Can an island transition from total oil and gas dependence to 100% wind and solar power within 15 years?

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Abstract

An economic energy transition for the Isle of Man has been tested and optimised by combining the results of energy system and power-flow modelling. The island lies between Ireland and the UK and currently relies on an 80 MW gas-fuelled power plant for electricity. The modelling shows that this plant can be replaced with 100 MW of local wind power and 40 MW of local solar photovoltaic energy by utilising a staged approach, first building a high voltage transmission line to the island's capital, then reinforcing the grid around relevant substations and finally installing an additional sub-sea cable. Balance and stability can be maintained with some or all of the following – interconnection, long-duration energy storage, short-duration energy storage, various forms of power electronics and synchronous condensers. The specific problem of intermittent supply versus variable demand is reflected in the fact that only 65% of the wind and solar energy can be used when it is generated – the rest has to be exported or stored. Whichever route is taken, the cost of renewable power is less than that from fossil fuels at current prices.

1 Introduction

Like many nations, the Isle of Man is committed to net zero emissions (NZE) by 2050. The island is almost entirely reliant on gas and oil for electricity, heating and transportation and there are currently no wind farms, solar parks or energy storage facilities [1]. Thus, 75% of the island's greenhouse gas footprint - 500,000 tonnes of CO_2 per year - is related to energy use [2]; the rest is from agriculture and other industry.

The Isle of Man lies in the Irish Sea, situated midway between the UK and Ireland (Fig. 1). The island has 85,000 residents, with a land area of 571 km^2 and a shallow territorial sea of 4000 km^2. In total, the island uses around 1300 GWh of energy per year, of which 360 GWh is electricity (Fig. 2), 90% of which is generated from the island's own combined cycle gas turbine (CCGT) power plant [3] with diesel engines in reserve. The island's capital is Douglas on the east coast of the island where 32% of the population lives and the majority of the offices are situated for the island's main source of income, the financial industry. Douglas is also where the key grid infrastructure is situated – the CCGT plant, the main substations and busbars (Middle River, Lord Street and Pulrose) and the interconnector link to the UK (Figs. 1 and 3).

To achieve NZE, traditional fossil fuels will have to be replaced by sustainable forms of power. Ambitious targets have been set on other islands to transition to a high proportion of renewable energy. For example, on the Faroe Islands, the public utility SEV aims to achieve 100% renewable electricity by 2030 [4]. There are other isolated power systems such as Cape Verde, Orkneys and the Canary Islands which share a similar vision [5] [6]. The Isle of Man has now set out on developing its own pathway [7].

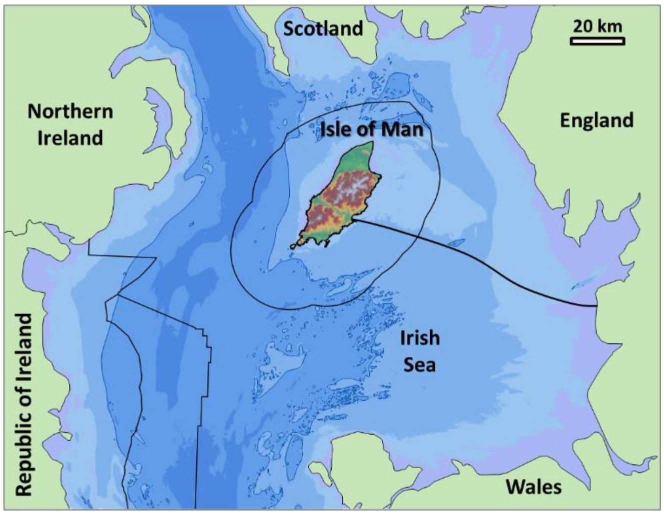

Fig. 1. Location map. Source

Variable and intermittent renewable energy sources present a problem to transmission system operators, especially on small islands. Without proper planning, there is a high chance of blackouts related to i) stability issues, ii) overloads caused by circuit faults and iii) power supply deficits. Therefore, the adaptation of electricity grids and their related energy systems requires careful planning to maintain reliability whilst ensuring that the cost of power does not increase.

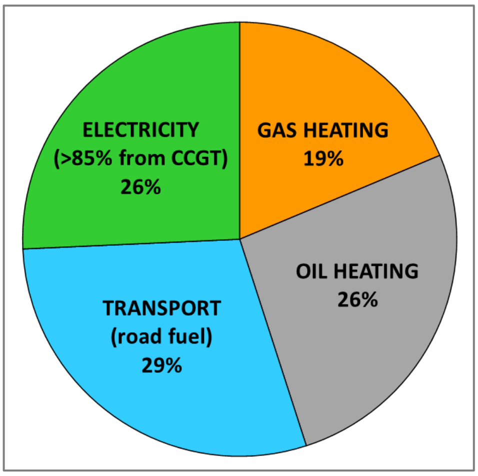

Fig. 2. Proportion of energy used in electricity, heating and transportation on the Isle of Man, out of a total consumption of 1400 GWh (electrical equivalent). Source ESC

Certain islands have already come a long way in the transition to 100% renewable electricity (Fig. 4). However, on the Isle of Man, there has been some hesitation on utilising the island's enviable natural resources of wind, water and mountainous terrain. There are valid worries about maintaining a resilient electricity system and the cost of reinforcing the grid to accommodate a high proportion of renewable energy. There are also questions about how to deal with the expected 2-3 times increase in electricity demand as heating and transportation are electrified. A practical solution promoted by the Government-owned grid operator, the Manx Utilities Authority (MUA), is to obtain a majority of its future power from low-carbon sources in the UK via an existing and a planned interconnector. However, due to the steep rise in market prices in 2022 and uncertainties in future supply, the question has changed to whether the Isle of Man can become self-sufficient in renewable energy and, if so, how and by when? This is the reason for the research reported here. The work focuses largely on meeting the current electricity demand from sustainable sources rather than fossil fuels. Nonetheless, heating and transportation form a large part of the island's energy system (Fig. 2) and the implications and solutions to decarbonise those will need to be considered relatively soon.

