100% RENEWABLE ENERGY SYSTEM FOR SCOTLAND

Demand Management and Energy Storage Course work

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Contents

TASK 1

It has been estimated that for Scotland to generate 100% electricity from Renewable energy (RE), the market has to provide an installation of 16 GW from mixed sources. This study will upscale the current generation from 2017 through 2018 with detailed consideration to the progression of each renewable energy sources (RES) to understand the possible increase of the energy in future; also attention will be given to the debates that have been raised against some RES due to their negative environmental impact.

Sizing Consideration

The data obtained from UK government energy [1] is visualised in Table 1, It shows that wind installation has the highest installed capacity (74%) and has been the only RES with a steady increase over the year. Large hydro has an installed capacity of 13% but with insignificant changes over the years. The offshore winds and the plant biomass generator is 2% each of total installations while the solar PV and small scale hydro have 3% each with gradual increment over the year. The landfill, these seven RES are forming the major generators which will be giving the most consideration in sizing.

Table 1: Installed capacity for the first quarter of 2016-2018 and their % increment. The onshore and offshore show the highest increase over the year while the large hydro experienced little or no increment. Future increment very possible for wind and others, while little increment may be experienced for large hydro.

	2016 (MW)	2017 (MW)	2018 (MW)	% in '18	%Inc ('16-17')	%Inc ('17-18')
Onshore Wind	5,585	6,877	7,582	73.7772	23.13	10.25
Offshore Wind	187	187	253	2.4653	-	35.23
Shoreline wave / tic	7	18	18	0.1744	145.22	-
Solar photovoltaics	304	315	317	3.0836	3.60	0.70
Small scale Hydro	240	280	313	3.0496	16.74	11.77
Large scale Hydro	1,339	1,341	1,341	13.0487	0.14	-
Landfill gas	116	116	116	1.1274	- 0.43	0.03
Sewage sludge dige	7	7	7	0.0705	-	-
Energy from waste	18	18	20	0.1897	-	11.43
Animal Biomass (no	13	13	13	0.1216	-	-
Anaerobic Digestior	32	44	45	0.4368	38.15	1.32
Plant Biomass 3	189	221	252	2.4551	16.42	14.40
Total (MW)	**8,038**	**9,437**	**10,277**	**100.0000**		

In 2001, the Scottish renewable energy commissioned to estimate the potential of the renewable energy in Scotland estimated the onshore wind capacity to be capped at 11.5GW and offshore wind at 25GW to avoid congestion of wind farm that may lead to public discomforts [2][3]. This study will cap the installed capacity for the onshore wind at 11GW to avoid adverse environmental impact, and any excess required will be added to the offshore wind since it has been suggested that a gradual increase will be experienced in the installation of offshore wind due to the reduction in investment cost and high potential in Scotland [4][5].

Sizing Calculation

To attain the required installation of 16GW, the percentage installation capacity for each RES in 2018 [1] is multiplied by the 16GW. It is observed that the installed capacity for onshore wind is beyond the recommended in capacity; therefore, 5% is deducted from onshore wind and added offshore wind. The new installed capacity for Scotland to achieve 100% RE is shown in table 2; table 2 shows that the onshore wind will dominate the production with a substantial increase in offshore wind and moderate increase across all other RES. The whole installation is **16GW.**

Table 2: The final and acceptable installed capacity for Scotland to achieve 100% of electricity from RES. The percentage installed capacity (red marker) is multiplied by 16GW, 5% is deducted from onshore wind and added to percentage of offshore (yellow marker) to give the new installed capacity for 2050 (blue marker).

	2018	% in 2018	Inst Cap (MW)	New %('18)	New inst. Cap (MW)
Onshore Wind	7,582	73.7772	11,804.36	68.7772	11,004.36
Offshore Wind	253	2.4653	394.44	7.4653	1,194.44
Shoreline wave / tic	18	0.1744	27.90	0.1744	27.90
Solar photovoltaics	317	3.0836	493.37	3.0836	493.37
Small scale Hydro	313	3.0496	487.94	3.0496	487.94
Large scale Hydro	1,341	13.0487	2,087.79	13.0487	2,087.79
Landfill gas	116	1.1274	180.39	1.1274	180.39
Sewage sludge dige	7	0.0705	11.28	0.0705	11.28
Energy from waste	20	0.1897	30.36	0.1897	30.36
Animal Biomass (no	13	0.1216	19.46	0.1216	19.46
Anaerobic Digestior	45	0.4368	69.88	0.4368	69.88
Plant Biomass [3]	252	2.4551	392.82	2.4551	392.82
Total	**10,277**	**100**	**16,000**		**16,000**

Capacity Factor Estimation (CF)

In the estimation of the capacity for all installation, the historical load factors provided by the government data will be used and compared with published literature to nullify any discrepancies in the operation of each generator such as intentional shutting down of RE plants when they are uneconomical at a particular time of the years. Detailed description for the CP selection will be given to wind being the RES covering 75% of the total installed capacity

Offshore and Onshore Wind CF

The data provided by BEIS [1] for CF was plotted in Figure 1, below and the least CF of 19%-20% was observed majorly at the 2nd and 3rd quarters of every year for onshore wind and for offshore the least CF 28%-30% was also observed for the 2nd and 3rd quarter for every year. The average for the four quarters is 24%.

According to a publication on onsite CF measurement at a different location in Scotland [6], the minimum annual load factor of 22.3 was observed at Kinloss which is lower than the average CF provided by BEIS data and with higher CF of average 30% observed for locations similar to be offshore (see figure 2). Therefore, the value of **22%** will be used for onshore and value of **30%** will be used for offshore which provides a worst case scenario for both technologies as experienced by on-site measurement of CF. These two chosen values are also within the ranges provided by BEIS which are also in the ranges estimated by reference [7].

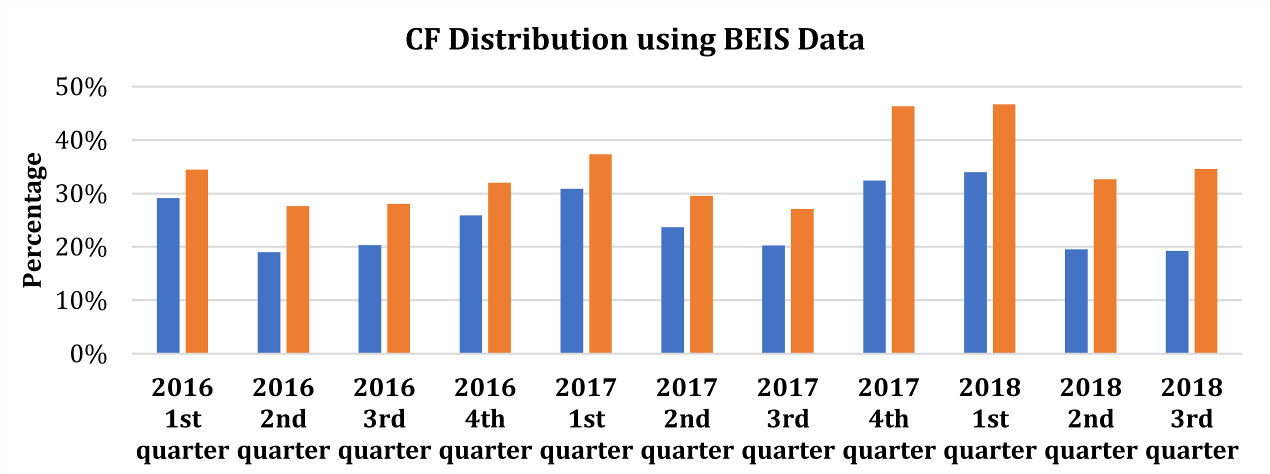


Figure 1: the CF for wind for four quarters in three years (2016 -2018) [1]. The CF ranges from 19-30%.

