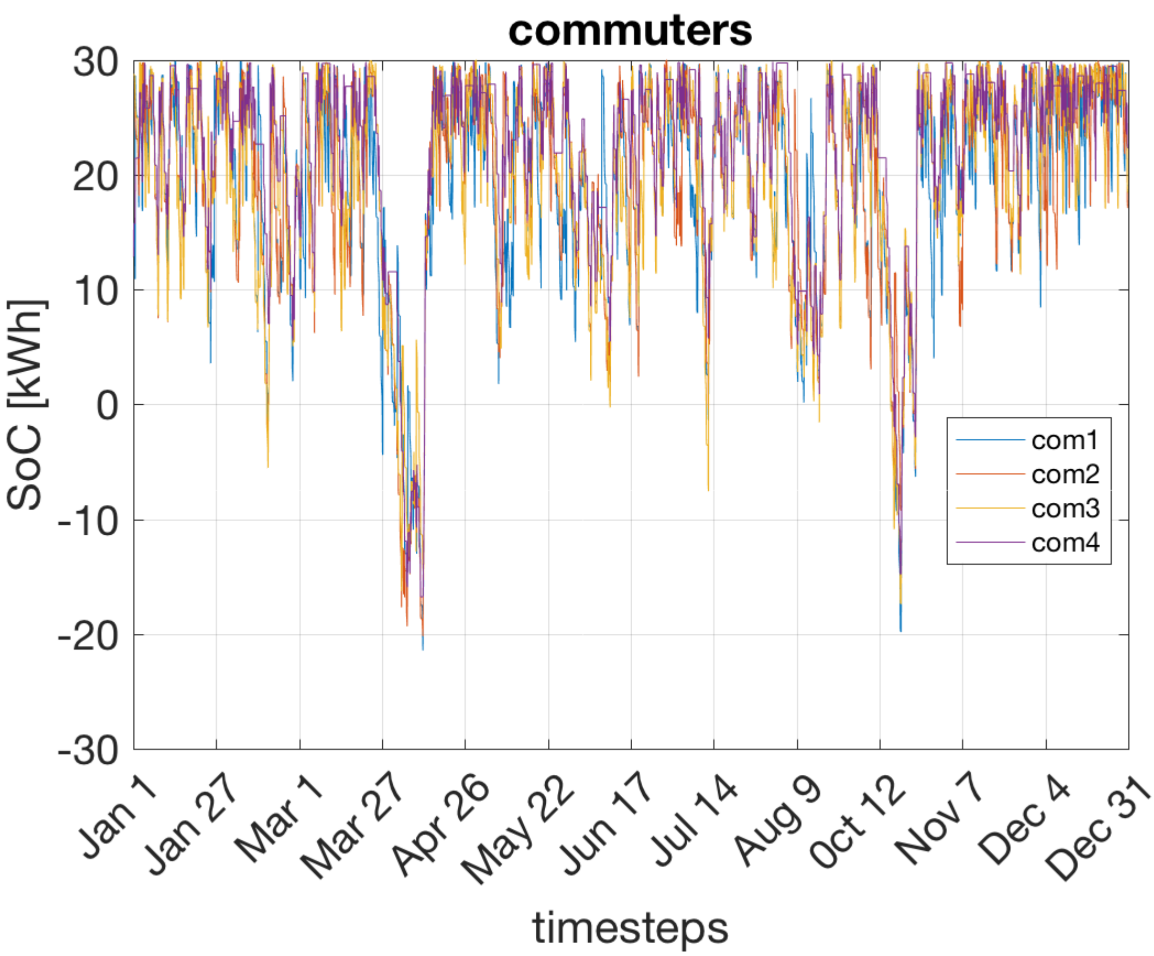

Figure 15: commuters vehicles SoC trends after removing delivery vehicles from the model

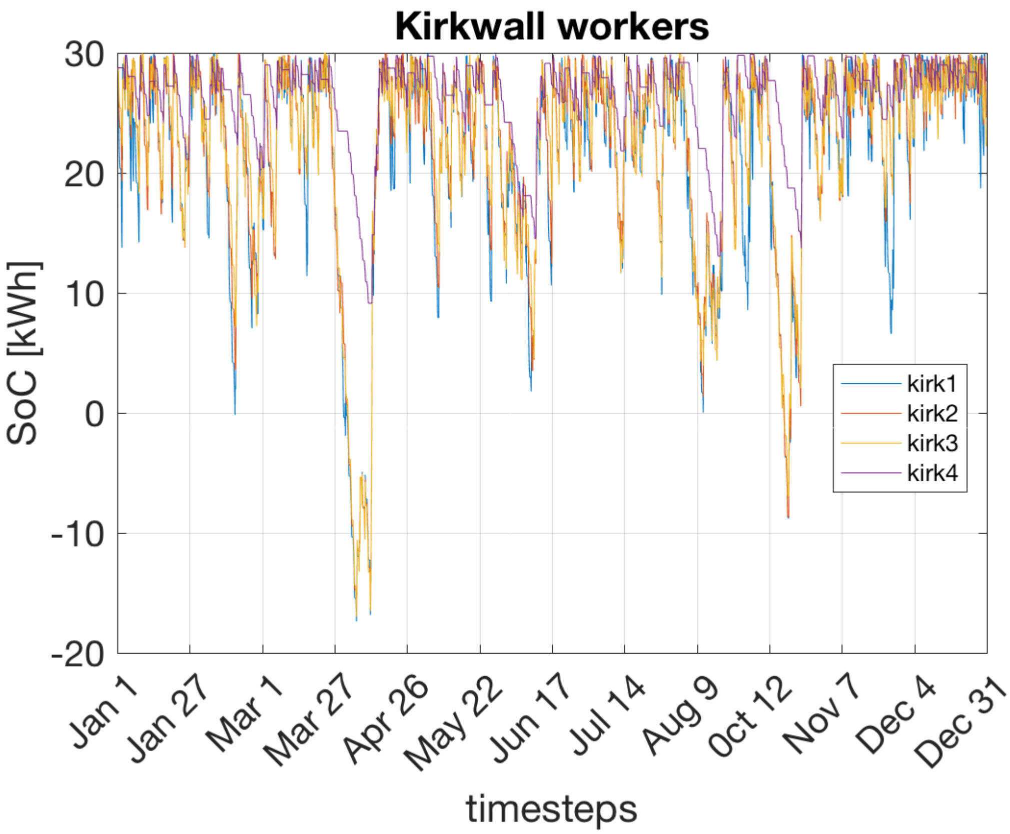

Figure 16: Kirkwall workers vehicles SoC trends after removing delivery vehicles from the model

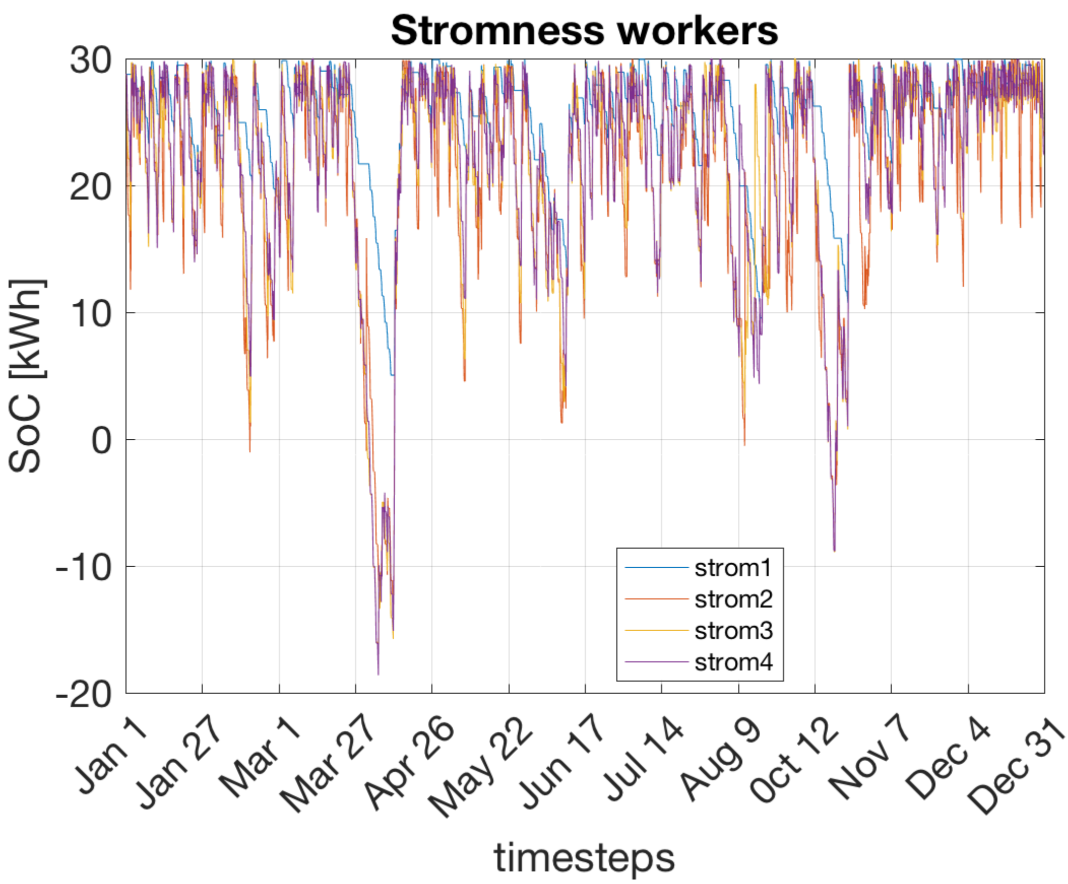

Figure 17: Stromness workers vehicles SoC trends after removing delivery vehicles from the model