2 Objectives of the study

The existing electricity grid system on the Isle of Man is illustrated in Figs. 3 and 5. The network was built to transmit alternating current (AC) at a voltage of 33 kV, mostly through underground cables, with supply provided by traditional thermal power plants, the main one being the 80 MW CCGT plant in Douglas. Supported by a 90 kV, 60 MW AC interconnector to the UK, the grid has N-1-1 resilience (secure against two component failure) and has therefore proven to be very reliable with virtually no black-outs. The challenge is now to integrate a high proportion of renewable energy without overloading what is essentially a relatively small power system, ensuring it has sufficient load-following capability.

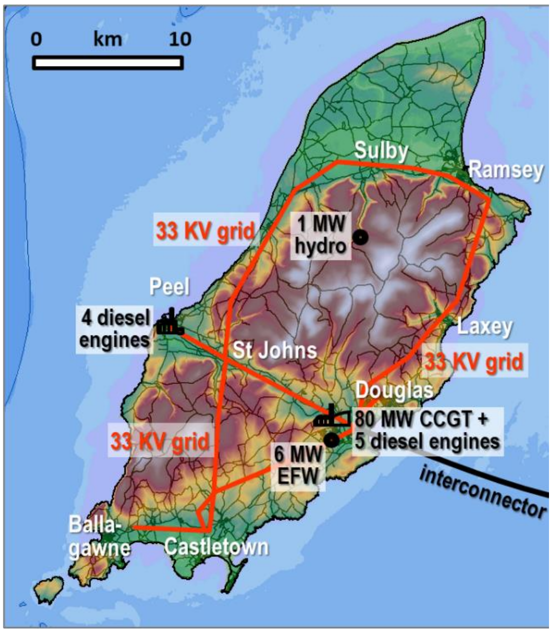

Fig. 3. Map of the existing electricity generators and 33 kV transmission grid on the Isle of Man. Source ESC

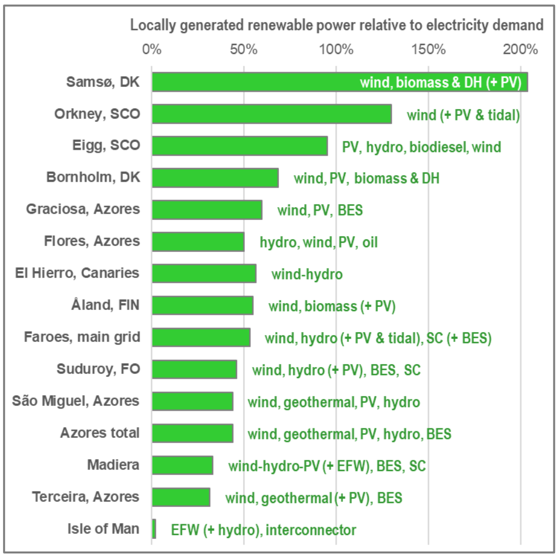

Fig. 4. The amount of renewable energy generated on selected islands relative to their electricity demand. 100% on the X axis means that enough sustainable power is generated for an island to be self-sufficient, assuming that there was sufficient energy storage. Data are from public sources plus information provided by G. Davies, F. Henriques and H. Trondheim. DH = district heating, PV = solar photovoltaic, BES = batteries, SC = synchronous condenser, EFW = energy from waste.

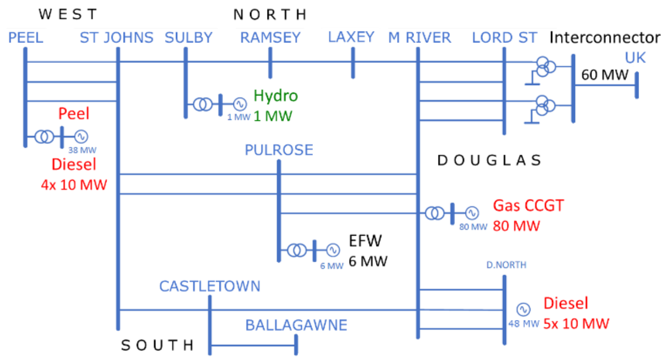

Fig. 5. Model of the main components of the Manx transmission grid system based on power data provided by MUA. The horizontal lines are the 33 kV cables and the vertical lines represent the busbar connections.

The goal of the current study was to develop a viable path for replacing the island's fossil fuel electricity generators with renewable energy from onshore Manx sources. We chose to combine energy system simulation with static power-flow modelling to test which options were both technically feasible and commercially viable, utilising a smart energy system approach [8] [9] [10] [11] [12]. The novelty of this study is the integration of transition scenarios with power-flow models of electricity loads. These were built as a set of steps where power supply and demand, costs and emissions were tested and optimised.

3 The existing electricity grid and future plans

At present the CCGT power plant operates between 25 MW and 80 MW with an average of 40-45 MW, providing both baseload and dispatchable power fed into the nearby Middle River substation in Douglas (Fig. 5). The CCGT baseload supply of 25 MW represents the minimum electricity demand on the Isle of Man. At less than 25 MW, the two gas turbines run inefficiently, with higher costs compounded by increased wear. Therefore, the grid operator, MUA's preference is that the CCGT plant continues to generate 25 MW or higher until it is decommissioned, probably some time between 2030 and 2035. The same site in Douglas also has five 10 MW diesel engines and there are another four 10 MW diesel engines at Peel, on the west coast (Fig. 3). These nine engines provide flexibility and back-up. In addition, there is a 6 MW energy-from-waste (EFW) plant and a 1 MW hydroelectric plant which, together with 25 MW baseload from the CCGT plant, provide a minimum load of 32 MW in the power-flow models.