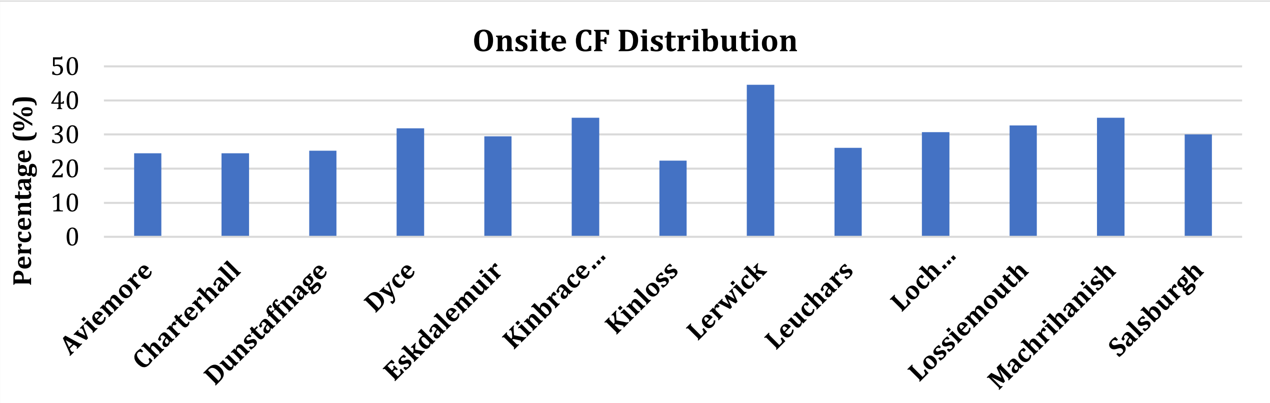


Figure 2: The onsite capacity factor measurement of different locations in Scotland [6].

Hydro Power (HP) CF

Figure 3 shows the load capacity of hydro CF provided by the BEIS data [8], it shows an inconsistent pattern with an average of 40%, picking a value might be underestimated or overestimated; therefore public literature for different hydropower plant will be used and compared with the average from the data, this shows that the CF for the two major Hydro Power station in Scotland is observed to be **40%** and this value will take in this study as the CF for HP [9][10].

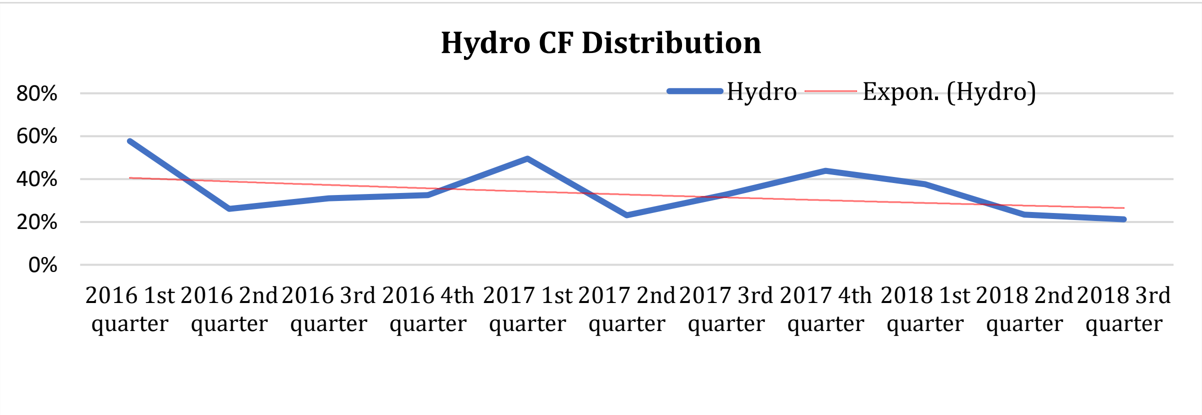


Figure 3: The trend of the CP from 2016 – 2018.

Solar PV CF

The load factor was not provided by BEIS [8]; therefore the CF will be calculated from the installation and generation provided by [1] using equation 1. The installed capacity for 2014 and 2015 are 165.9 and 213.1 MW and a generation of 148.2 and 183.9GWh was achieved respectively. Using equation 1, the calculated CF for these two years is 10.4% and 10.5%. Therefore CF of **10%** will be used for solar PV.

$$\text{Capacity factor} = \frac{\text{Energy genearted}}{\text{Installed capacity} * 8760} \qquad \text{(Equation 1)}$$

Wave and Tidal

Some of the installed tidal and wave generators are for educational and research purpose [11]; therefore, data from DECC are not reliable, since all the energy generation are not included. It has been suggested that the average CF across the UK for tidal and the wave is around **30%** and this will be used in this study [11].

Biomass and others

The biomass power plants are heavily reliant on the supply of the bioenergy resources; therefore, the capacity factor is dependent on the supply of the resources. The Scotland biomass estimated potential is well above the recommended install capacity for 2020; therefore it will be assumed that the supply of all the biomass will be available most times and the CF chosen is **70%** for all biomass power plants [12].

Total Electricity output

The annual total electricity output from all generators was computed in excel using the capacity factor already predicted above using equation 2.

$$\text{Electricity (GWh)} = \text{Installed Cap. (GW)} * \frac{\text{CF}}{100} * \text{Total hours in a year (equation 2)}$$

Table 3 shows the output of the calculation done and the output of the electricity, the annual production of 39,135GWh per annum which depict a worst-case scenario for the energy production by the RES and any excess can be export.

Table 3: The CF and annual electricity generation for all the upscale RES (red marker) and the yearly electricity generated is 39,135GWh.

	2018	% in 2018	Old Cap (MW)	New %('18)	New Cap (M\	New Cap (GW)	Cap Fac (%	Elect (GWh)
Onshore Wind	7,582	73.7772	11,804.36	68.7772	11,004.36	11.00	22	21,207.59
Offshore Wind	253	2.4653	394.44	7.4653	1,194.44	1.19	30	3,138.99
Shoreline wave / tic	18	0.1744	27.90	0.1744	27.90	0.03	40	97.75
Solar photovoltaics	317	3.0836	493.37	3.0836	493.37	0.49	10	432.20
Small scale Hydro	313	3.0496	487.94	3.0496	487.94	0.49	40	1,709.75
Large scale Hydro	1,341	13.0487	2,087.79	13.0487	2,087.79	2.09	40	8,230.09
Landfill gas	116	1.1274	180.39	1.1274	180.39	0.18	70	1,106.14
Sewage sludge dige	7	0.0705	11.28	0.0705	11.28	0.01	70	69.20
Energy from waste	20	0.1897	30.36	0.1897	30.36	0.03	70	186.16
Animal Biomass (no	13	0.1216	19.46	0.1216	19.46	0.02	70	119.34
Anaerobic Digestior	45	0.4368	69.88	0.4368	69.88	0.07	70	428.52
Plant Biomass [3]	252	2.4551	392.82	2.4551	392.82	0.39	70	2,408.79
Total	10,277	100	16,000		16,000	16		39,135

Electricity Storage System (ESS) Estimation

In sizing the storage capacity required for the grid to be stable (i.e. supply meets demand at all time), two factors are needed to be considered: they are power and energy. The power will be able to help in voltage and frequency balancing and also helps with load levelling while the energy requirement will help with balancing seasonal variation.