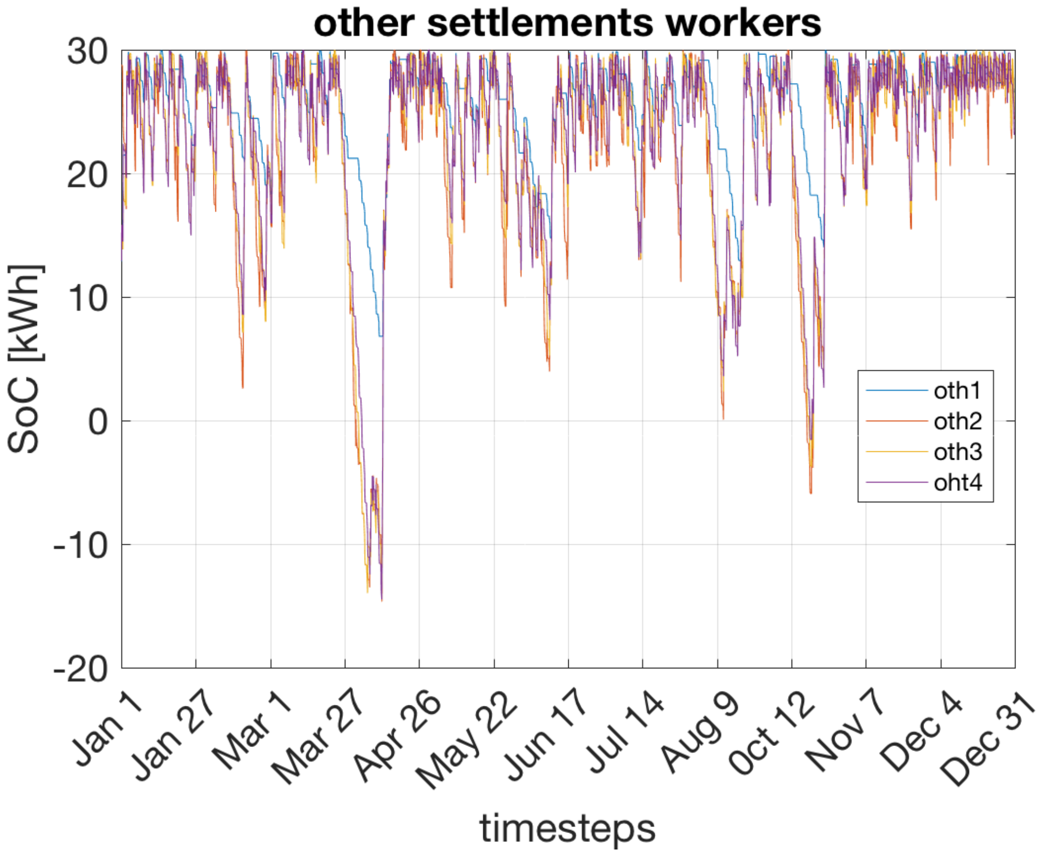

Figure 18: other settlements workers vehicles SoC trends after removing delivery vehicles from the model

Figure 19: unemployed and retired vehicles SoC trends after removing delivery vehicles from the model

At first glance, it seems that negative SoC peaks are less and toned down. This is easily explained because the same amount of electricity is used for charging a smaller number of electric vehicles. Moreover, since the model modus operandi provides for charging first EVs with the lowest SoC, removing delivery vehicles allows to charge in several critical time steps EVs that before were not charged.

The following bar graph displays the reductions of “problematic” time steps.

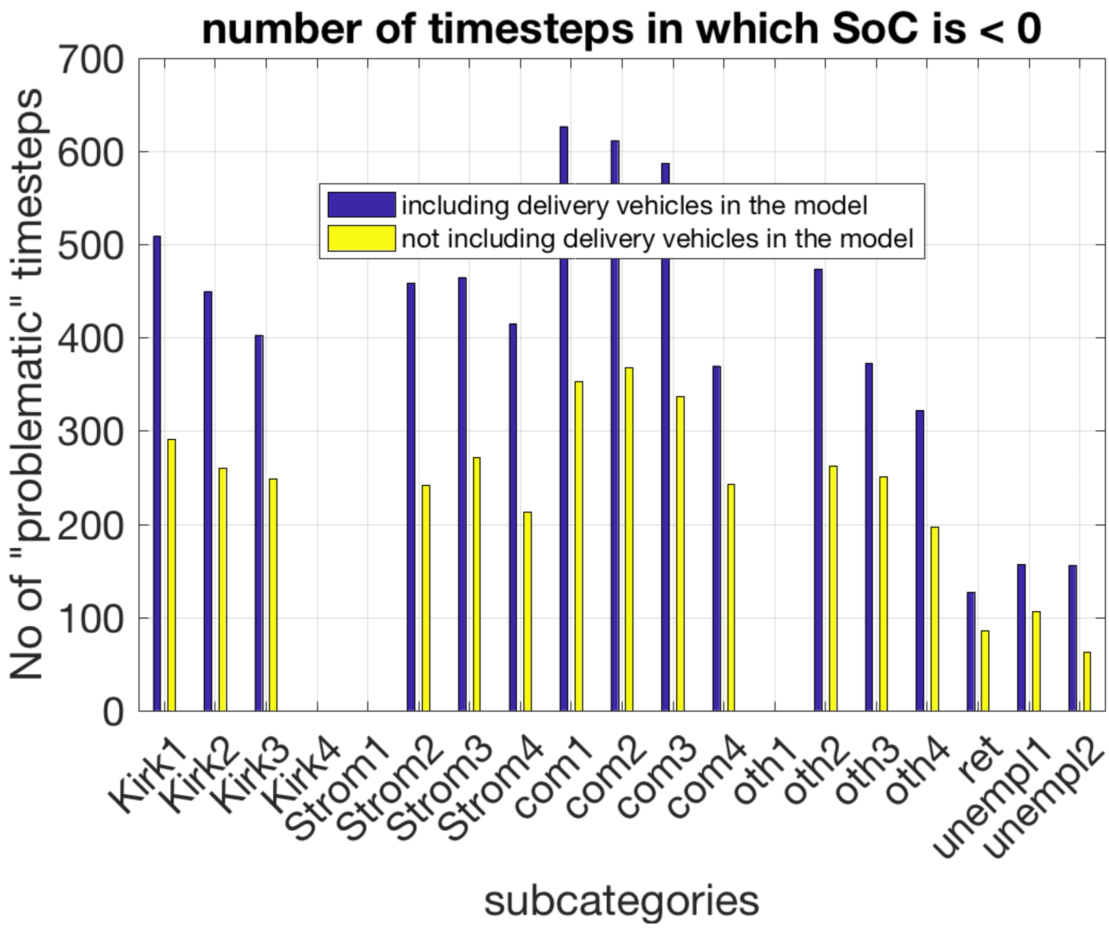

Figure 20: number of time steps in which state of charge is negative

It is relevant to observe that, for the subcategories “Kirk4”, “Strom1” and “oth1”, the respective state of charge is never less than zero over the entire time domain. This can be explained analysing again how the subcategories were formed. Table 16 and Table 17 display that these three subcategories have a common peculiarity: all of them do not include “Leisure/sport” journey type in their daily profile. This journey type accounts for the majority of *Kirkwall workers, Stromness workers and other settlements workers* categories daily mileage. Specifically, vehicles belonging to these subcategories are characterised by significantly lower daily mileage. This issue is child of the simplification made in *Traffic Model* in the creation process of the subcategories. It is worth to mention anew that is nearly impossible to standardise and then simulate the exact behaviour of all the vehicles. Therefore individual vehicle results must be taken with a grain of salt; nonetheless, the granularity level is high enough to consider the *Simulation Model* accurate.

This concern is also visible in Figures 15, 16, 17: *Kirk4, Strom1* and *oth1* SoC trends never assume values lower than zero because these EVs subcategories are characterised by a lower daily mileage than the others.

Table 25 displays how results vary after removing delivery vehicles from *Simulation Model.*

RESULTS COMPARISON	**including delivery vehicles in the model**		**not including delivery vehicles in the model**	
	GWh	percentage	GWh	percentage
total curtailments	41.183	100%	41.283	100%
total electricity used for EVs charging	19.762	47.9%	18.326	44,4%
total residual electricity	21.521	52.1%	22.957	55,6%

Table 25: results comparison after removing delivery vehicles from the model

This leads to an increase in the total residual electricity and a decrease in the total electricity used for EVs charging. Figure 21 shows how small these variations are. Delivery vehicles consist in a small fraction of the entire body car. For this reason, although they are defined by highest daily mileage, their electricity consumption accounts just for an irrelevant percentage of the total electricity used for EVs charging.