MUA is currently investigating options to build a new high voltage sub-sea interconnector between Douglas and the west coast of England in the UK. The idea is that this would be used to import UK electricity as a simple way of abating local CO_2 emissions – but evidently based on the assumption either that the UK electricity mix will become carbon-neutral or that reliable UK suppliers of emissions-free power can be sourced. MUA's initial suggestion is to install a 90 kV AC cable with a 70 MW capacity [13], the minimum amount of power required to meet conservative future demand projections [14]. This assumes that the current 60 MW cable is kept in operation, although it too will be reaching the end of its life in the next 10-15 years. The total capacity of interconnection is important because it may constrain the size of future renewable energy projects which the grid will accommodate. Surplus power will have to be exported to avoid overloads on local lines.

The problem with relying on imports to decarbonise the electricity system is that it does little to allay local fears and uncertainties about the steep rise in energy prices related to the Russian invasion of Ukraine in February 2022. Nor does it deal with issues of energy security associated with this war nor the possibility that more power will be required on the Isle of Man to meet the needs of a growing population and increased industrial activity. Also, there is no additionality in terms of reducing carbon emissions, rather it seems to be handing responsibility for action on climate change [15] over to another nation. It is clearly much better if all the island's electricity can be generated from local renewable sources, provided it can be made affordable.

4 Methodology

This section introduces the tools and methods used in the energy system and power-flow modelling, undertaken to devise a viable way of decarbonising the electricity generated and used on the Isle of Man.

4.1 Energy scenario simulation with EnergyPLAN

To evaluate and optimise the choices, digital models of the existing energy system and future scenarios have been built using EnergyPLAN, software [16] developed by Aalborg University (AAU) to run simulations of supply and demand over the year. EnergyPLAN has been used extensively to study different renewable pathways with more than 315 case studies in the academic literature [17]. It has primarily been applied for the for the analysis of national energy systems, where it has been used to investigate energy transitions in Germany [18], Denmark [19] [20], Ireland [21], Norway [22] [23], Hungary [24], Romania [25], Portugal [26], the European Union [27], Jordan [28], Chile [29], Singapore [30], Hong Kong [31] and China [32,33]. It has also been applied to small island settings such as Gran Canaria [6], Pico and Faial [34] and Favignana Island [35], as well as to cities like Aalborg [36] and Bozen-Bolzano [37].

EnergyPLAN is a simulation model appropriate to situations where different future transition pathways are to be explored and improved [38] [39]. It uses a one-year timeframe and aggregates all the generation, demand, flexibility and cost data into a single set of results which, if need be, can be broken down to single hour resolution.

Inputs to EnergyPLAN comprise hourly variations of power production from weather-dependent sources and conventional thermal plants, as well as hour-on-hour consumption of electricity, different forms of heat, fuels in vehicles and other forms of energy such as that used in providing ancillary services. Capital costs, operating costs, fuel prices, carbon emissions, grid constraints such as interconnector bottlenecks and energy storage [40] are also included.

EnergyPLAN then simulates the annual supply, demand and performance of the energy system based on a technical simulation strategy which is automatically optimised for efficiency as well as the costs of power supply, including the option to incorporate external drivers such as electricity market trading.

4.2 Power-flow analysis

Starting with the initial EnergyPLAN models, a power-flow study was carried out to investigate the amount of renewable power that the electricity grid on the Isle of Man can accommodate. The numerical models were based on steady-state conditions with emphasis on resilience against single component (N-1) failure.

The starting model was that of the existing transmission network using power specifications supplied by MUA (Fig. 5). The grid comprises a 33 kV transmission network with existing generators connected at the 11 kV level. Transmission lines and power transformers were represented by the sequence impedance parameters associated with their operational limits.

As mentioned earlier, the main source of electricity is the CCGT plant (connected to Middle River busbar), supported by back-up diesel plants, an EFW facility and a small hydroelectric plant (Figs. 3 and 5). Small quantities of power are exported or imported via the sub-sea interconnector (Fig. 1). A new interconnector is planned which will strengthen the grid meaning that the CCGT and some of the diesel plants could be repurposed or decommissioned without high risk of outages.

Once the model of the grid had been built, different future scenarios could be tested for constraints and overloads identified. This involved connecting new renewable energy facilities of various sizes at different busbar locations. For resilience purposes, any new renewable energy project was joined to busbars with at least two lines in either direction, i.e. part of a ring or mesh configuration.

The analysis focussed on the loads at maximum power output from the new renewable energy facilities, assuming a minimum load of either 32 MW or 7 MW, depending on whether the CCGT plant was providing 25 MW baseload or not. The criterion used to analyse potential overloads was failure of any single electricity line linking two busbars.

The power-flow modelling efforts were focused on estimating the upper limit to the amount of power that could be connected from large wind farms and/or solar parks. The need for critical reinforcements or a different connection was then assessed.

It is worth noting that the maximum loads resulting from the power-flow analysis were similar to the transmission constraints in the EnergyPLAN simulations but the detailed power-flow work allowed potential overloads to be located and quantified and then different solutions to be tested.

5 Energy system and grid models on the Isle of Man

This section details scenarios for the transition towards a renewable energy-based energy system on the Isle of Man.

In the energy system modelling, it was assumed that today's electricity consumption does not change. This of course is an over-simplification as the amount of appliances like domestic heat pumps and electric vehicles is expected to rise whilst the Manx Government is also looking to increase the number of residents and businesses by as much as 18% in 15 years [41]. Nonetheless, for comparison purposes, it serves as a valid starting point.

5.1. Starting premise

Strong and reliable winds represent the most economical source of energy on the Isle of Man with an average of ≥10 m/s at 50 m in the uplands [42]. Hence the future scenarios are based on a high proportion of wind power. However, each year there are periods of at least four days when there is virtually no wind on the island [2] meaning that, by itself, it is difficult to reliably cover even the baseload requirement of 25 MW. Also, variable wind strengths can disrupt the frequency and voltage if wind alone is connected to the grid. Therefore, different amounts of solar photovoltaics (PV), energy storage and interconnection have been tested to deal with surpluses and deficits of wind power.