Scotland annual demand

The annual electricity consumption is in the ranges of 37- 40TWh [13]. There has been a gradual decrease in the energy demand of Scotland in the last few years reaching a value of 37TWh. There is potential for even further reduction in future's consumption due different energy efficiency measures and demand side management [14][15]. Therefore the average of the annual demand **(38TWh)** will be used throughout this study.

Power

The power requirement of the storage is heavily dependent on energy sources that can supply energy at all time (continuously) bring forth a concept called BASELOAD. Baseload is the ability of a generator to meet power demand at all time (24/7) [16]. The intermittency of some renewable energy sources has restricted then from been used for this functionality [17]. RES such as wind and solar are not recommended to be used as baseload and might require complex analysis, but the hydropower and biomass generators will be able to meet the base load requirement as long as the needed resources are available and supplied at all time [17][18].

In power analysis, the efficiency of the generators is needed to be considered, and the efficiency of **80%** will be used for hydropower plants[19], and **80%** is used for the bioenergy generators [20], also the some of the baseload resources selected might not be able to offer baseload all the time, the baseload is multiplied by a factor of **0.8** to allow for uncertain in the chosen generators .

To calculate the storage's power requirement, the power demand used is a large power demand that has been experienced during the winter in 2007 [21]. Figure 4 illustrates baseload and power demand; this shows that in the worst-case scenario whereby all the intermittent energy sources are not available and only 80% of both hydro and biomass are available. The peak of the demand 6GW and the baseload peak is 2.3GW; therefore, energy storage must meet the difference between these two powers.
The red line indicates the storage capacity (difference) which is **3.7GW.**

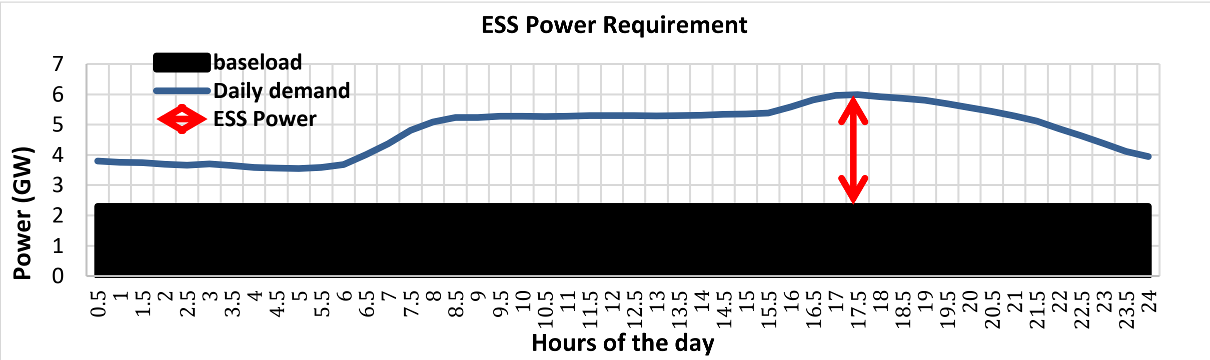


Figure 4: ESS Power requirement. The differences between the baseload and the maximum demand are the ESS power requirement (red line) which is equal to 3.7GW.

Energy

The current electricity grid was well designed during construction but was not designed for generators that provide power will high level of intermittency such as wind, therefore the excess energy during intermittency must be curtailed from entering grid [22]. This excess energy can be absorbed by storage during a surge in energy production and can be released whenever required. Therefore, the rating of ESS in terms of energy is the surplus energy that must be curtailed from entering the grid.
The grid currently is meeting an average demand of **220 GWh** [1].

$$\boldsymbol{E_{ESS} = E_{Surp} - E_{dem}} \quad \text{(equation 3)}$$

The maximum CF that has been experienced was used use calculate the excess energy [1], [13], whereby the wind and solar was upscale to the maximum capacity ever experienced as shown in Table 4, this shows a maximum of 229.09 GWh/day; therefore, using equation 3, the $E_{supply\ daily}$ is equal to **9.09 GWh.** This value is aggregated to the annual requirements.

$\mathbf{E_{ESS\ annual}} = \boldsymbol{E_{ESS\ daily}} * $ **366 = 9.09 GWh * 366 = 3.33 TWh (366 in case of a leap year)**

Hence, the ESS energy requirement is 3.333TWh which is equal to 8.7% of the demand.

Comparing this value to the recommended estimations, the electrical storage white paper [23] recommended that energy storage should be in the range of 2-10% of the electricity demand. The calculated ESS energy requirement is 8.7% of the demand showing that it's in correlation to the recommendation.

Table 4: The ESS Energy requirement. The red maker shows the upscaled capacity factor intermittent energy sources, and blue marker indicates the daily energy production.

	2018	% in 2018	Old Cap (MW)	New %('18)	New Cap (M\	New Cap (GW)	Cap Fac (%'	Elect (GWh)	New Cap	Max Daily Gen (GWh)
Onshore Wind	7,582	73.7772	11,804.36	68.7772	11,004.36	11.00	22	21,207.59	0.6	158.46
Offshore Wind	253	2.4653	394.44	7.4653	1,194.44	1.19	30	3,138.99	0.75	21.50
Shoreline wave / tic	18	0.1744	27.90	0.1744	27.90	0.03	40	97.75	0.7	0.47
Solar photovoltaics	317	3.0836	493.37	3.0836	493.37	0.49	10	432.20	0.5	5.92
Small scale Hydro	313	3.0496	487.94	3.0496	487.94	0.49	40	1,709.75		5.86
Large scale Hydro	1,341	13.0487	2,087.79	13.0487	2,087.79	2.09	40	8,230.09		25.05
Landfill gas	116	1.1274	180.39	1.1274	180.39	0.18	70	1,106.14		3.03
Sewage sludge dig	7	0.0705	11.28	0.0705	11.28	0.01	70	69.20		0.19
Energy from waste	20	0.1897	30.36	0.1897	30.36	0.03	70	186.16		0.51
Animal Biomass (no	13	0.1216	19.46	0.1216	19.46	0.02	70	119.34		0.33
Anaerobic Digestior	45	0.4368	69.88	0.4368	69.88	0.07	70	428.52		1.17
Plant Biomass [3]	252	2.4551	392.82	2.4551	392.82	0.39	70	2,408.79		6.60
Total	10,277	100	16,000		16,000	16		39,135		229.09

The storage sizing requirement is **3.7GW and 3.33TWh**

TASK 2

Potential and Sites for Pumped Hydro Storage (PHS) in Scotland

PHS requires regions with suitable mountains or highlands with varying elevations with high heads to make it economically feasible, i.e. if the proposed site of implementation is not suitable, the extra cost will be incurred to make necessary adjustment such as creating an extensive dam which will increase the investment cost and might render the project impracticable. The UK is general an Island which have a small potential of PHS and its evidence as the total installation now in the UK is 3GW compare to Germany (6GW) and Austria (8GW) [24][25].