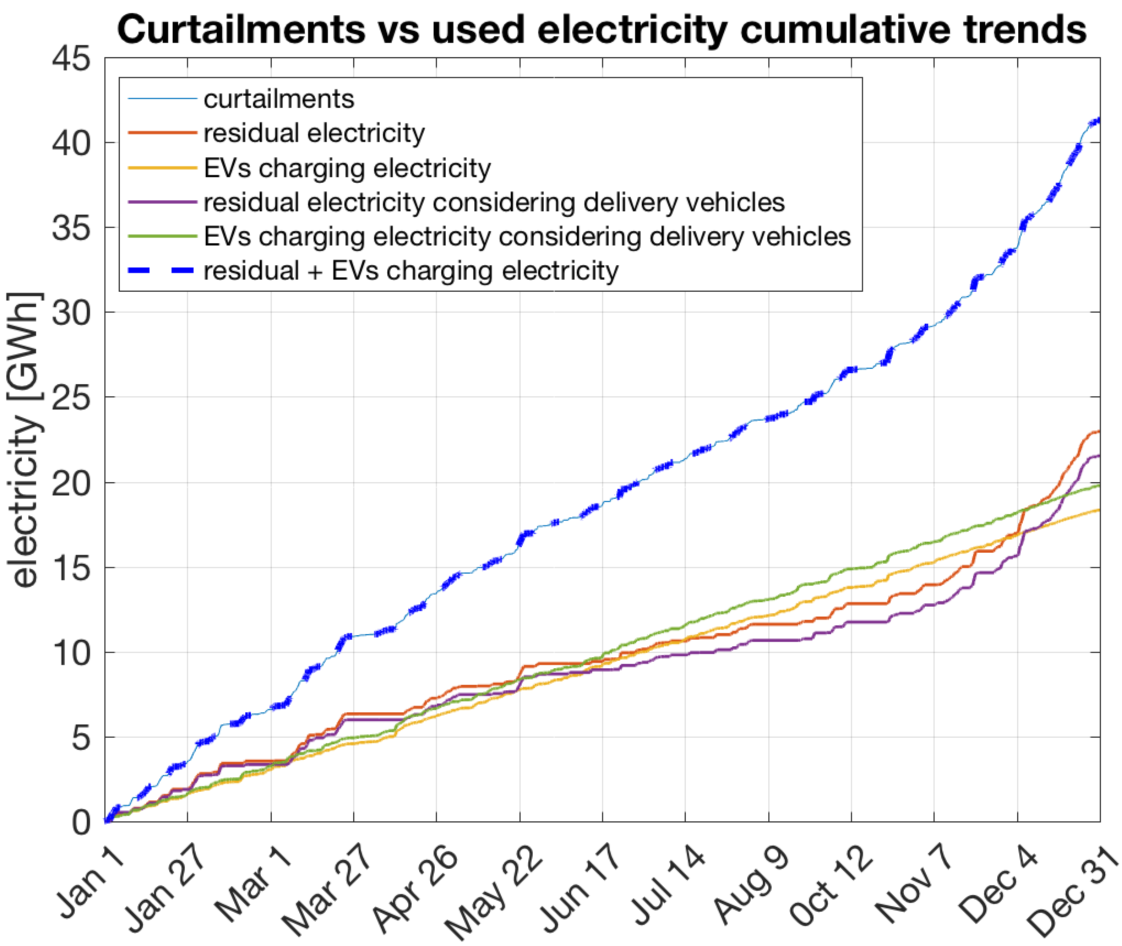

Figure 21: results trends comparison after removing delivery vehicles from the model

In conclusion of this section, it can be stated that the wind curtailed electricity is not sufficient to support a full introduction of electric vehicles in Orkney. More precisely, since wind power is an intermittent, variable and weather conditions dependent, the curtailed wind electricity cannot guarantee the demand meeting for each of the domain. Nonetheless, cumulative sum results prove that the total amount of curtailed wind electricity is more than twice the electricity needed for charging electric vehicles.

For this very reason, in the following, possible improvements of the model, that guarantee an always higher than zero state of charge for all EVs, will be presented in detail.

The amount of Hydrogen needed to fuel all Orkney buses is 75.16 tons of Hydrogen. The total Hydrogen production from residual electricity results to be around 410 tons.

Figure 22 below shows how is feasible to develop a 100% fuel buses environment in Orkney, only producing Hydrogen from a really small fraction of the curtailed wind electricity.

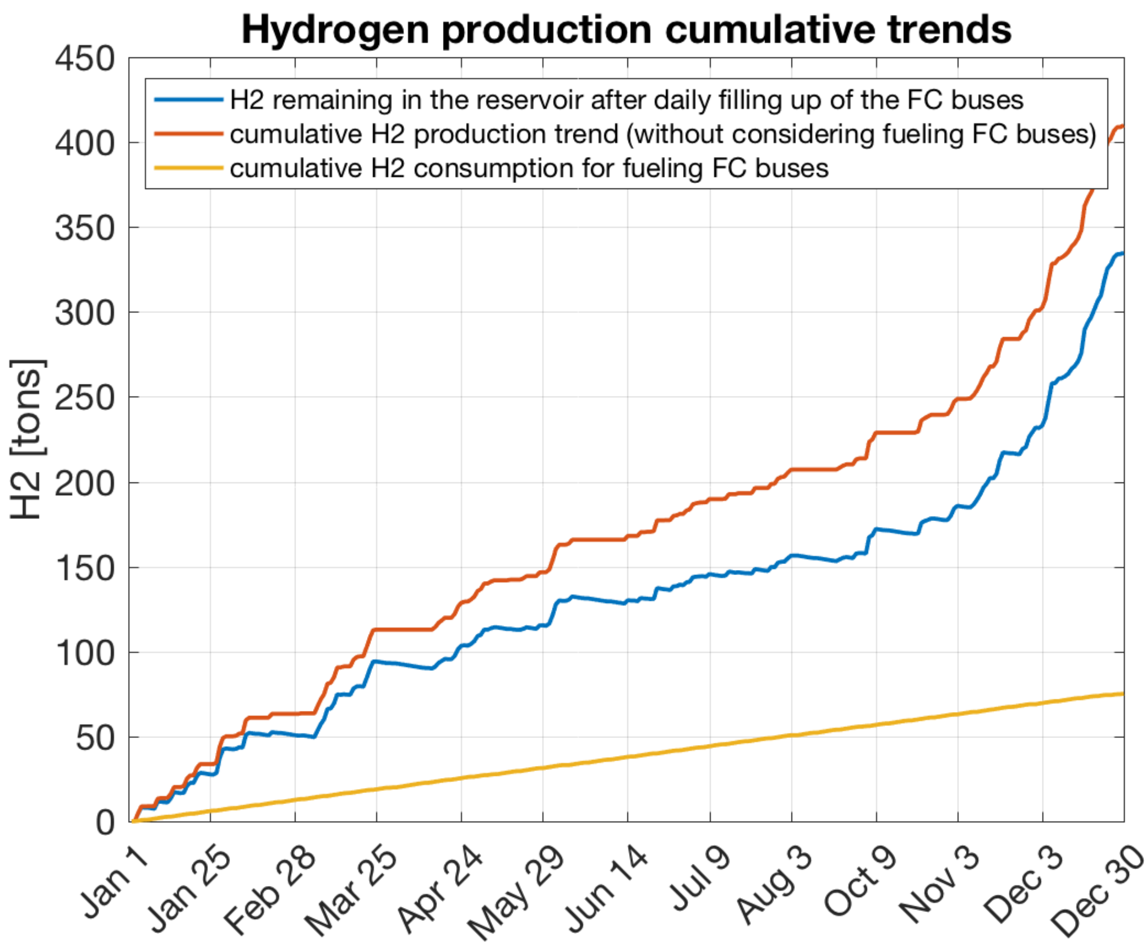

Figure 22: hydrogen production cumulative trends

It is worth to put in evidence that, the amount of hydrogen needed to fuel FC buses is more than four times smaller than the total amount of hydrogen produced from the residual electricity. This aspect can lead to a smaller hydrogen production & storage system sizing (in this case, a fraction of wind curtailed electricity would result lost) or to other additional usages of produced hydrogen, such as the introduction of hydrogen vehicles.

4.2. Consideration & possible improvements

From the overall results point of view, the model seems confirming the possibility of developing a 100% free-carbon road transport system in Orkney (at least considering body-type cars and bus public transport). However, as we discussed previously, in certain periods of the year curtailed wind electricity cannot assure the complete charging of all the EVs.

In particular, as things currently stand, commuter subcategory, which is the subcategory characterised by the highest daily mileage, experiences long-lasting negative state of charge lower than zero on February 19th, in the beginnings of April (2nd-4th and 10th-13th), on July 11th-12th, in the second half of October (16th-19th and 23rd), in addition to single isolated time step scattered across the temporal domain. Negative SoC peaks reach -20 kWh.

Concerning the other subcategories, they experience a lower amount of negative SoC time steps and negative SoC peaks are around -10 kWh. Nevertheless, negative SoC periods remain a big issue for these subcategories for these subcategories.

This part aims to describe new possible model configurations capable the prevent occurrence of the so-called 'problematic' time steps, in which any EV is characterised by a negative state of charge.

Suggested model modifications, from the simplest and easily applicable, to the most challenging and onerous, both from the technical and the economical point of view, are the following:

- Reduce the electric vehicles' number. The same amount of curtailed wind electricity per time step would be used for charging a smaller number of EVs;
- Use grid electricity for 'critical' time steps: when curtailments profile cannot guarantee an adequate EVs charging, the required electricity is directly taken from Orkney electric grid. However, this could lead to electricity network overload in peak hours and could require a renovation process of the electricity network;
- Introduction of hydrogen vehicles: since, as explained above, hydrogen production capability is more than four times higher than the amount of hydrogen actually needed for fuelling FC buses, a H2 vehicles deployment could be considered. Replacing a fraction of EVs with H2 cars would mean reducing the total amount of electricity needed for EVs charging purpose (cutting down the problem of the 'problematic' time steps) and at the same time increasing the amount of used hydrogen, justifying once more electrolysers installation;
- Increase wind power capacity: considered the Orkney wind potential, installing new wind turbines might be a legitimate intention. This would lead to a higher wind production and subsequently to higher wind curtailments profile. A greater amount of wind curtailed electricity could bring to avoid 'problematic' time steps;
- Consider installation of hydrogen turbine in order to produce additional electricity in the 'problematic' time steps.

4.3. First model modification

The first simple model modification, consists in decreasing gradually the number of electric vehicles. In order to appreciate the reduction of 'problematic' time steps number, the simulation was performed several times, each time varying the fraction of EVs, recording the number of time steps in which any state of charge of an EV was lower than zero. Results are displayed in Figure 23.