Initial screening work based on the data described in Appendix I showed that biomass, nuclear, tidal, and wave energies were too expensive or not feasible based on the island's geography. Also, other technologies were either non-starters (e.g. geothermal on the basis of Manx geology) or commercially immature (e.g. green hydrogen). The values associated with these options have been published elsewhere [44] [45].

5.2. Initial observations

Based on the EnergyPLAN simulations. the optimal pathway to 100% renewable electricity involves a staged progression over the next 10 years from the current situation of predominantly gas-fuelled CCGT power (Base Case) to 100 MW wind and 40 MW solar PV (Step 1D), as illustrated in Fig. 6 and discussed in Section 6.

The first outcome from the power-flow models was that 20 MW is a safe limit to the amount of renewable power that can be added to the grid at busbars away from Douglas, at least as it is currently configured. Thus, with the failure of a single line, some of the other lines can reach 60-65% of their maximum capacity. We therefore focussed on finding a solution to this grid limitation.

With the 20 MW out-of-town constraint, the best option to accommodate a large-scale renewable energy project is to build a new high voltage line to transmit the power directly to one or more of the substations in Douglas – Middle River, Pulrose or Lord Street (Fig. 5). These substations have busbars which can accommodate 80 MW of electricity from the existing CCGT power plant. Over and above the minimum load of 32 MW, around 80 MW is also the highest amount of additional power any of the Douglas substations can receive without upgrades.

6 Results of EnergyPLAN and power-flow modelling

This section details the staged pathway to 100% renewable electricity on the Isle of Man based on the EnergyPLAN and power-flow modelling, including consideration of the value of grid-scale energy storage.

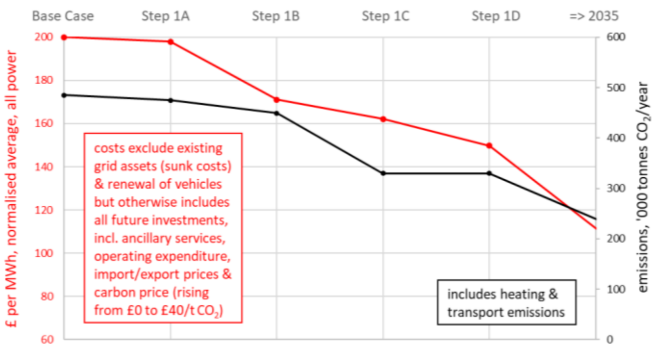

Fig. 6. The proposed steps to 100% renewable electricity on the Isle of Man over a time period of approximately 10 years based on five EnergyPLAN simulations. The costs of Step 1D do not include the grid reinforcements shown in Fig. 8.

6.1 Energy system scenarios

Multiple options were tested but it proved most economic to replace the existing CCGT power plant with a high proportion of wind energy coupled with some solar PV plus variable capacities of interconnection, short-duration energy storage and long-duration energy storage.

The best way to decarbonise power generation on the Isle of Man involves a stepwise transition through five steps from the current situation (near total dependence on fossil fuel thermal power plants) to self-sufficiency using renewable electricity (Fig. 6 and Table 1). Each stage is summarised below, including nominal completion dates.

Base Case (2023)

This model represents the existing supply-demand situation on the Isle of Man for electricity, heating and transport. Renewable energy provides only 2.9% of the total power or 9.6% of the electricity, sourced from the EFW and hydroelectric power plants. The unit cost for all power is £291/MWh, with no carbon tax. Annual emissions of carbon dioxide are 485,000 tonnes from gas, oil and related products.

Step 1A (2026)

The first stage involves incorporating a modest amount of renewable energy, 20 MW, the minimum planned by the Manx Government and MUA [13] [43]. These facilities are due to be in place by 2026, a relatively simple process as they require no upgrade or reinforcement of the existing 33 kV grid. Planning regulations have yet to be adapted to accommodate large onshore wind turbines, so it has been assumed that the power would come from a 20 MW solar park, including 10 MWh battery storage. Renewable energy then provides 3.9% of the total annual power requirement and 15% of the annual electricity supply, using a capacity load factor of 12% based on an average Manx annual solar irradiance. Compared to the Base Case, costs are reduced slightly (by £2/MWh) as are CO_2 emissions (a 10,000 tonnes/year reduction).

Step 1B (2028)

By this stage it is assumed that wind farms are permitted on the Isle of Man. As well as the 20 MW solar PV, 6 MW EFW and 1 MW hydro, the CCGT plant is still providing 25 MW of baseload power which constrains the size of any new renewable energy projects. The largest capacity of wind power that can be accommodated on the grid is 60 MW, provided the electricity is brought directly to one of the main substations in Douglas such as Middle River (Fig. 7). A new high voltage transmission line is required from the wind farm or farms but no further upgrades are needed to the grid *per se*. Nonetheless, 70 MWh battery storage is also included in the model for ancillary services to stabilise the grid. Export of surplus electricity can be accommodated through the existing interconnector to the UK whereas, during times when there is insufficient renewable power, excess demand is dispatched from the CCGT plant. Renewable energy then provides 11% of the total power (including heating and transport) and 54% of the electricity over the year. The unit cost of all power falls to £252/MWh, despite the introduction of an assumed carbon tax of £20/tonne CO_2. Annual emissions of CO_2 are 449,000 tonnes from combustion of gas, oil and related products.