Scotland is a region with relatively high potential for PHS compare to most of UK, it has highland and mountainous but most are very far from large energy demand and additional cost might be incurred for transportation of electricity down to the demand area [24]. Scotland has been limited in the installation of PHS, and for the past 40 years, the only one large scale sit has been discovered (Cloire Glas) which was initially planned to be 600MW but was increased to 1500MW [26][10].

Literatures has suggested that getting sites with vast potential has been difficulty find and small sites are now discovered based on different algorithms and also some these small sites will require substantial investment, discounts and incentives from the government to make it profitable.

Forrest used an automatic detecting algorithm to evaluate the potentials hydropower resource in Scotland. He discoversed that a total of 657MW in 1015 sites of hydro potential if the government offer 8% discount for 25 years [27]. Duncan built on the research of Forrest with a more significant discount rate (8%) estimated the potential in the range 400 – 893MW [28]. These two pieces of research suggested that some of these potentials estimated can be explored in the creation of new PHS.

There is currently 740MW fully operational PHS in Scotland with additional 1510MW in the planning stage[24] as seen in figure 5. An upgrade of the existing 440MW Cruachan scheme has been proposed to the double the power and capacity and the project at Balmacaan is also in the proposal stage (red box in figure 5) [25][10].

If all the planned and proposed schemes are installed, UK will have a total installation of 6238MW with 65% installed in Scotland only (4050 MW) and a possibility few hundreds of MegaWatt can be derived from the suggested potential of hydropower in Scotland by Duncan and Forrest [24][25] [27][28]; therefore the potential can approach **5000MW**.

The estimated ESS power in Task1 is 3.7GW; this is the minimum power that must be provided for grid stability. If a roundtrip efficiency of 80% is assumed, the required installation must be 4625MW. It has been estimated that the potential of can approach 5000MW; therefore, the potential in Scotland will meet the power requirement which will be made possible by a substantial discount rate to build the capacity. Also, for grid stability, energy demand must need the supply at all time, this is an energy parameter, and the energy requirement is 3.33TWh (i.e. **713KWh/KW**), this a relatively high capacity per power installed which will require a substantial amount of investment but still achievable with government support.

Scheme status	Name	Power (MW)	Energy Capacity (GWh)
Operational	Dinorwig	1,728	9.1
	Cruachan	440	10.0
	Festiniog	360	1.3
	Foyers	300	6.3
Planning	Coire Glas	300-600 +900	30-40
	Sloy *(conversion)*	60	20-40
	Glenmuckloch	400	TBD
	Muaitheabhal	150	TBD
Proposed	Glyn Rhonwy	100	1.2
	Balmacaan	300-600	30-40
	Cruachan *(upgrade)*	+440-600	+7.2

Figure 5: The total installed, planned and proposed PHS in the UK with the Scotland Installations in red boxes [25].

Cost of building the (Pump Hydro Storage) PHS

The economical assessment and estimation of the installation cost are highly dependent on numerous factors; PHS is generally known to have a high capital cost, long life and low operational and maintenance cost [29]. A factor that determines the significant part of the costing is the location of implementation, just like hydropower, even higher cost that might make the PHS project unprofitable may be observed if implemented in a not suitable geographical location [30],[31]. In determining the cost of the proposed storage, the power cost is usually determined in £/KW and energy in £/KWh.

Different ranges of cost been estimated for the construction PHS in various location across the world. Globally, the IRENA estimated the energy capacity cost of PHS to be in the ranges of $10 - $100/KWh in 2017 and anticipated no change in this cost by 2030 because this technology is matured and well understood [32]. A study by Deane et al. supported this range. Deane estimated the cost of implemented of the PHS system across different regions such as Europe, USA and Japan to be in the ranges of £470 - £2170/KWh and was able to obtain the cost of a new 7000MW installation PHS to be £5.8 billion across these regions [31].

Nationally the DECC 2050 calculator estimated the installation cost in the ranges of £500/KW - £5000KW but used a £2100/KW as the referenced cost in calculator with £260/KWh for the capacity [33]. Locally, the different cost has been incurred in the construction of different PHS in Scotland with varying capacity and power:

1. The proposed 400MW will cost £150millions with capacity of 1.7GWh; therefore the power cost is £375/KW and a capacity of 4.25KWh/KW with a capacity cost of £88/KWh [34].
2. An upgrade of 600MW/10GWh of the current PHS at Cruachan has an estimated cost of £1billion. The power cost is, therefore, £1667/Kw and capacity is 16.7KWh/Kw and capacity is £99.4/KWh. This high value is expected as the project involved different construction cost in expanding the current capacity [24][35].

3. The Dinorwig project at North Wales also incurred a cost of £850/KW and a capacity cost of £162/KWh. Both values are estimated to recent year money value using the appropriate inflation rate [25][35]. Figure 6 shows that there is no correlation between the plant's size and cost for the three local plants.

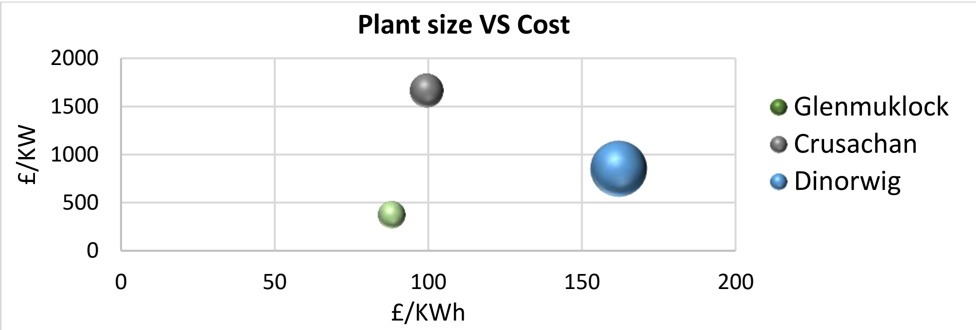


Figure 6: shows some the locally installed PHS with the bubble size depicting the size of installed power, with recently published cost £/KW and £/KWh. No correlation between size and price.

There is a consistency between the global and locally installed PHS which is in the range of **£375 -1600/KW** for the power and capacity cost ranging from **88-162KWh**. But a lower range compared to the national prediction because the national predicted is extrapolated to the entire of UK and Scotland has a better potential compare to the whole of UK which will make PHS have a lower capital cost during construction.

The proposed power **is 3.7GW** (peak output) assuming a round trip efficiency of **80%,** the power is installation required is **4.625GW,** and energy requirement is **3.33TWh**. Therefore capacity is **713KWh/KW**. Using the ranges that have been observed from the local installation in Scotland that correlate with the predicted international cost (**£375 - 1600/KW)**, the investment cost is **£2billion – £7.5billion,** this cost will be incurred in the installation of new PHS and upgrade of the existing ones to scale up to the required installation. This range of investment will also be able to meet the capacity construction for the PHS.