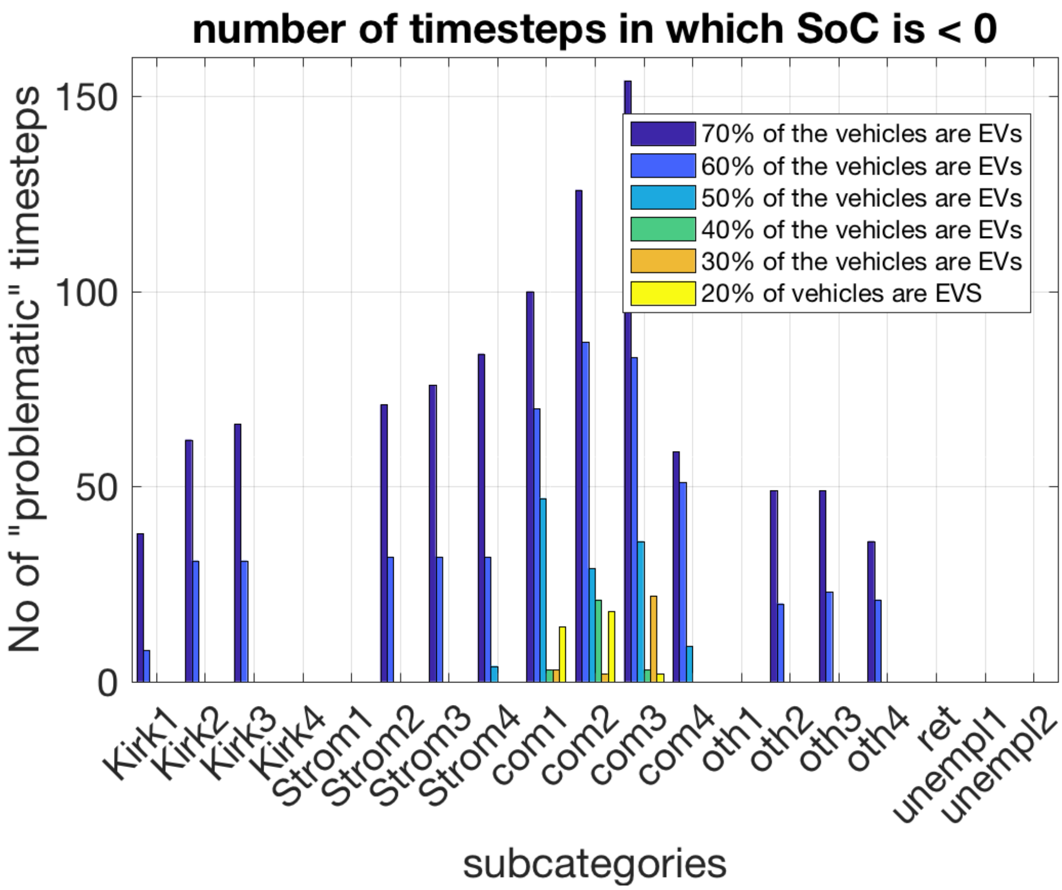

Figure 23: "problematic" time steps drop compared with EVs number reduction

Figure 24 let us better understand how the number of 'problematic' time steps dramatically decreases. The number of failures, intended as the total number of time steps in which any EV's state of charge is lower than zero, is shown in Figure 24.

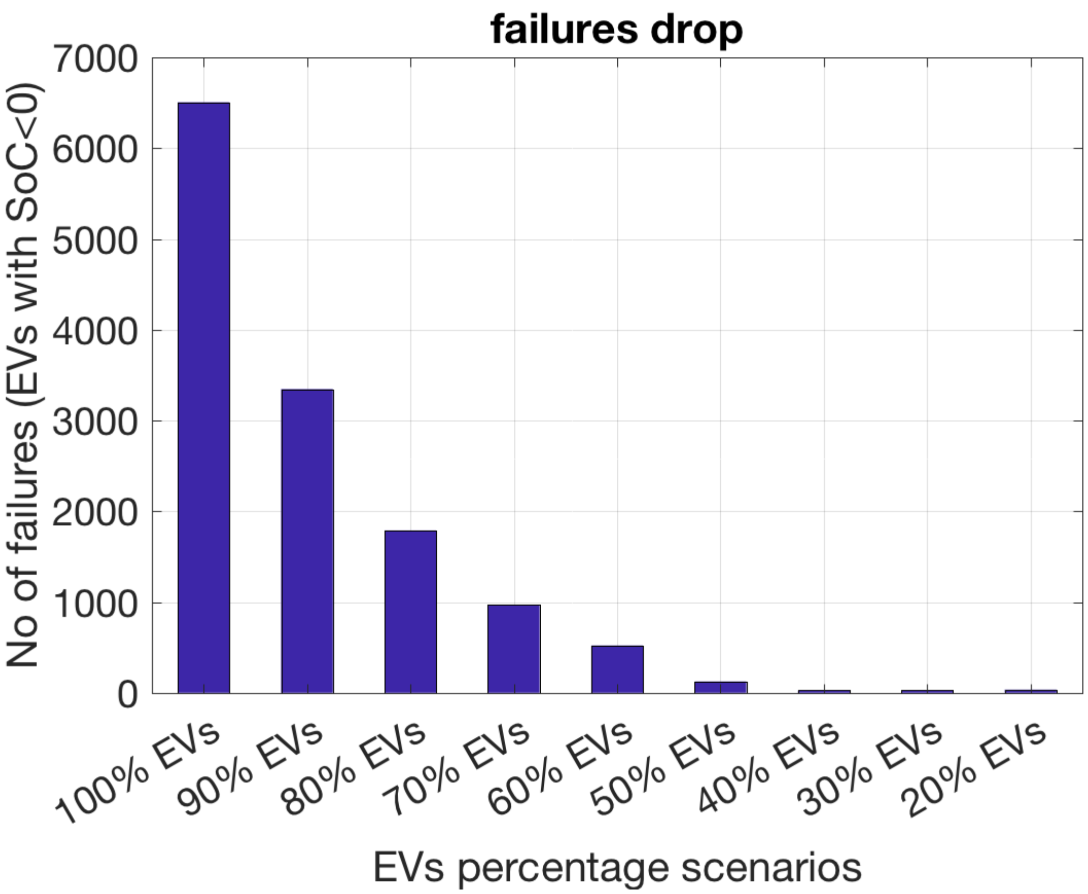

Figure 24: overall number of "problematic" time steps drop

The number of failures decreases exponentially with the reduction of EVs. By diminishing electric vehicles number by 30%, the number of failures comes to be more than six times smaller.

On the other hand, as Figure 15 well displays, the 'problematic' time steps issue persists (although in a extremely lower scale) even reducing significantly the EVs fraction in the model. The intermittent and unpredictable nature of wind power generation is echoed in the curtailments profile. As analysed previously, there are at least two periods of the temporal domain in which, for some reasons, the scarcity of wind curtailed electricity leads to the inability of charging properly all the EVs in those periods.

Finally, decreasing the EVs total amount, decreases consequently the share of curtailed electricity used for EVs charging purposes. As Figure 25 demonstrates, while for a 100% EVs environment the electricity used for EVs charging is slightly lower than 50% of the total curtailed electricity, reducing the EVs fraction, it drops gradually up to less than 10% of the total curtailed electricity.

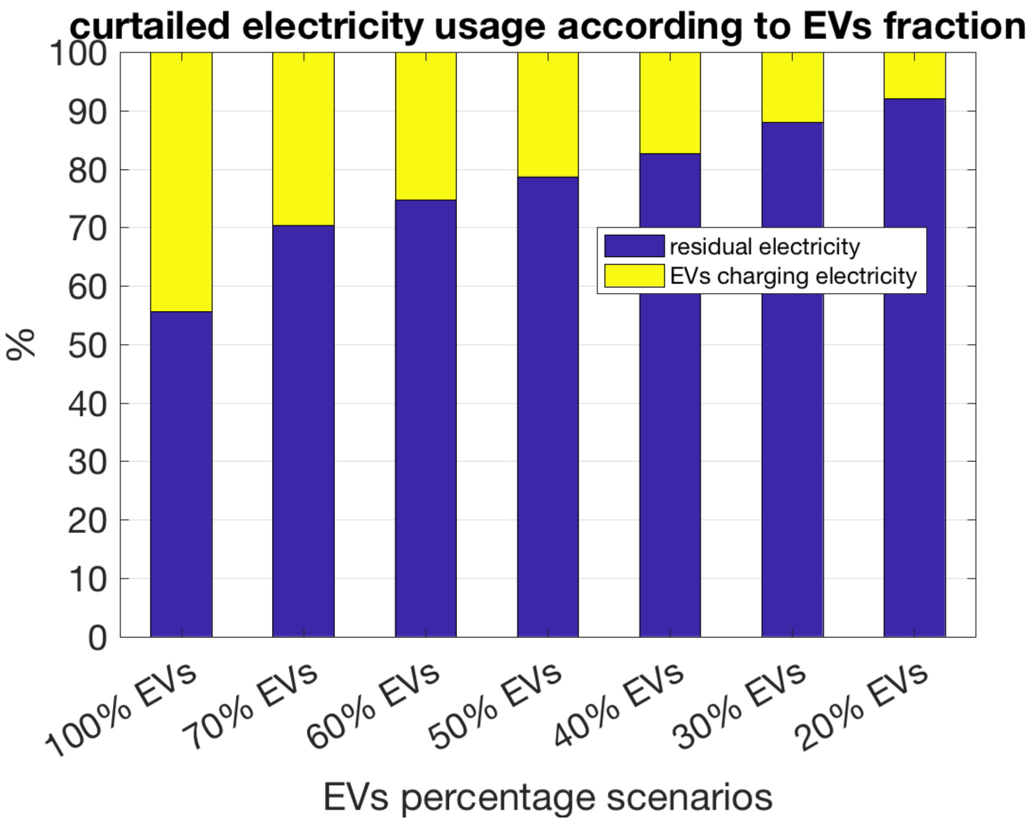

Figure 25: how curtailed wind electricity is used according to EVs number

Hence, rather than decreasing dramatically electric vehicles' number, it is more suitable to maintain an adequately high fraction of EVs in the model, guaranteeing a smart use of the curtailed electricity, and search for other solution to fix the 'problematic' time steps concern.