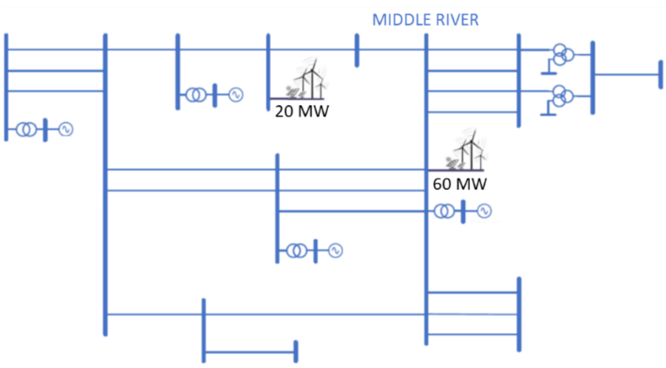

Fig. 7. Example grid configuration for Step 1B. Other components of the electricity grid are illustrated in Fig. 5.

Without curtailing or storing the power on site, more than 80 MW of renewable energy can only be accommodated by reinforcing the 33 kV grid.

Step 1C (2030)

The next stage involves switching the CCGT plant off so that it no longer provides 25 MW baseload power. Nonetheless, it is assumed that the EFW and hydroelectric plants still provide up to 7 MW. More renewable energy can now be accommodated, amounting to a maximum of 80 MW wind and 30 MW solar PV, with 90 MW transmitted directly to Douglas through high voltage cables (as per Step 1B) and 20 MW via the 33 kV grid (as per Step 1A). 80 MWh battery storage is also included, largely to ensure ancillary services are covered, but the model also allows the batteries to be used for a limited amount of peak shaving. Export of surplus electricity can be accommodated through the existing Isle of Man-UK interconnector.

Import of electricity is also required because there is a net deficit of 70 GWh over the year. Renewable energy then provides 20% of the total annual power and 81% of the electricity, the rest supplied via the interconnector. The unit cost of all power is £240/MWh, assuming a constant price of £220/MWh for imported and exported electricity and a carbon tax of £40/tonne CO_2. Annual emissions of CO_2 are 330,000 tonnes from oil and gas in heating and transport, the same as today. Of course, it is expected that electrification will reduce this but for these analyses we have only looked into supply-side changes not modal shifts in electricity demand as these are more speculative. This makes comparisons easier (Table 1).

In scenarios with more than 110 MW of renewable energy, the grid has to be reinforced with a new interconnector and additional 33 kV cables and at least one new transformer in Douglas (e.g. Fig. 8) in order to maintain grid resilience.

	Base case	Step 1A	Step 1B	Step 1C	Step 1D
depreciated CAPEX, £ mill/yr	3	5	17	23	29
fuel & OPEX, £ mill/yr	386	380	351	318	303
annual per capita cost	£4,599	£4,552	£4,422	£4,102	£4,020
normalised energy cost, £/MWh	200	198	171	162	150
total energy produced, GWh/yr	1334	1334	1420	1403	1446
electricity demand, GWh/yr	358	358	358	358	358
electricity from gas, GWh/yr	320	300	250	0	0
wind-solar generated, GWh/yr	0	20	160	250	320
net exports electricity, GWh/yr	0.2	0.2	90	-70	0
CO_2 emissions, '000 tonnes	485	475	449	330	330
nominal carbon cost	£0	£0	£20	£40	£40
emissions cost, £ million	0	0	9	13	13

Table 1. Summary of before-profit costs, energy share, net exports and CO_2 emissions for a stepwise transition to 100% renewable electricity on the Isle of Man (Fig. 6). Costs already invested in existing assets are not included, nor are the costs of the grid reinforcements shown in Fig.8 to support Step 1D. The normalised energy cost, £/MWh, is a rolled-up average for electricity, heating and transport.

Step 1D

Step 1D explores how much renewable energy is needed to exactly meet the Isle of Man's electricity demand. The scheme that works best comprises 100 MW wind and 40 MW solar PV. 140 MWh battery storage has also been included to account for the costs of ancillary services. However, in order to assess the degree of match between intermittent power generation and electricity consumption, these batteries are not used for peak shaving.

Grid reinforcements will be required to avoid potential overload issues both around Douglas and in the interconnector but there are a number of different options (e.g. Fig. 8) so their costs have not been included.

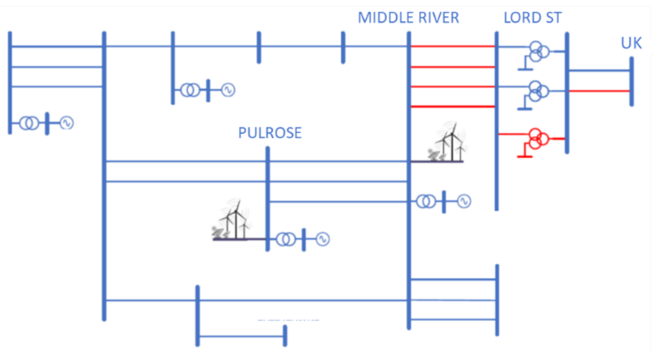

Fig. 8a.

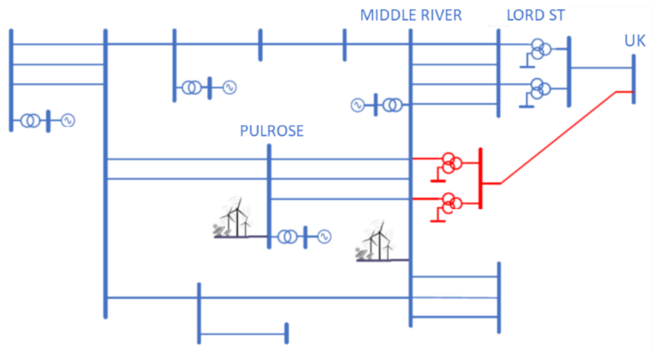

Fig. 8b

Figs. 8a and 8b. Example grid configuration to accommodate the energy system scenario in Step 1D. Components in red are where grid reinforcements are required, either new cables or new transformers.

