Regional Integration of Renewable Energy Systems in Ireland – The Role of Hybrid Energy Systems for Small Communities

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Abstract

Due to a lack of indigenous fossil energy resources, Ireland's energy supply constantly teeters on the brink of political, geopolitical, and geographical unease. The potential risk to the security of the energy supply combined with the contribution of anthropogenic greenhouse gas emissions to climate change gives a clear indication of Ireland's need to reduce dependency on imported fossil fuels as primary energy source. A feasibility analysis to investigate the available renewable energy options was conducted using HOMER software. The Net Present Cost, the Cost of Energy, and the CO_2 emissions of each potential energy combination were considered in determining the most suitable renewable and non-renewable hybrid energy system. Wind energy was shown to have the greatest potential for renewable energy generation in Ireland: wind energy was a component of the majority of the optimal hybrid systems both in stand-alone and grid-connected systems. In 2010 the contribution of wind energy to gross electricity consumption in Ireland approximated 10%, and the results of this feasibility study indicate that there is great potential for wind-generated energy production in Ireland. Due to the inherent variability of wind energy the grid-connected system results are particularly relevant, which show that in more than half of the analyses investigating electrical energy demand the incorporation of wind energy offset the CO_2 emissions of the non-renewable elements to such a degree that the whole system had negative CO_2 emissions, which has serious implications for Kyoto Protocol emissions limits. Ireland also has significant potential for hydropower generation despite only accounting for 2% of the gross electricity consumption in 2010. Wind and hydroenergy should therefore be thoroughly explored to secure an indigenous primary energy source in Ireland.

Keywords: Hybrid energy systems, HOMER modelling software, renewable energy in Ireland, wind energy, hydropower.

1. Introduction

In 2010 Ireland's final consumption of electrical energy amounted to almost 91 million gigajoules with an even greater demand recorded for thermal energy for space and water heating [1]. To meet this combined energy demand fossil fuels are consumed: in 2010 86% of the fossil fuels consumed were imported [2]. Recurring international tension places a constant risk on the security of supply of oil and natural gas into Ireland; this fact, combined with the contribution of anthropogenic greenhouse gas emissions to climate change provides clear reasoning as to why Ireland needs to act immediately to reduce dependency on imported fossil fuel as a primary energy source.

Ireland has a number of indigenous renewable energy options which could be implemented to increase the security of energy supply. As an island nation, Ireland has access to wind, wave, tidal, biomass, hydropower, geothermal, and solar energy resources. The Irish government has set ambitious targets for the penetration of renewable energy into the electricity market, aiming for 40% electricity generation from renewable sources by 2020 [3]; in 2010 the share of renewables in the Irish electricity market was 14.8%. It is clear that significant efforts must be made if the 2020 targets are to be met.

Renewable energy in Ireland is not a new area of research. A number of authors have investigated pathways to a renewable energy industry in Ireland (e.g. [1, 4-6]), the majority of which have focussed on Ireland's main renewable resource: wind. Connolly et al. [4] reported the maximum realisable penetration of wind energy into the Irish energy network is 30% from both an economic and a technical viewpoint. Carton and Olabi [5] reported on the performance of a single wind turbine installed in 2005 on-site at a third-level education institution on the east coast, described as the first urban turbine in Ireland. The turbine has a maximum output of 850KW and provides approximately one third of the on-campus electrical energy demand, saving €125,000 annually. As an education campus the majority of the electrical demand is for administrative facilities; a small residential village which houses approximately 550 students is also serviced by the turbine. Intermittency of supply has been addressed by the incorporation of 500 kWh flow battery for energy storage [7].

Consistency of supply is a significant issue associated with a number of renewable energy resources. Wind and solar energy systems are subject to both diurnal and short-term variation due to, for example, gusty periods and clouds [8]. This variation in supply is not always synchronous with consumer demand, however. In an effort to overcome the asynchrony associated with these renewable energy systems and to provide a reliable energy supply which adequately meets demand fluctuations, renewable energy systems can be combined with non-renewable energy systems and/or energy storage technology. This combined system of renewable and non-renewable energy could accommodate fluctuating consumer demand with reduced fuel consumption and carbon footprint compared to the existing energy system [9].