TASK 3

The parameters estimated in task one is used to build the scenario in EnergyPlan [36] for 100% electricity production using RE and storage only. The UK model of EnergyPlan of 2020 is downloaded and inputted into EnergyPlan data folder to provide a closer approximation for the Scotland model [37].

Demand

The demand for Scotland is estimated in Task1 to be 38TWh; this value is inputted in EnergyPlan as shown in figure 7. Every other demand requirement such as heating, cooling, transportation and desalination are all set to 0. This demand includes the total demand for Scotland and the energy requirement for charging the storage system.

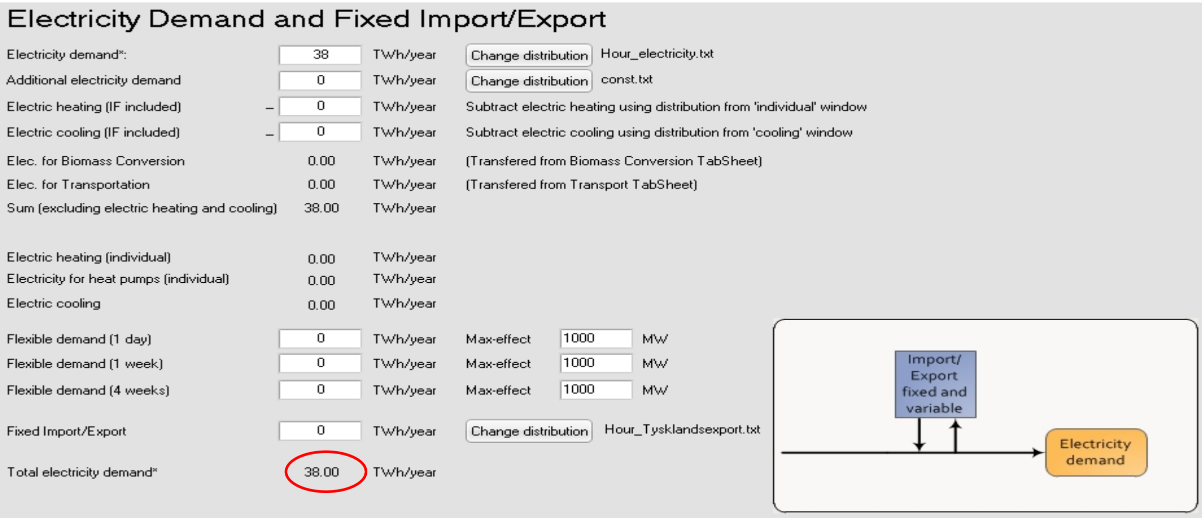


Figure 7: EnergyPlan Demand input.

Supply

The scaled parameters for the supply are also inputted into EnergyPlan. The supply is categorised into three different sections: The central power plant, Waste Incinerations and Variable RE.

Central Power Plant (CPP): This depicts both large and small power plants that can be used as baseload to provide grid stability. Three plants are used in EnergyPlan: PP1, PP2 and Dammed Hydro as seen in figure 8.

The scaled plant biomass (392.80MW) in Task 1 is used as PP1 in EnergyPlan been the most abundant biomass. It is configured to provide 100% of its output as electricity (no heating). The Animal (19.46MW) + Anaerobic (69.88MW) are both used as the PP2.

The large-scale hydro (2087.79MW) is used as the dammed hydro in EnergyPlan. The water supply is 10.29TWh/years which gives the exact value of the calculated electricity generation (8.23TWh) in Task 1.

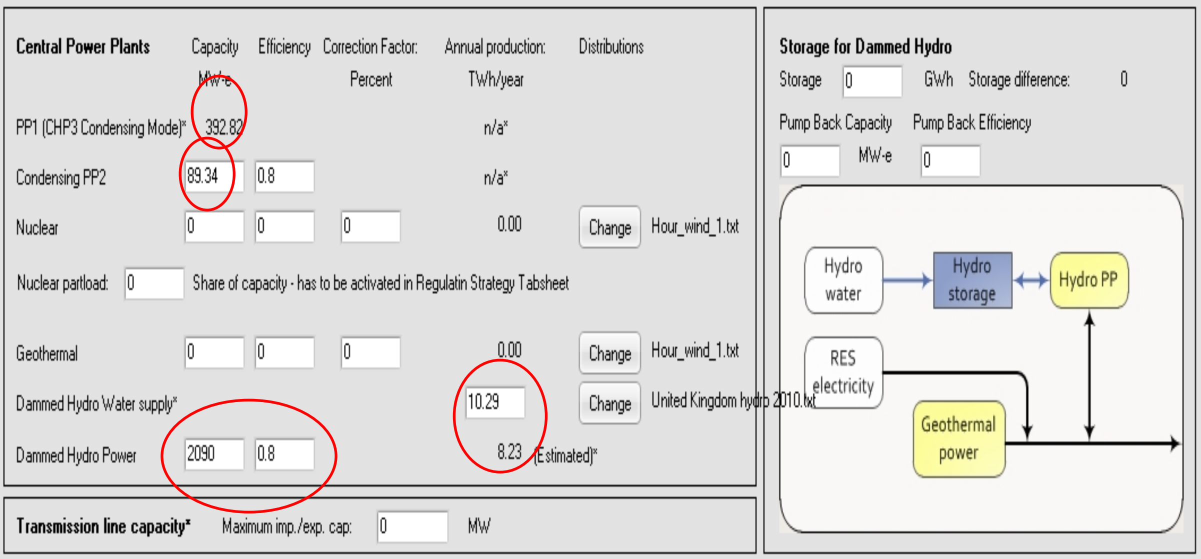


Figure 8: PP1, PP2 and large hydro input in EnergyPlan.

Fuel for CPP: The study aims to design a 100% RE system. Hence any fuel used must also be from a renewable source. Both PP1 and PP2 require fuel inputs; therefore, Biomass will be used to supply 100% of their requirements. Figure 9 shows an in 1(one) for PP1 and PP2 in the fuel distribution fields. This means that the fuel for both plants will be supplied by 100% biomass.

Distribution of fuel	Coal	Oil	Ngas	Biomass	Electrofuels(Oil) *)	
(TWh/year)	Variable	Variable	Variable	Variable	Fixed **)	
DHP	0	0	0	0	0	DHP: Boilers in district heating group 1.
CHP2	0	0	0	0	0	CHP2: Combined heat and power in district heating group 2.
CHP3	0	0	0	0	0	CHP3: Combined heat and power in district heating group 3.
Boiler2	0	0	0	0	0	Boiler2: Boilers in district heating group 2.
Boiler3	0	0	0	0	0	Boiler3: Boilers in district heating group 3.
PP1	0	0	0	1	0	PP1: Condensing mode operation of combined heat and power in district heating group 3.
PP2	0	0	0	1	0	PP2: Condensing power plant in 'Electricity only'.

Figure 9: Distribution of fuel.