4.4. Second model modification

The second modification approach is complementary to the first one. Keeping the fraction of EVs sufficiently high, it will be calculated the amount of grid electricity needed to avoid any failure.

This model modification prescribes for each time step, according to the availability of slow chargers, the possibility of charging electric vehicles that have not yet been charged, if their state of charge is lower than a fixed threshold, approximately equal to 10% of the battery. More exhaustively, if the current time step is characterised by a non-zero curtailment, wind curtailed electricity is in first place used for EVs charging purposes. Thereafter, if there are still EVs with SoC lower than the established threshold that have not been charged in the current time step, and if there are still chargers that have not been used in the current time step, these EVs are charged using grid electricity. Therefore, charging priority is any case given to wind curtailed electricity. On the other hand, if the current time step's curtailment is equal to zero, it is possible to charge EVs with grid electricity, only if their state of charge is lower than 10%.

This modification ensures on one side the minimal use of grid electricity: it is used for EVs charging purposes only when their SoCs are critical. On the other side, it guarantees that each EV is characterised by a positive state of charge over the whole temporal domain.

Figure 26 displays the grid electricity intervention: peaks in its usage occur exactly in those year periods in which 'problematic' time steps issue previously arose.

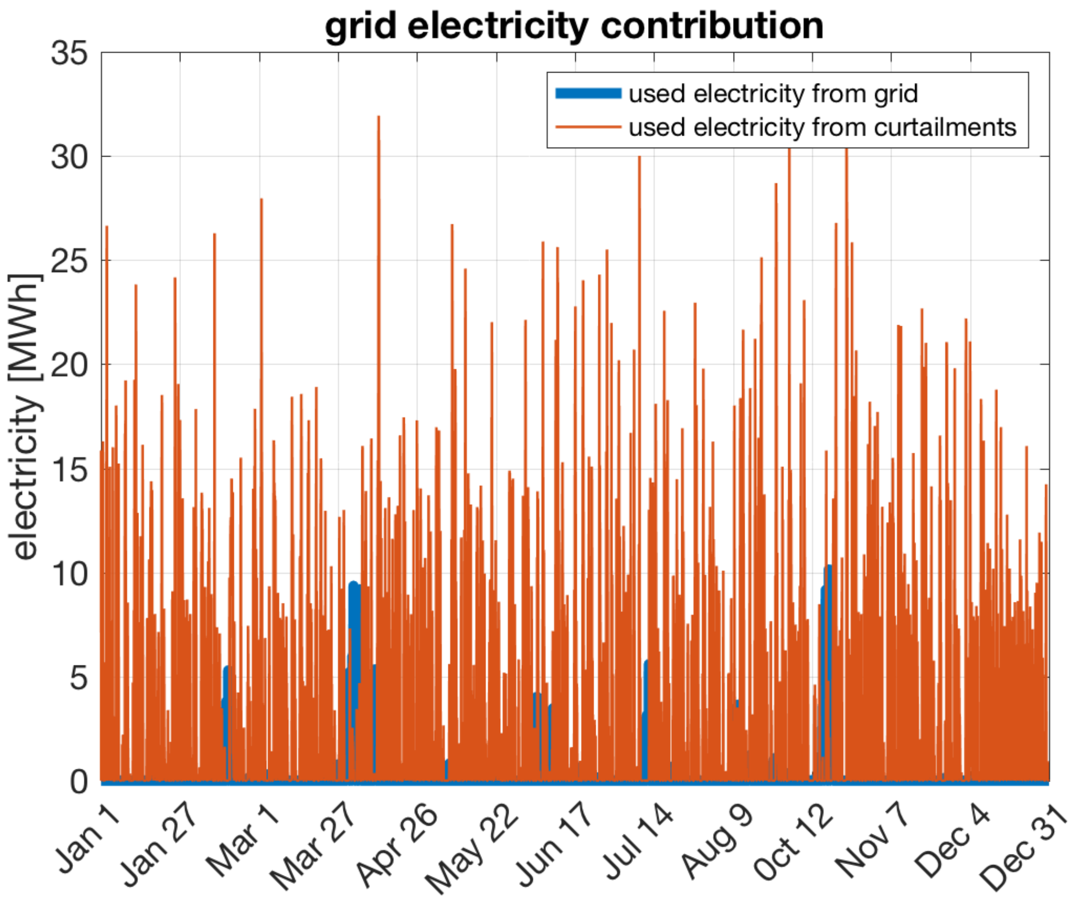

Figure 26: grid electricity contribution

Furthermore, it is relevant to remark that grid electricity gives its contribution mainly in periods in which curtailments profile significantly drops for a prolonged number of time steps.

The total amount of used grid electricity is equal to 408.2 MWh: 77% of this quantity takes place in time steps in which there are no curtailments. Hence, grid electricity has principally the function of fictitious back-up power source: as a consequence of a limited energy storage (namely the 30 kWh EV batteries) and due to the aleatory and intermittent profile of wind curtailed electricity, its intervention is essential to ensure the necessary charging capability over the whole temporal domain.

Figure 27 shows how the electricity taken from the grid represents a really modest percentage of the total amount electricity used for EVs charging function.

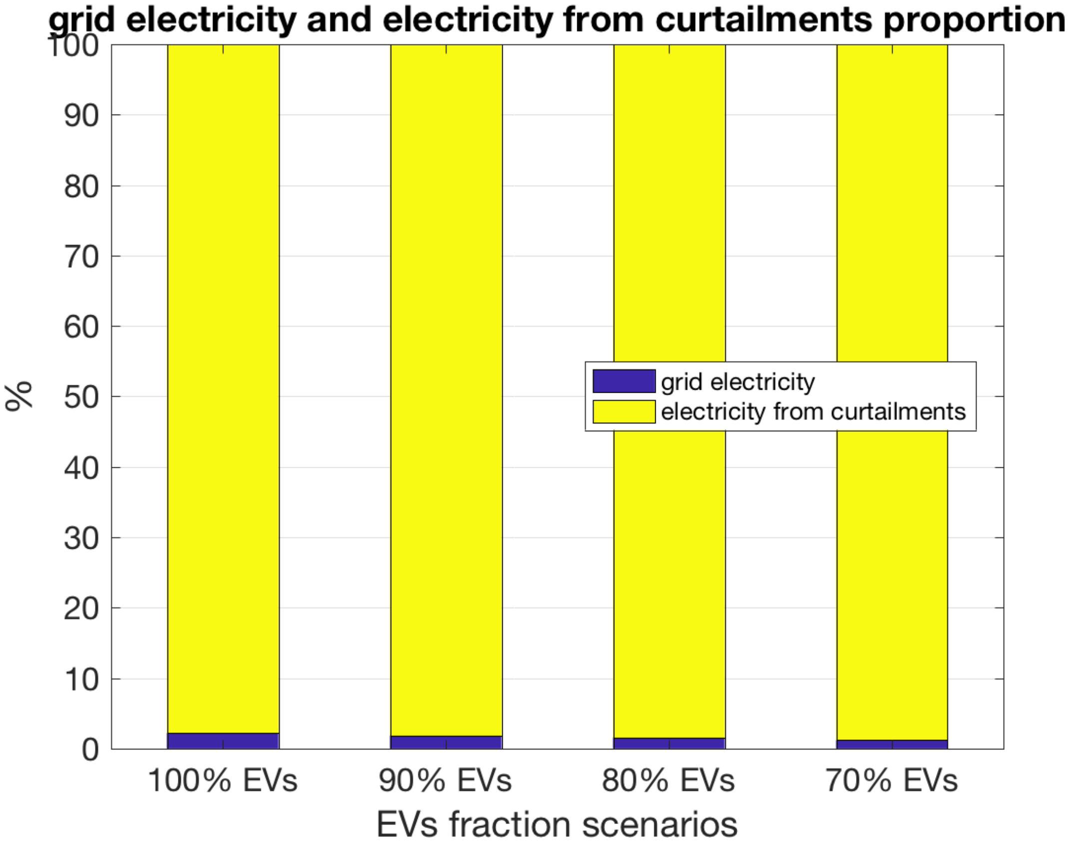

Figure 27: grid electricity and curtailed used electricity share in EVs charging

Grid electricity usage varies from 2.2% of the total used electricity when all body-type cars in Orkney are EVs to 1.2% of the total used electricity when 70% of the body-type cars in Orkney are EVs.

Conclusively, this section analysis, proves that, in absence of adequate energy storage systems, the use of electricity coming from the exterior is crucial.

4.5. Third model modification

Having established that use of electricity coming from the grid is necessary in any case, it is opportune to seek a system configuration characterised by the lowest carbon footprint. Therefore, targets consist, on the one hand, in exploiting as much as possible curtailed wind electricity, and on the other hand, using to the least extent possible electricity coming from the grid.

The strong constraint represented by the target of avoiding 'problematic' time steps is still binding. This section prescribes the introduction of Fuel Cell Electric Vehicles (FCEV) in the model. Fuel Cell Electric Vehicles represent a viable and attractive opportunity to secure more sustainable transport, using a powertrain technology that is clean, efficient and makes better use of natural resources. Using hydrogen gas as a fuel for generating electric power, FCEVs produce no harmful tailpipe emissions when being driven – only water vapour. The system they use is durable and compact and provides a consistent driving character regardless of the environment or climate, so consumers experience no major compromises in terms of practicality and performance compared to conventional petrol and diesel-powered vehicles.