The results of the EnergyPLAN modelling provide a couple of key values relevant to the transition from gas-fuelled thermal power to renewable power from intermittent sources. The most important of these is the amount of wind and solar energy that can be used at the time it is generated – 65%. The remaining 35% is surplus to requirements. This has to be exchanged to balance the system, an amount equivalent to exporting 120 GWh and importing 120 GWh each year (Fig. 9).

A separate analysis using the hourly data from the EnergyPLAN model shows that most of the renewable energy generated on the island could be utilised rather than exported if 4.8 GWh of long-duration energy storage was to be built. In this case, a minimal amount of energy (<1 GWh) would have to be imported over the year. The value of this scale of storage facility depends on the price of electricity at the time of import and export – likely to be high when wind production is low and demand is high, corresponding with the times when importation is required in the model. Additional value comes with resilience to failures in the interconnector, as well as protection from other energy security issues, and the fact that long-duration energy storage such as pumped hydro provides stable AC power. This is discussed further in Section 6.3.

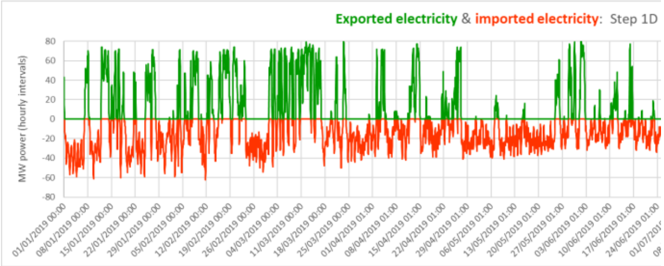

Fig. 9a.

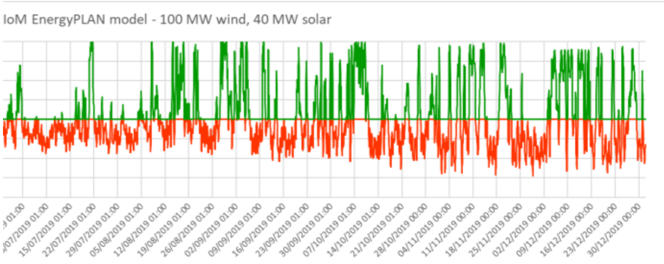

Fig. 9b.

Fig. 9a-9b. Annual exports (green) and imports (red) of electricity to balance supply and demand (Fig. 7c) when the island's CCGT power plant is replaced with 100 MW wind and 40 MW solar PV (Step 1D). The net exchange deficit is zero. The data is based on weather and electricity demand in 2019 (Appendix I). Fig. 9a shows the first half of the year (January-June) and Fig. 9b shows the second half of the year (July-December).

Step 2 (2035)

Later models assume that the grid is reinforced with additional lines and transformers around Douglas plus an additional interconnector to the UK. The scale of the renewable energy projects that can be accommodated above the 110 MW in Step 1C depends on the size of the new sub-sea cable. Two examples of how this could be configured are shown in Figs. 8a and 8b.

Renewable energy then provides 26% of the total power (100% of the electricity), or more if exports are included.

6.2 Upgrades to the transmission system

In parallel with the EnergyPLAN simulations, grid resilience was tested using power-flow models with which reinforcements were devised (e.g. Fig. 8). These models show that significant renewable energy capacity can be added to the existing Isle of Man electricity grid whilst maintaining N-1 resilience, provided system constraints are dealt with.

- Beyond Douglas, the existing 33 kV grid can accommodate a renewable energy capacity of at least 20 MW linked to existing busbars.
- An additional 60 MW of renewable power can also be accommodated by transmitting it directly to Middle River, Pulrose or Lord Street substations in Douglas with no further grid strengthening.
- More than 80 MW renewable energy will require grid reinforcements (Fig. 8), specifically:
  a) additional short lines and transformers around Middle River and Lord Street substations;
  b) a second interconnector from Lord Street or Middle River to the UK with a capacity of at least 80 MW.

To deal with the possibility of an outage in the existing interconnector, the new sub-sea cable should have the capacity to accommodate all the exported power. Also, the larger the size of the interconnector, the more flexibility that is introduced to the system, for example, avoiding the curtailment of wind power.

6.3 The value of energy storage

One key question is how to match the intermittency of power generated from renewable sources with the variability of electricity demand. Coupling wind with solar helps to a certain degree because the two often complement each other, particularly during daytime in the summer months. Strong winds rarely coincide with strong sun on the Isle of Man [2] meaning that troughs and peaks in power generation from one source can be partly smoothed out by the other. Nonetheless, solar energy has a relatively low capacity load factor (c.12%) compared to that of wind (c.32%), with limited availability of sun in the winter and absence at night, meaning that intermittency still needs to be managed to ensure electricity supply meets demand.

In a scenario with 100 MW wind and 40 MW solar PV, only 65% of the power can be used when it is generated: the rest either has to be exported or stored. Likewise, a similar amount has to be imported or regenerated to avoid undersupply. This is illustrated in Figs. 9a-9b showing i) the electricity that is surplus to requirements (assuming there is no long-duration energy storage, batteries only being used for fast frequency response) and ii) the deficit when demand exceeds supply (assuming that the CCGT plant is no longer in operation). This represents a total exchange of 240 GWh of electricity over the year between the Isle of Man and the UK, with approximately equal amounts exported and imported (120 GWh) to deal with the mismatch between the local renewable generation and electricity consumption.

If, instead, 4.8 GWh of long-duration energy storage was available on the island, then the total net import falls to 0.4% of this amount, less than 1 GWh, if none of the stored energy is exported. However, due to the fact that large profits can be made from arbitrage, it is highly likely that the interconnector will be used for market trading, assuming the cable is large enough. This would also allow revenue to be made by importing surplus power when it is particularly cheap, as well as a paid service to reduce loads on the British grid.