Waste Incineration Plants: These are biomass regarded as waste; they can also offer baseload in EnergyPlan. The landfill (180.39MW) in Task1 is modelled as Group1 while the sewage (11.28MW) and energy from waste (30.36) are modelled as Group2 and Group3 respectively. It is configured only to provide electricity (no heating). The combined electricity production for the three generators is 1.3TWh (see figure) which is equivalent to the prediction made in Task1 (222MW CP 0.7 = 1.3TWh)

Waste Incineration

Waste is defined geograhical on the three district heating groups. Only one hour distribution can be defined and storage of waste is not considered an option.
Heat production is utilised and given priority in the respective district heating groups. Electricity production is fed into the grid. Biofuel production for transportation is transfered to the transportation window.
And biofuels for CHP and boliers is substracted from the fuels in the respective district heating group. "Various" represent non energy products such as food.
The economic value is substrated from the cost of the waste energy recource.

Strategy CHP-Boiler: 1.Coal/2.Biomass — Fuel Substitution

Distribution of Waste: Change const.txt

	Waste input	DH production		Electricity production		Biofuel transportation		Biofuel CHP-Boiler		Various (Food etc.)		Income from Various*	
Unit:	TWh/year	Efficiency	TWh/year	Efficiency	TWh/year	Efficiency	TWh/year	Efficiency	TWh/year	Efficiency	TWh/year	MGBP/TWh	MGBP
Group 1:	1.58	0	0.00	0.7	1.11	0	0.00	0	0.00	0	0.00	0	0.00
Group 2:	0.01	0	0.00	0.7	0.01	0	0.00	0	0.00	0	0.00	0	0.00
Group 3:	0.27	0	0.00	0.7	0.19	0	0.00	0	0.00	0	0.00	0	0.00
Total:	1.86		0.00		1.30		0.00		0.00		0.00		0.00

Figure 10: Waste Incineration Input.

Variable Renewable Energy: These are the intermittent energy sources.

Onshore Wind: The exact onshore wind power estimated in Task1 was inputted in EnergyPlan. The correction factor of -0.999999 was used in achieving a capacitor factor of 22% which subsequently give the exact electricity output (21.7TWh) calculated in Task1. This correction factor is essential because the data provided by the EnergyPlan UK model (2020) provide a capacity factor of 24% [37]. Onshore wind cannot contribute to the grid stability; therefore, its stabilisation share is set to 0.

Offshore wind, Solar and wave: Similar to onshore wind power, the exact power estimated in Task1 for offshore wind(1200MW), Solar (494MW) and wave/tidal(28MW) was inputted into EnergyPlan and the correction factors were varied until the exact capacity factor predicted in Task1 was achieved shown in figure 11 (0.14, 0.44 and 0.64 respectively). These RE sources do not contribute to grid stability; therefore, their stabilisation factors are all set to 0.

River Hydro: The small-scale hydro plants in Task1 is used in modelling this input for EnergyPlan. The estimated value (488MW) was used with a correction factor of 0.62 to give a capacity factor 0.4 as predicted in Task1. Small scale hydro can contribute to grid stability but not entirely [16]; therefore, a fraction of 0.8 as the stabilisation share, i.e. 80% of the production will be used as grid support or baseload.

Variable Renewable Electricity

Renewable Energy Source	Capacity: MW	Stabilisation share	Distribution profile*		Estimated Production TWh/year	Correction factor	Estimated Post Correction production	Estimated capacity factor
Wind	11005	0	Change	United Kingdom v	27.95	-0.99999	21.71	0.22
Offshore Wind	1200	0	Change	United Kingdom v	3.05	0.14	3.21	0.30
Wave Power	28	0	Change	United Kingdom v	0.07	0.64	0.10	0.40
River Hydro	488	0.8	Change	hour_wind_2.txt	1.13	0.62	1.73	0.40
Photo Voltaic	493.37	0	Change	Hour_solar_prod1	0.34	0.44	0.45	0.10
Wave Power	0	0	Change	Hour_solar_prod1	0.00	0	0.00	0.00
CSP Solar Power	0	0	Change	Hour_solar_prod1	0.00	0	0.00	0.00

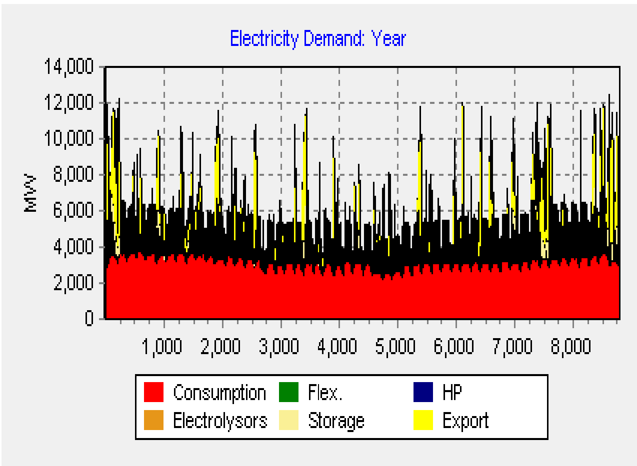
Figure 11: The intermittent energy sources input in EnergyPlan.

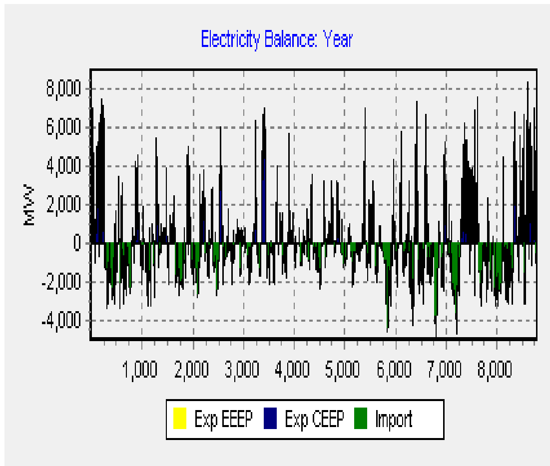
Simulation result

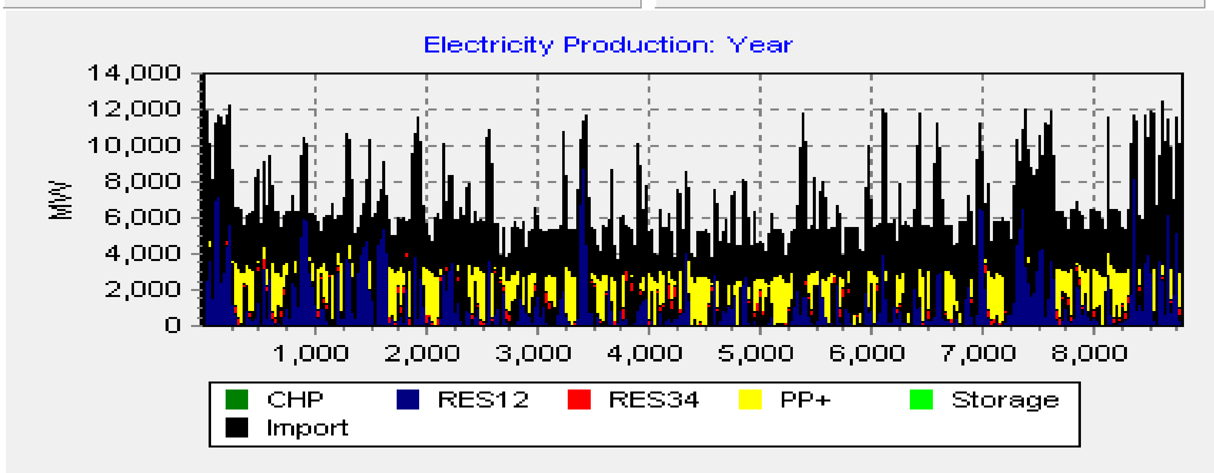
The simulation result will be described in two case scenarios; the first case scenario will depict the result of a grid entirely supplied by RE sources only with no storage, no CEEP correction. The second case scenario simulates the first case scenario with CEEP correction and the estimated storage capacity from Task 1 and optimisation will be done if need be.