Paska et al. [10] define a hybrid energy system as one of co-operating units generating electricity or electricity and heat from a diversified range of renewable and non-renewable primary energy sources. The operation of such a system is dictated by the load demand (electrical or electrical and thermal) that the system serves [10]. Paska et al. [10] describe power-producing energy sources as either controlled or uncontrolled: controlled sources can meet system demand at any time. Increasing the penetration of electricity generated from uncontrolled sources such as intermittent renewable energy sources in an electrical power system affects the operation of the controlled energy system: the operation schedule of the controlled sources becomes more volatile with more frequent ramping and an increased number of start-ups to meet demand [11]. Where an intermittent renewable energy source has a high level of penetration, an energy storage component can be incorporated into the energy system to overcome the need for ramping when electricity generation is asynchronous with consumer demand and reduce the overall cost of energy production [12].

1.1 Renewable energy resources in Ireland

In Ireland electrical and thermal energy demand is primarily met through the combustion of natural gas and coal. The only indigenous fossil fuel, peat, contributed just over 5% of the primary energy demand in 2010 with renewable energy accounting for 4.5% of the total final consumption [2]. Electrical demand is met by generation in a number of large-scale, centralised power stations while thermal demand is mainly met through electric (storage) heating and the direct consumption of natural gas or domestic heating oil on-site. As mentioned previously, Ireland has the potential to produce energy from a variety of renewable resources including wind, wave, biomass, and hydropower. Renewable energy currently plays a role in electricity generation mainly through hydroelectric and wind-generated power. The degree of penetration of these renewable options has been limited, however. In 2011 there were 148 wind farms actively generating electricity in Ireland with a total installed capacity of 1600 MWe [13]. The total capacity of hydroelectric stations was approximately 240 MW in 2009 [14]. Much of Ireland's hydropower resource potential has already been tapped in terms of medium-scale hydroelectric schemes however opportunities remain for small-scale decentralised generation: in a study conducted in 1985 the Department of Energy identified 483 potential sites for small-scale hydroelectric power [15]. Hydroelectric power accounted for just over 2% of the gross electricity consumption in 2010 in Ireland [2].

Wind energy has the greatest potential for both large-scale and small-scale decentralised generation of renewable energy in Ireland. Indeed, Ireland has a wind energy resource four times the European average [6] due to its geographical location. The estimated technical potential is rated at 613 TWh per year [6] with only 2.41 TWh utilised in 2008 [16]. The resource is widely available throughout the country with the greatest potential along the western and north-western Atlantic coastlines. To address the issue of intermittency of wind energy, and in particular over-generation of electricity during times of low demand, Carton and Olabi [5] investigated the possibility of hydrogen production and storage in conjunction with wind power in Ireland. In this wind/hydrogen system the excess power produced when demand is low is used in an electrolyser to produce hydrogen. This hydrogen is stored and can be utilised when needed as a controlled energy source in fuel cells or internal combustion engines to produce power in an environmentally benign manner [5]. Gonzalez et al. [17] described hydrogen production, storage, and utilisation as not yet mature as a technology and that further research and development into the different components of the system were warranted. In addition, the current status of the fuel cell and hydrogen production technology leads to excessive costs, making it widely unfeasible.

An alternative option for excess supply from wind energy is to convert to hydro energy by pumping water into storage stations. This technology is already practiced in Ireland and is therefore considered a realistic alternative for further implementation due to existing technological knowledge. During times of additional electricity generation the energy is used to pump water into an elevated storage facility. When electrical demand rises the water is passed through turbines to convert the hydro energy back into electrical energy [18].

Ireland experiences the most suitable climate in Europe for biomass growth [6]. Purpose-grown energy crops refer to short rotation forestry such as short rotation coppice (SRC) willow, which Ireland has the ideal climate to produce [19]. Most recent figures indicate that just over 3000 ha are currently sown with a purpose-grown energy crop [20]. Assuming an average yield of 10 t DM ha^{-1} and a three-year harvest cycle [21], this produces approximately 10,000 t DM ha^{-1} of woody biomass. The primary method by which woody biomass is used to generate electricity and heat in Ireland is the combustion of wood pellets with an average energy content of 17 GJ t^{-1} [22] either on-site or in centralised power stations.

A further renewable energy option for Ireland is the generation and capture of biogas from decomposing organic material. Biogas can be harvested in purpose-built anaerobic digesters or from landfill sites and then used in place of natural gas for the generation of electricity and/or heat. The current penetration of biogas production into the generation market in Ireland is low: the total contribution of landfill, biomass, and other biogases to electricity generation in Ireland was 3 PJ, equivalent to 1.5% of the total energy input in 2010 [2]. The low contribution of biogas to electrical generation is due partly to the widespread on-farm use of animal manures as fertilisers and partly due to economic factors such as the high capital investment required to establish an anaerobic digestion facility [23]. The extent of anaerobic digestion of organic wastes in Ireland is expected to increase in coming years as a direct result of the introduction of the EU Landfill Directive (99/31/EC), however.