There are currently only two FCEV models available to own in the UK –Hyundai's ix35 fuel cell and the Toyota Mirai- though they will be joined by the Honda's Clarity Fuel Cell in 2018.

The current hydrogen refilling infrastructure (more precisely the lack or scarcity of it) represents the biggest constraint to a wide FCEVs deployment: currently there are less than half a dozen publicly available refilling stations in UK. The technology is more restrictive than buying a battery electric car since at least most people have access to a home-based socket with which to charge the EV. Given that very few households have a hydrogen refuelling unit in their garage, living within a convenient distance of a public hydrogen refuelling station is essential. Apart from the lack of locations, refuelling a FCEV is almost as simple and quick as using a petrol pump, and anyone who has used an LPG vehicle will find plenty of similarities. The driver fixes the refuelling station's nozzle to the car and locks it in place creating a sealed system. Using a state-of-the-art 70 MPa refuelling dispenser, a few minutes refuel will provide most FCEVs with around 300 of range miles - as opposed to the half an hour rapid charge for a battery electric car offering around 100 miles of driving.

In terms of tailpipe emissions, like fully electric vehicles, FCEVs are a technology that can be used for improving air quality. The only emission from a Fuel Cell Electric Vehicle is water vapour. On the other hand, in terms of non-tailpipe emissions, a distinction must be made according to the energy sources that generate hydrogen (or electricity in the EVs' case): in this project the primary energy source consists in the wind curtailed electricity, which is non-pollutant, as it comes from wind energy [54].

At the present only a few models are commercially available. Unfortunately, these remain expensive compared to similarly sized petrol, diesel or even battery electric rivals. Toyota's Mirai, for example, costs around £60,000 with Toyota expected to lose money on every one sold. This price includes the £4,500 Category 1 UK Plug-in Car Grant (PiCG) which includes the Mirai as an eligible vehicle.

In the UK, it isn't yet possible to buy a FCEV outright; Hyundai and Toyota only offer cars on lease. While this is mainly due to the limited refuelling infrastructure, it also protects owners from any technical and durability issues associated with a new technology. Hydrogen is sold in kilograms rather than volume (litres or gallons), and current prices are around £10 to £15 per kg. As the Mirai's tank holds approximately 5 kg, a full hydrogen refill would cost between £50 and £75 meaning that hydrogen FCEVS are more expensive per distance able to travel than both internal combustion vehicles and EVs. With increased hydrogen use though, costs are likely to come down in the future. Manufacturers are removing this problem though by incorporating fuel costs into the cost of the lease.

The rest of the car's running costs again bear a close resemblance to EVs: servicing costs are significantly less than an internal combustion car because of reduced numbers of moving parts, while consumables such as brake pads are used less because of brake energy recuperation.

For these reasons the share of introduced FCEVs only varies between 5% and 20%.

As for the electric vehicles modelling phase, the model generates randomly the initial state of charge of each FCEV (expressed in H_2 kg in the tank). On the other hand, the charging mechanism is slightly different: FCEV are filled up completely only if their tank level is below 15%, and only during daytime. Furthermore, refuelling process takes place only if the hydrogen storage is sufficiently high to ensure daily refilling of FC buses.

Hence, in this case the filling process of FCEVs is made possible by the hydrogen storage, produced over the whole temporal domain with the wind curtailed electricity not used for EVs charging purposes. Thus, the authentic source of energy, both for EVs, FCEVs and FC buses charging, is wind energy.

In conclusion, the only non-clean contribute could come from the grid electricity: even though, as we discussed before, main electrical supply for Orkney comes from a mix of wind farms, small point-of-use windmills, PV panels installed on homes or workplaces. In addition to the current wind and solar capacity, Orkney is a test bed for experiments in tidal and wave power. Nevertheless, traditional power generation systems, such as Kirkwall Power station and Flotta gas turbine continue to produce electricity, even though their contribute in Orkney electricity mix is progressively decreasing and they work essentially as back-up electricity sources.

However, there are also times that the renewables, together with the traditional power sources, do not meet local demand for power, which then requires importing power from the mainland. In 2015, Orkney imported power every month of the year, and was a net importer seven month of the year

[55].

Imported electricity comes from GB electricity transmission network. More in detail, renewables were the single largest source of electricity generated in Scotland in 2015 (42%)- higher than both nuclear generation (35%) and fossil fuels generation (22%) [56].

Therefore, in order to pursue the highest carbon-free scenario, it is important to limit as much as possible the use of the grid electricity.

Table 21 shows how electricity shares vary with EVs variation.

% EV - % FCEV	wind curtailed electricity [GWh]	EV charging used electricity [GWh]	residual electricity [GWh]	grid electricity [GWh]
95% EV - 5% FCEV	41,286	17,031	24,251	0,3429
90 % EV - 10% FCEV	41,286	16,1237	25,1589	0,2969
85 % EV -15% FCEV	41,286	15,3225	25,9601	0,2638
80% EV - 20% FCEV	41,286	14,4458	26,8368	0,2309

Table 26: electricity utilisation share according to different body-type car scenarios

Decreasing the number of electric vehicles, both the contributions of curtailed electricity and electricity taken from the grid used for EVs charging purposes decrease, while residual electricity share consequently increases.

At this stage level, the entire amount of residual electricity feeds the electrolysers that produce hydrogen. Table 22 displays how generated hydrogen is used.

% EV - % FCEV	H_2 used for fueling FC buses [tons]	H_2 used for fueling FCEV [tons]	stocked H_2 [tons]
95% EV - 5% FCEV	75,157	48,956	308,947
90 % EV - 10% FCEV	75,157	98,0291	276,0807
85 % EV -15% FCEV	75,157	140,8584	247,5592
80% EV - 20% FCEV	75,157	187,5701	216,5025

Table 27: hydrogen utilisation share according to different body-type car scenarios

The amount of hydrogen employed for fuel cell electric vehicles filling up increases with the number of FCEVs, while, on the contrary, the tons of stocked hydrogen decrease.

Even in the scenario with the highest number of FCEVs, the amount of stocked hydrogen at the end of the simulation is remarkably high. Thus, it is necessary to size properly the hydrogen production

& storage system. The reasons for implementing this measure essentially lie in economical and practical considerations: not sizing accurately the hydrogen production system would lead to an extremely high nominal peak power of the electrolysers, and subsequent excessively low utilisation factor of the latter. ITM's most commonly deployed electrolyser models nowadays in Orkney are 1 MW or 500 kW. Nonetheless, ITM electrolysers are designed to customer specifications and can be produced in many sizes from 100kW to Multi MW. Furthermore, electrolysers efficiency varies with the load. Electrolyser system efficiency of 70% HHV or 56 kWh/kg at rated power is a good assumption. (If the model is to look at part load operation then linear increase to a peak efficiency of about 78% (50kWh/kg) at 50% load then it falls off to 70% at 40% load and drops away below that).

From the model, the highest of residual electricity over the whole temporal domain results to be 44.12 MW, while its average value (considering only time steps in which residual electricity is non-zero, i.e. it is possible to produce hydrogen) is equal to 7.79 MW. The choice of rated nominal power of the H2 production system must, on one side, maximise the utilisation factor of the electrolysers and on the other side ensure the filling up process of EVFC cars and FC buses over the whole temporal domain.

Subsequently, rated nominal power influences the size of the hydrogen storage system and its cost.

The hydrogen production & storage sizing process has been performed iteratively, introducing in the model two controls, driven by two important parameters:

- electrolysers total rated power: it influences directly hydrogen production. When the residual electricity of the current time step is higher than nominal power, the electrolysers group works at full load (the remaining part of residual electricity is unused). On the other hand, when residual electricity is lower than nominal power, the electrolysers group works at partial load. The electrolysers group efficiency has been selected considering the overall utilization factor of the latter.
- Hydrogen storage system size: represents the maximum amount of H_2 that can be stocked. This means, that in the model, H_2 will not be produced if the maximum capacity of the storage system is already reached.

As a consequence, it results that a fraction of residual electricity will remain unused.

The chosen scenario in which perform H_2 production & storage system sizing is the one with 95% share of EVs and 5% share of FCEVs.

The total rated power of the electrolysers group results to be 8.7 MW, while the overall size of the hydrogen tanks is equal 7 tons.

Figure 28 displays the state of charge of the hydrogen storage across the temporal domain, compared with daily hydrogen production and with daily hydrogen consumption, distinguishing between FC buses and FCEVs H_2 utilization.