Case 1

The first case is shown in figure 12. This indicates that the PES is supplied entirely by RE and the total production of RE is greater than the demand (103%) as shown in figure 14. Therefore, approximately 10000MW interconnection will be needed to supply both export and import in meeting grid stability figure 12. This study aims to avoid interconnection. Case 2 provides the solution to the interconnection requirement of case1. Case1 shows that the sized RE in Task1 will be sufficient to provide electricity demand throughout the year.



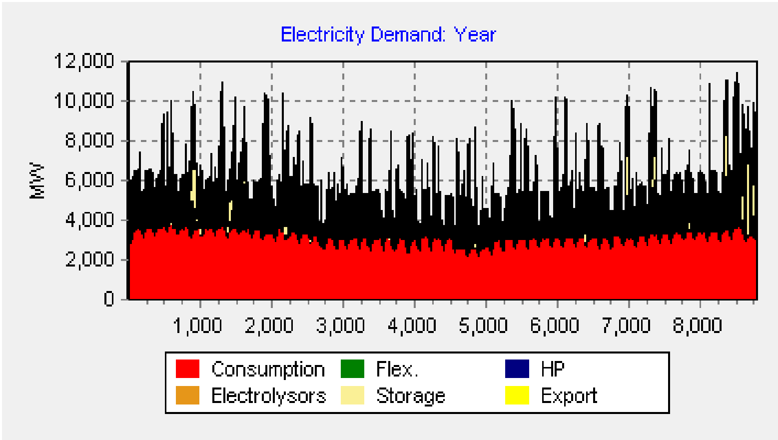


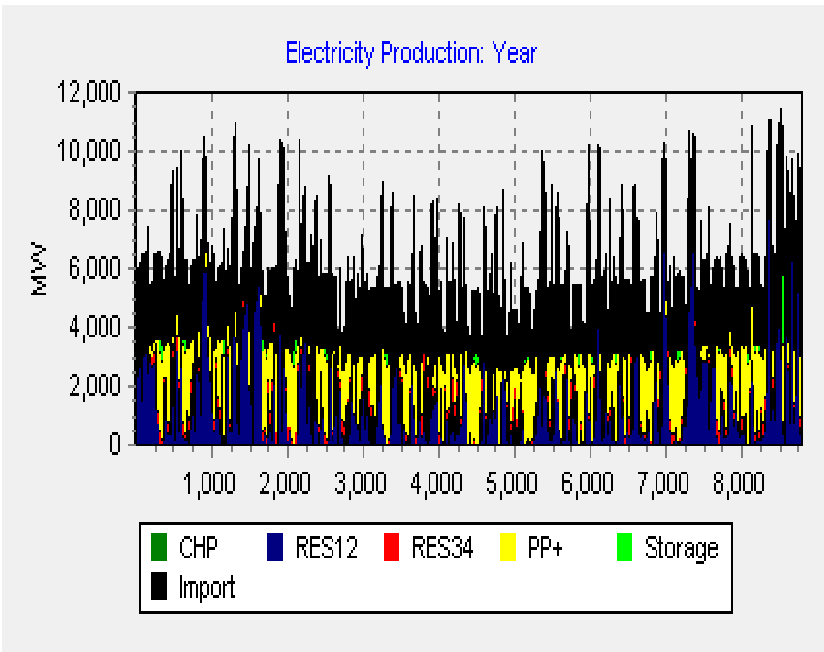


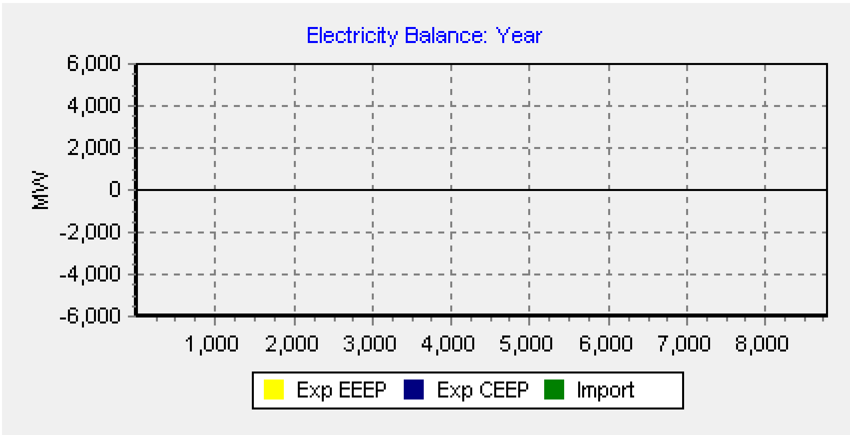
Case 2

The aim now is to ensure no interconnection. The CEEP was set to 1 meaning that the RES1 and RES2 (Onshore and offshore wind – been the largest RES generators) will reduce their output to avoid excess production thereby avoiding export requirements (see appendix A) The minimum stability share for waste is also configured to be 1 so that the entire waste incineration plant production will be used for grid stability. The estimated storage in Task 1 is inputted into EnergyPlan, and the minimum PP was configured to be 400MW (see appendix B). And lastly, the Minimum Grid Stabilisation Production Share (MGSPS) is set to be 0.3. Detailed analysis of this input will be done in the next task.

Figure 13 shows the graphical result of the case 2 scenario. The scenario shows no error, no import and no export as also seen in figure 13 which is the required aim of this study. This indicates that the combined effect of estimated storage and other grid stability parameters will be adequate in ensuring a stable grid.







TASK 4

Ancillary services, Grid stability and ESS

Ancillary services are services render by specific energy sources to ensure voltage and frequency stability in the grid. The conventional method of ensuring this stability is usually by using large CHP in energy networks. Large CHP are usually made of natural gas power plant, nuclear, hydro and coal power plant [38][39]. The power plants that can depict these characteristics in this study are the large hydro and biomass which contribute 17.5% of the generation; this might not be sufficient to provide ancillary for a stable electricity grid system [39]. Large CHP are usually operated by a synchronous generator that can provide and consume reactive power to control voltage instability and also produce varying active power to control frequency [38].

The wind energy sources which contribute 75% of this scenario are usually fitted with asynchronous generators limiting them from producing ancillary services because asynchronous cannot not provide reactive power to control voltage and frequency instability [38]. However, there are different power electronics such as inverters that can be used to provide reactive in regulating voltage in the grid but still wind energy generators cannot provide constant active power to meet required demand [40]; therefore there is a possibility for a mismatch that may cause frequency instability. Hence, other method to solve this problem is required.