There are losses and inefficiencies associated with the generation and transmission of centrally-produced electricity: the average losses associated with electricity production in Ireland currently stand at 55% [2]. This efficiency is in line with the average efficiency of power plants reported by Connolly et al. [4]. The introduction of decentralised electricity generation using renewable energy systems could mitigate some of the losses by producing electrical energy in close proximity to consumer demand [24] while also reducing the overall environmental impact of generation [25].

As a number of the uncontrolled renewable energy options available to Ireland are intermittent, having a back-up controlled option is essential. Natural gas accounted for 60% of the total electricity generation in Ireland in 2010 [2] and so was considered as the main controlled energy source in any hybrid system modelled in this investigation. Diesel is theoretically also an option for electricity generation: it accounted for 2.3% of the total energy input for electricity generation in 2010 in Ireland [2].

Finding the most efficient and reliable combination of controlled and uncontrolled electricity and heat generation resources for Ireland depends on both the reliability and availability of each technology. The objective of this work, therefore, was to model the most appropriate hybrid system to generate electrical and heat energy for Ireland using indigenous, renewable energy resources.

2. Methodology

An array of renewable energy options has been introduced in a number of countries, including wind, solar, geothermal, and anaerobic digestion with methane capture for electricity generation. For example, renewable energy contributes 7% of Australia's electricity supply through hydroenergy and wind power however it is anticipated that this will increase as the Australian government has set a target of 20-25% renewable energy generation by 2020 [26]. The proportion of wind and solar energy has increased recently and both resources are expected to increase further to meet the 2020 target. Shafiullah et al. [26] conducted a feasibility study which considered geographical and topographical features specific to Australia to determine the most suitable locations for additional installations of grid-connected solar and wind energy facilities.

Another area to consider when introducing renewable energy either alone or as part of a hybrid energy system is the economic feasibility of such a system. Asrari et al. [27] investigated the economic feasibility of introducing a hybrid energy system to electrify rural areas of Iran. The site investigated experiences both wind and solar exposure which are deemed sufficient to meet the electricity demand of the village, which is currently met by a combination of the electricity grid and diesel generator. Each of these studies were conducted in a similar method to that used in this research, whereby the aim was not to completely remove the fossil fuel-derived electricity supply, but to augment this supply with renewable energy which would both increase the security of the electricity supply and reduce the detrimental greenhouse effects associated with providing electrical energy to a national population.

2.1 Renewable resource availability

Ireland is a relatively small land mass which experiences substantial variation in regionally-available energy resources. The focus of this research is decentralised energy generation from renewable sources: it was therefore necessary to divide the total area into localised regions in order to assess the most suitable hybrid energy system for each region, determined by locally-available renewable energy resources. The Republic of Ireland[1] was therefore divided into eight regions as shown in Figure 1: Northwest, West, Southwest, South, Southeast, East, Midlands North, and Midlands South. The boundaries were cast to differentiate between the regional resources and to provide a basis upon which to assess the availability and feasibility of each

[1] From this point forward 'Ireland' refers to the 26 counties comprising the Republic of Ireland, unless otherwise stated.

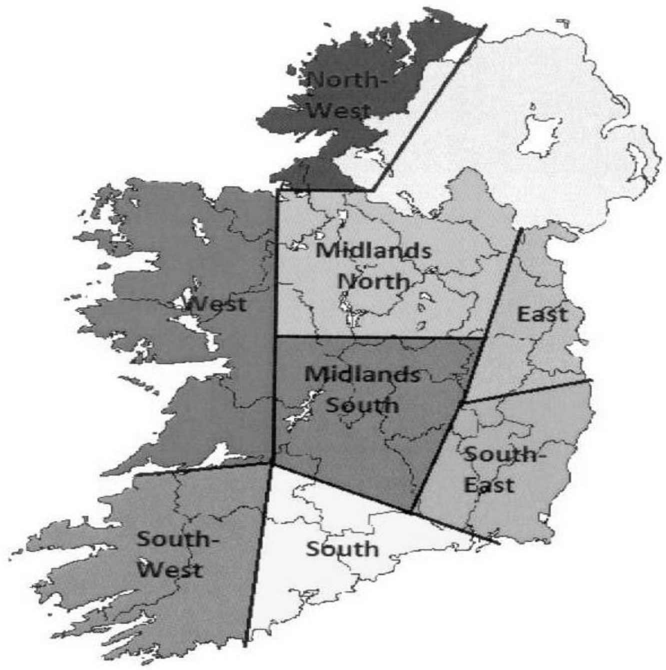

Figure 1: Regional boundaries assumed for a decentralised energy generation network for Ireland

renewable resource in each region with the goal of establishing a decentralised network of renewable energy generation.