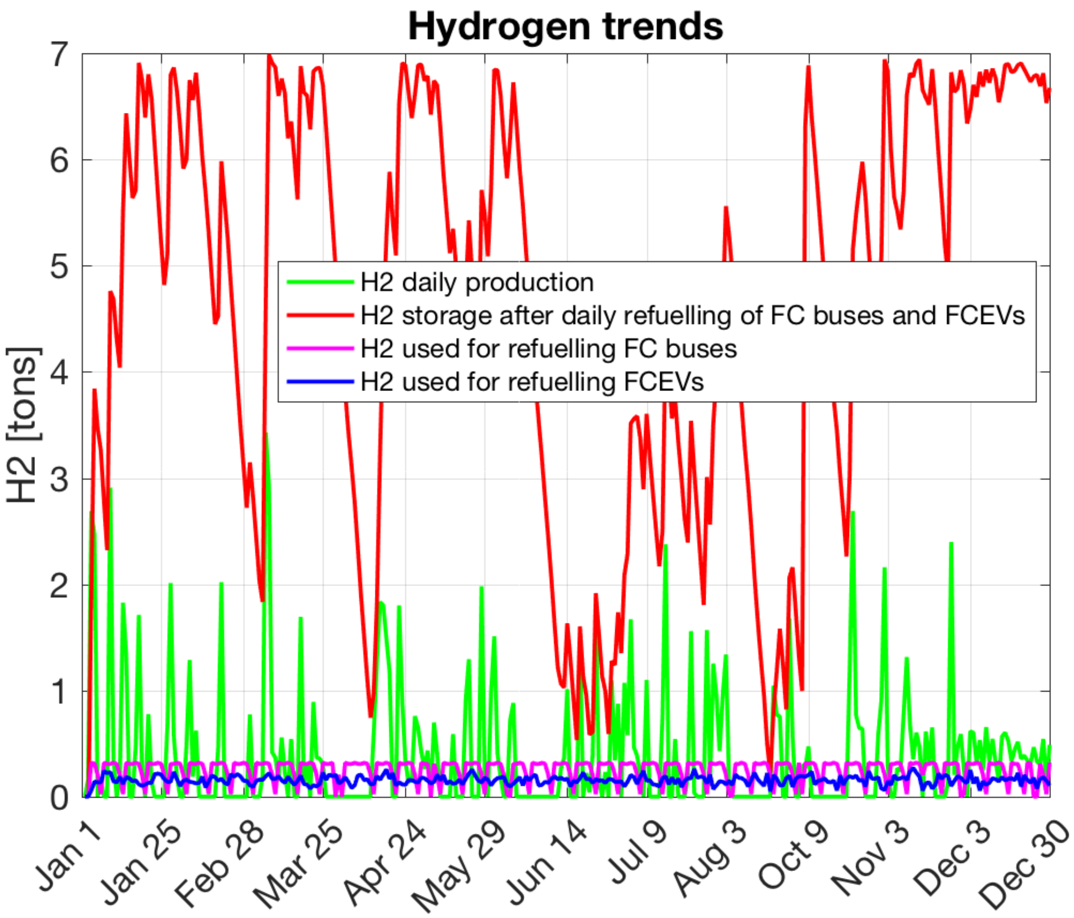

Figure 28: H_2 storage state of charge compared with daily H_2 production and consumption trends

Considering the hydrogen reservoir empty and the beginning of the simulation, the electrolysers group is able to reach the maximum tank capacity by the end of January, due to high wind generation. Nevertheless, when wind curtailed electricity is extremely low and can barely satisfy demand for electric vehicles charging, hydrogen production cannot take place. In particular, during summer, when wind blows with lower intensity than in winter and in autumn, the hydrogen storage system experiences significant drops in stored hydrogen level.

Furthermore, as a consequence of sizing H2 production and storage system, a fraction of the residual electricity is not used for hydrogen production. At this modelling level, the possibilities of not exploiting entirely wind curtailed electricity are the following:

- After charging EVs in the current time step, the residual electricity is higher than the electrolysers group peak power;
- After charging EVs in the current time step, there is no need to use the total amount of curtailed electricity due to hydrogen storage system sufficiently full.

Figure 29 shows the shares of various curtailed electricity utilization, as things currently stand.

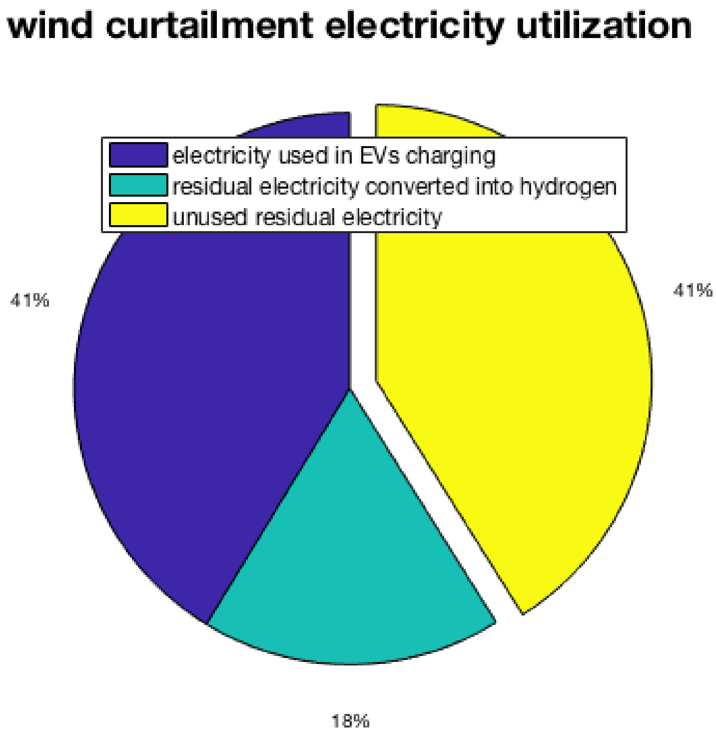

Figure 29: wind curtailed electricity utilization

Figure 29 finally puts in evidence that just 59% of curtailed wind electricity in 2013 (i.e. 41.28 GWh) is sufficient to guarantee yearly operation of 10,457 electric vehicles, 566 fuel cell electric vehicles and 32 fuel cell buses.

This could potentially lead to a replacement of the traditional fuel-based road vehicles in Orkney in favour of zero-emission vehicles. Furthermore, the majority (98%) of electricity that would be used for EVs charging comes from wind power generation.

Figure 30 displays how produced hydrogen is used. At the end of the simulation, 5% of the hydrogen produced over the temporal domain remains unused in the storage system.

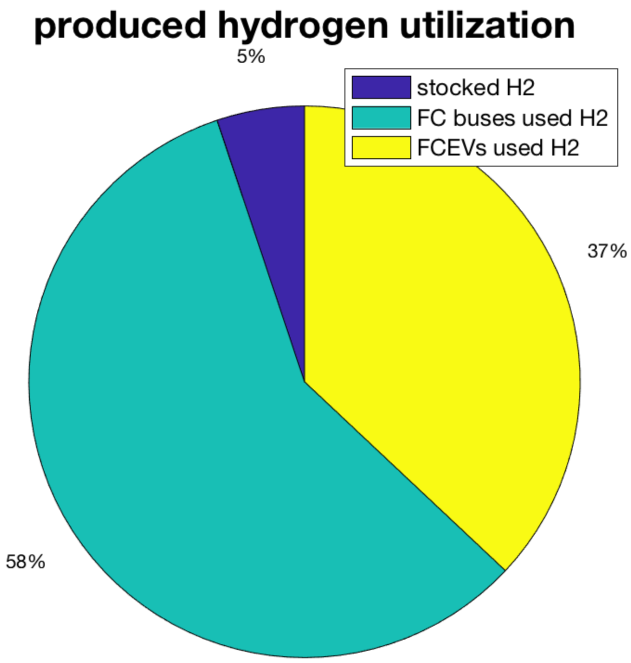

Figure 30: produced hydrogen utilization

Since, as stated above, it is required a total rated electrolysers power of 8.7 MW, it is now relevant to calculate the utilization factor of the electrolysers group and study how it varies for the various electrolysers, according to their peak power. The most common ITM electrolyser models, as mentioned earlier, are characterized by a nominal power of 100 kW, 500 kW or 1 MW. It is therefore crucial to split in the optimal way the 8.7 MW electrolysers group nominal power. The number and the size of the electrolysers influence strongly the global and single utilization factor, as well as capacity factor of each electrolyser.

Firstly, it is relevant to put in evidence that, according to the model results, the electrolysers receive input power for only the 36% of the temporal domain: in the remaining time steps they are simply turned off, because there is not place for hydrogen generation (absence of wind curtailed electricity, wind curtailed electricity entirely used for EVs charging or H_2 storage completely full).

For each electrolyser of every combination a capacity factor, defined as the unitless ratio of the actual electricity input and the rated power of the electrolyser, has been calculated[9]. The optimal combination will be the one with the highest weighted average capacity factor.

Considering in first place a fictitious 8.7 MW electrolyser, it would have an average capacity factor

[9] Capacity factor is only calculated when electrolysers group is operating.

of 31.24%.

As mentioned before, ITM’s electrolysers efficiency varies between 70% and 78% from 40% load to full load operation, with a peak at 50% load, then drops away below 40% load.

Actually, most of the time capacity factor is either higher than 40% or really close to zero. More in detail, capacity factor of the fictitious 8.7 MW electrolyser is higher than 40% (electrolysers works approximately at relatively-high efficiency) for 32.9% of the time and is lower than 5% (extreme partial load operation that strongly affects electrolyser efficiency) for 61% of the time electrolysers is working. For the remaining 6% time the fictitious 8.7 MW electrolyser work with a capacity factor between 5% and 40%, with its efficiency progressively dropping with load reduction.

Hence, splitting the total peak electrolysers capacity into differently-sized electrolysers could help to overcome the issues linked to fictitious electrolyser operation at capacity factor lower than 40%.

The proposed combination for splitting total capacity consists in seven 1 MW electrolysers, three 0.5 MW electrolyser and two 100 kW electrolysers.

When capacity factor (previously calculated for the fictitious 8.7 MW electrolyser) is lower than 5% can either operate one or both the two 100 kW electrolysers, or, according to the input power provided by wind curtailment, one of the 0.5 MW electrolysers at partial load. The 1 MW electrolysers are turned off in these periods.

In order to make each electrolyser work as much as possible with a capacity greater than 40%, an algorithm has been implemented. It takes as input the hourly curtailed wind electricity share provided to the hydrogen generation unit and, according to its amount, establishes which are the electrolysers that must operate in the current time step. Furthermore, an additional algorithm goal is to let the electrolysers work at maximum efficiency (i.e. 50% load) as much as possible. This leads to a maximisation of each electrolyser’s utilisation factor.