Firstly, the storage system is modelled to be 100% PHS, PHS can supply ancillary services as they are having turbines similar to hydropower plants but might be constrained due to the potential PHS in Scotland as explained in Task 2. If the potential in Scotland is not adequate, the Battery Energy Storage System (BESS) can be used. BESS can be installed in different locations to provided grid stability.

BESS just like PHS will store excess energy from the intermittent RE sources during the off-peak hour and release it whenever needed. It provides grid stability with the help of inverters which can produce both reactive and active power during peak hour to balance both supply and consumption in attaining both voltage and frequency stability. NaS is a very good example of BESS gradually gaining popularity for this application [41].

Secondly, the EnergyPlan have a way of configuring the grid stability. It offers some grid restriction method shown in Appendix A. The Minimum Grid Stabilisation Production Share (MGSPS) is a fraction denoting the minimum of production that must always be available to provide grid stability, it is recommended to use 0.3 [42]. The minimum PP input set to 400MW meaning that the PP1 and PP2 must always make 400MW available for grid stability. All these were able to ensure a stable grid as seen in Figure 15.

Weakness

The hydropower modelled in the simulation is 4.625GWh for PHS and 2.090GWh for dammed hydro. Therefore, the total hydropower is 6.715GWh; this amount of water energy may be not available in Scotland. This can be solved by using different technologies of storage system such as battery energy storage system BESS in different fractions from the PHS capacity at different locations as explained in the previous section.

The second weakness is the energy simulation approach used by EnergyPlan. The yearly aggregate of the electricity demand of Scotland (38GWh) was inputted into EnergyPlan rather than hourly power demand or lower time interval which would have provided the closer to real life scenario for the simulation. EnergyPlan used the 38GWh to calculate the hourly power requirement which may not represent the real-life scenario because there may be time with peak power demand greater than the EnergyPlan calculated power.

Interconnection Effect

Figure 14 shows the simulation result of the scenario with the interconnection of 1000MW while figure 15 shows the result of the simulation without interconnection. The CEE P input for the interconnected scenario was set to zero to allow for free flow of any excess electricity through the transmission line, and the storage system was also removed given way to a lower cost system (£10,753 million). The final output generation from RE sources is 39.27TWh, which is the maximum obtainable electricity as estimated in Task 1 providing 103% of the demand.

Figure 15 shows the system without interconnection. This scenario have an annual cost of £11,627 million which is higher than the interconnection due to storage cost. The RES supplied 91.4% of the demand in this scenario and storage supplied the remaining 8.6% because the CEEP was configured to be 1.

For both scenarios, the RES share of the PES is 100%.

Interconcetion

```
SHARE OF RES (incl. Biomass):
RES share of PES                        100.0 percent
RES share of elec. prod.                103.4 percent
RES electricity prod.                   39.27 TWh/year

Electricity exchange                              995
Import                                                      995
Export                                                     -992
Bottleneck                                                  992
Fixed imp/exp                                                 0

CO2 emission costs                                  0
```

Variable costs	966
Fixed operation costs	6892
Annual Investment costs	2896
TOTAL ANNUAL COSTS	10753

No Interconnection

SHARE OF RES (incl. Biomass):		
RES share of PES	100.0	percent
RES share of elec. prod.	91.4	percent
RES electricity prod.	34.54	TWh/year

Electricity exchange	0	
Import		0
Export		0
Bottleneck		0
Fixed imp/exp		0

Variable costs	2074
Fixed operation costs	6820
Annual Investment costs	2732
TOTAL ANNUAL COSTS	11627

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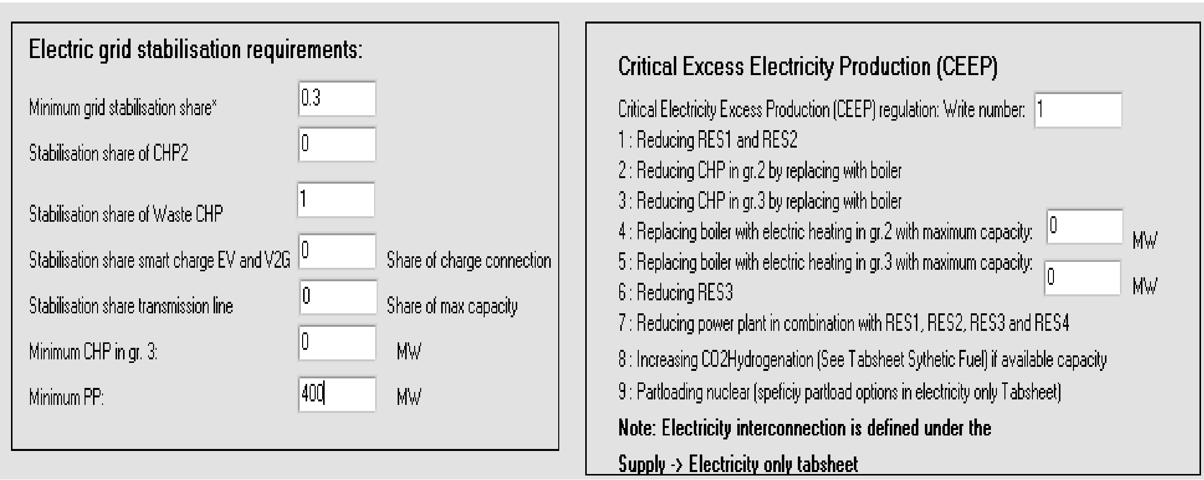
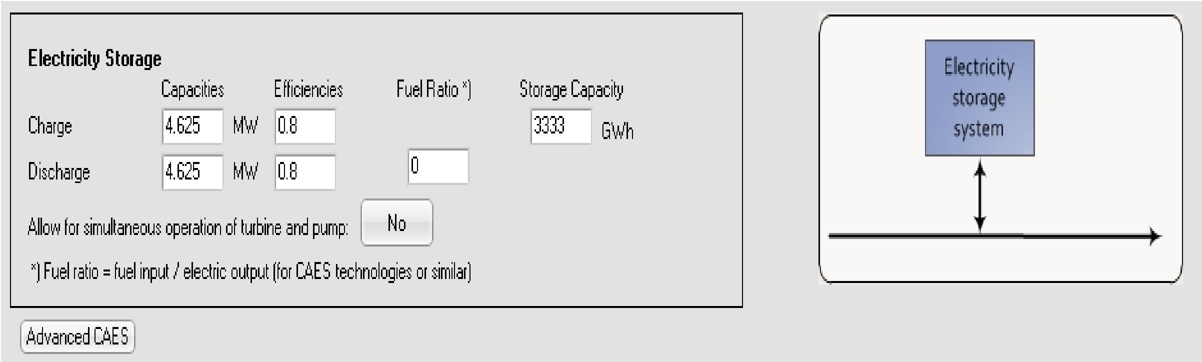
APPENDIX A



APPENDIX B


Electricity Storage
Capacities
Efficiencies
Fuel Ratio *)
Storage Capacity
Charge
4.625
MW
0.8
3333
GWh
Discharge
4.625
MW
0.8
0
Allow for simultaneous operation of turbine and pump:
No
*) Fuel ratio = fuel input / electric output (for CAES technologies or similar)
Advanced CAES
Electricity storage system