Table 1 shows the key renewable and non-renewable energy resources assumed to be in each region shown in Figure 1. Wind features strongly with a large and widespread technical resource, predominantly in Atlantic coastal regions. Solar energy is restricted to the lower latitudes of the south and east regions of the country where the climate is less influenced by Atlantic weather fronts. Ireland's biomass resource is theoretically available throughout the country as it can be stored and transported, however biomass is considered a key renewable energy resource in areas of the midlands where fertile arable land for crop production is located. Biogas from landfill gas recovery plants and anaerobic digestion has been identified as a key resource in the northern midlands. The Northwest, West, and Southwest regions were

Table 1: Energy resources assumed to be available in each region

Region	Renewable Resources	Non-Renewable Resources
Northwest	Wind, Hydro	Diesel, Electricity grid
West	Wind, Biomass, Hydro	Diesel, Electricity grid, Natural gas grid
Southwest	Wind, Solar, Hydro	Diesel, Electricity grid
South	Wind, Solar, Biomass	Diesel, Electricity grid, Natural gas grid
Southeast	Wind, Solar, Biomass	Diesel, Electricity grid
East	Wind, Solar	Diesel, Electricity grid, Natural gas grid
Midlands North	Biomass, Biogas	Diesel, Electricity grid
Midlands South	Solar, Biomass	Diesel, Electricity grid

identified as having potential for hydropower due to the average annual rainfall and topography in these areas.

Connolly et al. [4] described the electricity, thermal, and transport sectors in Ireland as being very segregated, with electric heating being the only significant crossover. With the rollout of electric cars there will soon be an additional crossover, however it is anticipated that this will not cause a major shift in balance in the immediate future. As such, the feasibility study conducted in this research focussed on meeting the electrical energy demand with no energy crossover from the transport sector and with thermal energy incorporated from a point of view of electrical heating only, i.e. any thermal energy generated during the production of electrical energy is not recovered for further use.

2.2 HOMER software

In order to determine the optimal hybrid energy system for Ireland it was necessary to consider each specified region and their respective locally-available resources in addition to diurnal and seasonal changes in electrical demand. This was performed using Hybrid Optimisation Model for Electric Renewables (HOMER) software[2]. HOMER was selected for this feasibility study as it facilitates the examination of the electricity sector as a single entity unlike, for example, ENERGYPLAN which considers the three primary sectors of the energy system [1]. HOMER was therefore considered more appropriate to accurately model the Irish energy demand profile, i.e. to model the electrical demand of a country in which on-site oil-based heating systems feature strongly, and in which only 0.2% of the transport energy demand was met by electrical energy [2].

HOMER was developed with the aim of overcoming the challenges of intermittency, seasonality, and unpredictability associated with renewable energy [28]. The software takes into account the technical and economic features of the components of a hybrid system and provides performance and economic comparisons between specified system design sensitivity options [28]. The optimum hybrid system is determined through simulation, sensitivity, and optimisation analyses. HOMER was also used by Shafiullah et al. [26] to model hybrid energy solutions for Australia and by Asrari et al. [27] to model the feasibility of electrifying rural Iran, a comparable investigation to the decentralisation of electricity generation in Ireland. Although the renewable energy resource in these studies (solar and wind) have different potentials to those modelled for Ireland, the premise is similar.

Specifications of the system components are inputted along with data relating to the energy resources available. HOMER operates on the basis of 8,760 hourly data points for a year of operation which can be inputted as real data or synthesised by the software using averaged data to define loading and energy resources. The software determines, on an hourly basis, if the

[2] Developed by the US National Renewable Energy Laboratory (NREL), Colorado, USA.

output from the renewable energy technology components defined for the system are sufficient to meet the load at a particular hour. If a deficit exists in production from these energy resources the software supplements the power derived from the renewable components with the operation of a defined auxiliary power production method such as a diesel generator or the national electricity grid [29]. A shortcoming of the software, however, is that it does not allow modelling of pumped hydroelectric storage, which is particularly relevant to Ireland where this technology is already in place.