Table 28 displays utilisation factors and capacity factor for each electrolyser of the hydrogen generation group.

Electrolyser	size	utilisation factor[10]	corrected utilisation factor[11]	capacity factor
little.1	100 kW	0,321	0,901	0,311
little.2	100 kW	0,094	0,263	0,964
medium.1	0.5 MW	0,127	0,358	0,866
medium.2	0.5 MW	0,113	0,319	0,883
medium.3	0.5 MW	0,102	0,287	0,945
big.1	1 MW	0,138	0,388	0,896
big.2	1 MW	0,135	0,380	0,895
big.3	1 MW	0,131	0,367	0,897
big.4	1 MW	0,127	0,357	0,892
big.5	1 MW	0,124	0,347	0,892
big.6	1 MW	0,120	0,337	0,887
big.7	1 MW	0,117	0,328	0,885

Table 28: utilization factors and capacity factors of the electrolyser

[10] Calculated with respect to the whole temporal domain.
[11] Calculated with respect to timesteps in which hydrogen generation group is fed with residual wind curtailed electricity.

6. Conclusions

The initial purpose of this work was to identify and evaluate a possible and feasible solution for exploiting wind curtailed electricity in Orkney. The driving idea behind this project consists in using this amount of electricity for replacing traditional fuel-based body-type cars in Orkney with electric vehicles, bolstering EVs' charging process with curtailed electricity.

In order to assess the feasibility of this option, a complex model has been built and implemented on Excel and Matlab. The model firstly estimates on yearly basis the hourly mileage of each body-type car circulating in Orkney. Thereafter, taking as main input the hourly profile of wind curtailed electricity in Orkney for the year 2013, the model evaluates the possibility of using it for EVs charging purposes. This means that the model operates with the strong assumption that all body type-cars in Orkney are electric vehicles or fuel cell electric vehicles.

The model also considers and calculates the usage of grid electricity when curtailments profile cannot assure a sufficient charging of the EVs and assesses the hydrogen production option for fuelling FC buses and FCEV vehicles, when curtailments profile is significantly high.

In this section, the definitive version of the model will be described. Then will be briefly analysed issues and impediments that can nowadays impede the actualization of the model.

For each hourly time step of the temporal domain, wind curtailed electricity is:

- Used for charging electric vehicles, according to the state of charge of the individual vehicle and to the availability of EVs charging units. The model prescribes that 95% of body-type cars in Orkney are EVs. For each time step, EVs are charged in increasing state of charge order. Electricity from grid is used for EVs charging purpose only when strictly necessary, that is when EVs' state of charge is below the 10% and the current time step curtailed electricity cannot fulfil the charging process in the current time step.
- Used for powering hydrogen production unit, if the hydrogen storage system is not completely filled. Produced hydrogen is used to fuel FC buses for public transport in Orkney and FCEVs, which consist in 5% of the body-type cars in Orkney.
- Released, if EVs do not need to be charged and if the hydrogen storage system is full.

Figure 31 briefly recaps how the final simulation model operates.

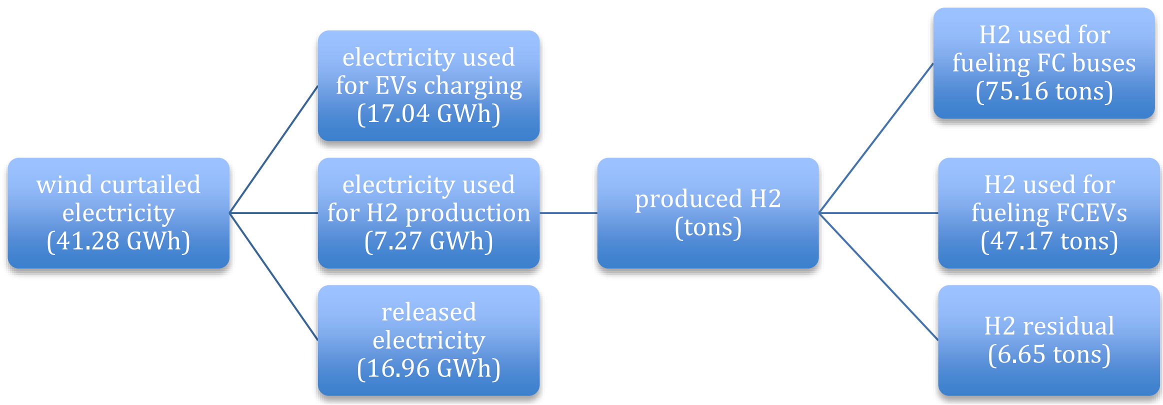

Figure 31: conclusive model operation scheme

The total amount of wind curtailed electricity used for charging EVs during the simulation is equal to 17.04 GWh; its hourly maximum is 45.26 MWh.

Two important outcomes from the simulation have been obtained: the feasibility of supporting a 100% electric vehicles environment in Orkney mainly using wind curtailed electricity and the opportunity of producing hydrogen with the wind curtailed electricity share not used for EVs charging.

According to Department of Energy and Climate Change, personal car petrol and diesel consumption in 2012 was respectively 2.7 and 1.8 thousands of tons [57]. This means that replacing the fossil fuels–based traditional cars with EVs would lead to avoid a yearly emission of 11 thousands of tons of CO_2[12].

Electric vehicles must operate during the year with a state of charge always higher than zero. The amount of energy needed to fulfil this target is 17.39 GWh. 98% of this electricity derives from wind curtailments, while the remaining 2% comes from the Orkney electricity network.

As explained in section 4.4, is necessary the intervention of grid electricity is required in order to guarantee EVs charging in the periods of the simulation in which curtailments profile drops significantly. Electricity taken from the Orkney grid is equal to 0.35 GWh and contributes only for 2% in EVs charging. Its hourly maximum across the temporal domain results to be 9.72 MWh. This

[12] According to IEA survey [58]

should present no significant problems in the Orkney distribution network operation.

6.1. Model weaknesses

It is worth to briefly highline the weak points of the model and to shortly discuss aspects that have not been addressed in this dissertation.

The first and biggest weakness of the model consists in the *Traffic Model* structure and in its stochastic essence. Its purpose was to estimate with the best approximation the traffic volume of body type cars in Orkney with a hourly time step on a annual basis. Apart from previous works on this topic [50], the only useful data was represented by the yearly volume of road traffic, provided by National Transport of Scotland. Starting from this value, and according to the Orkney population habits and routine [50], the entire amount of body-type cars present in Orkney has been divided into 19 clusters, each one characterised by a different hourly and daily mileage.

Therefore, this part has not mathematic foundations, but relies on strong and reasonable assumptions.

The other weaknesses have technical, practical or economical nature. It has been always taken for grant during the dissertation, but replacing 10 thousand of traditional cars with new EV models may strongly affect local economy[13]. Moreover, it must also be considered the installation cost of the charging unit (approximately one per EV car). Another issue concerns EV charging units and their utilisation: it is likely and common for EVs' owners to charge their vehicle overnight, for reasons of practical and economic (lower electricity price overnight) convenience. However, the purpose of this work is to exploit wind curtailed electricity. Due to volatile nature of wind energy, curtailment profile is unpredictable. In order to avoid wasting a significant share of curtailed electricity share, the model does not make differentiations in charging overnight or charging during the day. Is therefore necessary a change in owners behaviour. In the immediate future, smart grids will be able to provide a great contribution in organising and programming the optimal charging of electric vehicles linked to the grid, according to live electricity demand, availability of wind curtailed electricity, current state of charge of EVs and to availability of EV charging units.

As mentioned in chapter 2.5, Orkney electricity grid has a maximum capacity of 31 MW. The maximum hourly wind curtailed electricity is equal to 45.26 MWh. This means that, as things

[13] current price of Nissan LEAF is around £ 22,000

currently stand, the existing electricity network is unable to accept the entire amount of wind curtailments. As discussed in the introduction, nowadays some wind turbines in Orkney are subject to curtailments because of both the low electricity need by Orkney community and the limits and weaknesses of the existing network. Furthermore, another aspect that must be considered is the actual Orkney electricity demand. According to Simpson et al. [55], overall Orkney electric power consumption in 2016 is equal to 142.23 GWh. Thus, the average hourly electricity consumption can be approximated around 16 MWh. Actually, this value is strongly season-dependent: as Figure 2 displays, in a winter month like December demand is most of the time higher than 20 MW, whereas in late spring and summer, hourly average electricity consumption drops to 12 MWh. Furthermore, during the day, electricity consumption is slightly higher than overnight. Considering, for reasons of simplicity, an hourly average electricity demand of 16 MWh, the actual grid in the existing conditions can only take the 42.56% of the total curtailed electricity. Nevertheless, thanks the to electricity network reinforcements scheduled for 2020, this issue will be definitely resolved. On the other hand, grid reinforcements can help the electricity network to export to mainland Scotland the share of wind curtailed electricity for which Simulation Model does not prescribe an utilisation.

Finally, the last weak point involves electrolysers, in particular their operating condition that suddenly vary from ON to OFF and vice versa, according to the extremely volatile curtailment profile. Switching ON and OFF an electrolyser several times per day could seriously stress the appliance, even causing damages in the appliance.

6.2. Suggestions

In conclusion, it will be presented a brief list of possible starting points that may take place from this project.

As Figure 30 displays, 41% of wind curtailed electricity do not find a place for being properly used and therefore would be released. Ancillary projects can prescribe and find a use for this amount of electricity. Apart from exporting a big share of it, once the network reinforcement with mainland Scotland will be completed, other suggestions can be enhance electric domestic heating systems or increase the size of the hydrogen production and storage system. In this way, which is obviously way more expansive, all the residual wind curtailed electricity would be converted into hydrogen.

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