If the Isle of Man does not build energy storage facilities, then it will be largely reliant on exports-imports to and from the UK to balance the intermittent supply of renewable power to the variable electricity demand. This introduces a significant uncertainty to the economics of the entire system because future energy prices are highly unpredictable. On the other hand, the necessary size of grid-scale storage would require considerable up-front investment as well as clear direction from the Government to support major projects such as pumped hydro. Nonetheless, it would secure the island against interconnection outages.

Traditionally, it has proven difficult to commercialise investments in energy storage, despite its value in trading on energy markets. Ultimately its commerciality depends on the price of electricity at the time the power is required versus the cost of buying and storing surplus power. As the proportion of renewables continue to increase on the British grid, electricity prices are high when both wind production is low and demand is high (and vice versa). Assuming an average price of 40p/kWh, when electricity would otherwise have to be imported, corresponds to an annual cost of £48 million for a total of 120 GWh/year. This is one way of assessing the economics of energy storage. Additional value comes with resilience to failures in the interconnector and protection from other energy security issues. It is also worth noting that long-duration energy storage based on pumped hydro technologies can be designed to provide dispatchable AC power similar to that from the existing CCGT plant, helping to maintain grid stability. This is discussed in the next section.

A cost-benefit analysis is recommended on the different alternatives for energy storage and export-import, including the option to build an interconnector to Ireland. There will also be value in analysing other smart energy options such as flexible demand, domestic efficiencies and, most importantly, integration of heating and transportation into the electricity system.

6.4 Grid stability

The variable nature of wind and solar power means that there will be more emphasis in the future on controlling the frequency and voltage of the grid. Power electronics with batteries can nowadays provide stable current based on technologies such insulated gate bipolar transistors (IGBTs) and grid-forming inverters.

A more mechanical way to stabilise electricity is with a synchronous condenser as is demonstrated on other islands (Fig. 4). This in turn, offers a second life for the CCGT power plant on the Isle of Man. By disconnecting the two existing gas turbines, and introducing a clutch mechanism, the electrical generators can be run as synchronous condensers powered by renewable electricity and batteries. This provides inertia and instantaneous reactive power to keep the grid stable. A small-scale synchronous condenser is used for the same purpose on the isolated island of Suðuroy in The Faroes [46], allowing the grid to be run on 100% wind power.

7 Recommended pathway

Energy system and power-flow modelling has identified a number of grid-related constraints on the Isle of Man but a workable solution has emerged on the basis of the following sequential stages:

Step 1A)-Step 1B) – when the CCGT plant is still generating 25 MW baseload power, a maximum of 80 MW renewable power can be transmitted to Middle River, Pulrose or Lord Street substations in Douglas without the risk of overloading the system. During times when peak renewable energy generation coincides with low on-island demand, all the power is surplus and will have to be exported through the existing interconnector to the UK. In the case of more than 80 MW of renewable capacity, and without upgrading the 33 kV grid, then there will be times when surplus energy has to be stored rather than transmitted to Douglas, otherwise generation will have to be curtailed.

Step 1C) – up to 110 MW renewable energy can be accommodated once the CCGT plant is no longer running. Surplus power can be exported to the UK or stored on the island. When there is insufficient wind and solar energy, then the interconnector and/or energy storage will have to meet the electricity demand on a flexible and dispatchable basis. When this requirement is most pressing, it is likely that electricity prices will also be high in the UK for the same reasons – an absence of wind and sun coinciding with peak consumption. This is where grid-scale, long-duration energy storage can add significant value, allowing the system operator, MUA, to match intermittent supply to variable demand. In this respect, pumped hydro storage would provide extra value as the turbines provide inertia and the scheme can also be designed to replicate the flexibility of the CCGT plant, without the cost of gas fuel or the limited duration and short lifespan of batteries.

Step 1D)-Step 2) – assuming a second interconnector is built, more than 80 MW renewable energy can be transmitted to Douglas. This allows surplus power to be exported assuming that appropriate grid reinforcements are made around the main substations (e.g. Fig. 8). The maximum amount of renewable power is largely determined by the total capacity of the two interconnectors. The export revenue which can be earned through arbitrage with the UK market depends on the size of the second interconnector and the energy storage capacity. An economic analysis should be made comparing the value of energy storage to export-import and to the cost of curtailment.

Even without long-duration energy storage, and ignoring sunk costs, the modelling shows that there is an overall decrease in the before-profit energy costs delivered by a move away from fossil fuel-sourced electricity to renewable energy (Fig. 6 and

Table 1). This is due to the savings made by not purchasing high-priced gas or oil. These results are similar to SEV's experience on the Faroes [4] [46] [47].

8 Discussion and further work

The pathway discussed here is essentially a British Isles-style transition involving full electrification based on wind and solar energies. However, unlike the UK, biomass-fuelled power stations are not included for environmental and cost reasons. In many European and Nordic countries there is more emphasis on district heating projects and green hydrogen for energy storage, including power-to-x to produce liquid synthetic fuels. Despite the different emphasis, most energy transition strategies involve all or most of the following elements:

- Phase in renewables through subsidies.
- Phase out fossil fuels through legislation.
- Support the development of energy storage, ancillary services and interconnection to maintain grid balance, stability and resilience.
- Upgrade the grid and related infrastructure for a 2-3 times increase in electricity demand, allowing heating and transport to be electrified.
- Incentivise sustainable heating such as district heating and heat pumps whilst banning new gas and oil boilers.
- Incentivise electric vehicles whilst increasing taxes related to petrol and diesel engines.

Whether sustainable heating is introduced on an individual or community-scale basis and whether the majority of future electric vehicles are powered by batteries or green hydrogen is yet to be determined. We have therefore focussed on the first three elements, showing that 100% renewable electricity is achievable. This represents an important stage in the transition to net zero emissions. Future work will involve the second three elements, heating and transport (Fig. 10), which will require significant investments in infrastructure.

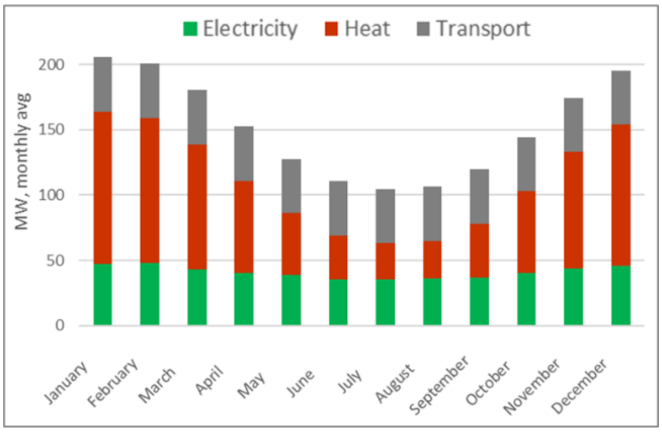

Fig. 10. The current average monthly power demand over the year on the Isle of Man.

Additional analysis is also recommended into the costs and value of importing-exporting electricity versus energy storage. Matching intermittent supply to variable demand, as well as dealing with inherent stability issues associated with renewable power, require either a give-and-take arrangement with the UK or significant on-island energy storage, including both long-duration and rapid frequency response facilities.

Finally, three critical issues threaten the idea of building grid-scale renewable energy on the Isle of Man. Firstly, the legislation is not ready. For example, it is uncertain whether current planning and environmental regulations would permit the erection of large free-standing structures such as commercial-sized wind turbines. Secondly, the Isle of Man Electricity Act effectively prevents private developers generating power for public supply. In other words, the Government-owned system operator, MUA, has an effective monopoly. MUA does not have to buy electricity from a third party and can prevent access to the grid on the basis of grid capacity limits. Thirdly, even if a private developer was granted grid access, it is not clear who should provide balancing and ancillary services.

9 Conclusions

The Isle of Man has a legal commitment to net zero emissions by 2050 but it has been Russia's invasion of Ukraine which has really focussed minds on whether the island can shake off its reliance on imported energy.

The results of EnergyPLAN and power-flow models show that there is an economic route. This involves replacing the island's gas-fuelled power plant with 140 MW of Manx wind and solar PV, plus associated cabling and grid reinforcements. In terms of economics and sustainability, the headline numbers related to the transition to 100% green electricity are:

- Renewable energy generation rises from 3% to 23% of the total annual consumption of power: to 320 GWh/year.
- The annual cost of all energy falls on a MWh basis by 23%: largely due to savings in imported fossil fuels.
- The amount of imported gas falls by 68% (a decrease of 710 GWh/year) and the amount of imported oil by 4%: the remaining fossil fuels (1290 GWh/year) are used in heating and transportation where no shift to green energy has been modelled.
- Emissions fall by 32%: representing a decrease in 155,000 tonnes of CO_2 per year and, by inference, a significant reduction in anticipated future carbon taxes.

These results assume that there is no change in electricity demand and no change in the current consumption of gas and oil in heating and transportation. It is nonetheless self-evident that providing affordable renewable electricity opens many options for a fully integrated energy system with low to zero carbon emissions from all sources of power.

Once the CCGT power plant is switched off, the island still runs the risk of becoming reliant on imported electricity from the UK, unless enough long-duration energy storage is built to cover periods of low wind and high demand. A cost-benefit analysis is required to determine whether, for example, pumped hydro storage provides an economic and reliable solution, particularly if arbitrage can be used to sell power at profit on the UK market. There is also the advantage that energy storage improves the resilience of the grid by adding security against interconnection failures.

Overall, a staged transition from gas power to self-sufficiency in renewable energy offers the attractive prospect of the Isle of Man undertaking a relatively rapid and economic transition to a sustainable society. To attract the necessary investment will require political will to change the current legislation and develop policies that support decarbonisation.

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11 Appendix I: application of EnergyPLAN

The inputs to EnergyPLAN comprise hourly electricity supply-demand, wind and solar data for 2019 obtained from the Manx Utilities Authority and from https://globalwindatlas.info/, https://globalsolaratlas.info/, www.renewables.ninja/, and https://globalatlas.irena.org/workspace. Data on representative emissions, average energy prices and CAPEX and OPEX were for the second half of 2022 sourced from the Isle of Man and UK governments as well as www.ons.gov.uk/economy/inflationandpriceindices/timeseries/ewms/ppi, https://tradingeconomics.com/commodity/uk-natural-gas, www.energy-stats.uk/wholesale-energy-pricing/ and www.racfoundation.org/data/wholesale-fuel-prices-v-pump-prices-data. Average specifications for northern European technologies and energy production-consumption related to wind, solar PV, fuel, waste, energy storage, ancillary services, cabling, transformers and other transmission equipment were based on information from the Danish Energy Agency (e.g. https://ens.dk/en/our-services/projections-and-models/technology-data), UK Department for Business, Energy and Industrial Strategy (www.gov.uk/government/publications/beis-electricity-generation-costs-2020), UK National Grid (https://data.nationalgrideso.com/data-groups) and a selected set of EU, UK, international and Manx sources (e.g. https://ec.europa.eu/energy/data-analysis/market-analysis_en, https://data.europa.eu/data/datasets/database-of-the-european-energy-storage-technologies-and-facilities, www.emd.dk/el/, https://grid.iamkate.com/, https://www.epexspot.com/en/tradingproducts#intraday-trading, www.lowcarboncontracts.uk/cfd-register/, https://www.nordpoolgroup.com/historical-market-data/, www.gridwatch.templar.co.uk/, www.statista.com/statistics/273990/residential-electricity-prices-in-selected-eu-countries/, www.entsoe.eu/data/map/, www.energysustainabilitycentre.im, https://manngis.gov.im/LocalViewWeb/Sites/manngisonline/, www.energysustainabilitycentre.im/knowledge-hub, www.netzero.im/resources/resource-hub/, www.manxgeology.com).

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