Optimisation in HOMER is carried out on an economic basis in terms of lowest total net present cost (NPC). The optimum energy system defined by HOMER is one which is capable of meeting the specified loads under the specified user constraints with the lowest net production cost [28]. Net present cost refers to the lifecycle of the system and includes all aspects of the systems over the entire defined lifespan [28]. HOMER also calculates the CO_2 emissions associated with each system based on the carbon content of the fuels and the specifications of the equipment used. The model is based on one year of operation of each system with CO_2 emissions outputted by the model as kg CO_2 yr^{-1}. Where a renewable energy option is coupled with a non-renewable option, a negative value for emissions can be returned if a large amount of low-emissions power from the renewable energy sources is exported to the national grid due to low-emissions power displacing high-emissions power [28].

The focus of this research is to evaluate all renewable energy options available in Ireland for decentralised electricity generation. To this end HOMER software was employed to examine all potential options for a hybrid energy system for both a rural and an urban community according to the resources listed for each region in Table 1. To model the expected mix of dwelling types in each scenario and the geographical differences between regions, the analysed load was based on assumed occupancy of a number of dwellings. The rural community consisted of ten detached dwellings and one non-domestic building; a community consisting of 11 apartments, three terraced houses, three semi-detached houses, and one non-domestic building was considered more representative of a comparable urban community in Ireland. In each case the total occupancy of the residences was 40 persons and a 200 m^2 floor area non-domestic unit was modelled in each community. The non-domestic unit was considered to be a retail unit or an office-based commercial business. The loads were designed to be comparable in that they serve the same number of people in different regions and dwelling-type scenarios. Modelling at this scale allows for scaling of community demands and resources in each region. For example, in a submission to the Irish Department of Agriculture, Fisheries, and Food it was recommended that every community in Ireland should have an anaerobic digester [30]. The capacity of the digester and therefore the output of energy from the digester would be determined by the relative size of the community.

Values determined by Yohanis et al. [31] on the relationship between residential floor area, occupancy, and electricity consumption were used as guidelines to quantify the relevant loads for the communities investigated in this feasibility study. These values relate to dwellings with separate non-electrical heat systems and are shown in Table 2. Dwellings using electric storage heaters will tend to have a higher annual electricity consumption as the demand for heat is also met through electricity consumption. Residences which do not use storage heating fulfil their thermal energy requirement by employing an alternative method of heat generation such as an oil-burning system. The fuel costs and emissions associated with producing heat energy must

Table 2: Floor area and occupancy classification of dwellings investigated

Dwelling type	Floor area (m^2)	Assumed occupancy	Consumption (kWh/yr)	Thermal load[a] (kWh/m^2/yr)	Thermal load (kWh/m^2/yr)
Apartment	80	2 persons	4153	50	-
Terraced house	100	3 persons	5133	140	-
Semidetached house	120	3 persons	6113	100	-
Detached house	180	4 persons	9053	-	150

[a] It is assumed that the urban community consists of apartments, terraced houses, and semi-detached houses; it is assumed that only detached houses are found in the rural community.

be considered when determining the optimum electricity and heat producing system [28]. Considering the recent downturn in Ireland's economy and in particular the significant decline in the rate of housing construction, it was assumed that any fossil fuel boilers included in this feasibility study are pre-existing as opposed to new installations and therefore do not bear any additional cost.

For the purpose of this investigation three methods of meeting the thermal load were considered: by night use of electrical storage heaters; by a separate fossil fuel boiler system; and by recovered heat from a combined heat and power generator. In the case of the storage heaters no separate thermal load needs to be defined. Thermostats are not widely used for temperature regulation in private dwellings in Ireland; instead the domestic heating schedule was assumed to be 07.00-09.00 hours and 17.00-23.00 hours for a heating season of October to May inclusive, based on guidelines issued by the Sustainable Energy Authority of Ireland (SEAI) [32]. The thermal load consists of both space heating and a baseline demand for sustaining water heating. For non-domestic premises the thermal load is defined by office hours, in line with the electrical demand. The domestic thermal loads considered in this study are listed in Table 2; the thermal load for the non-domestic unit in the community was assumed based on values reported by Jones et al. [33] conducive with the daily electrical load. Fossil fuel consumption was assumed to be for water and space heating. Jones et al. [33] reported typical fossil fuel consumption to be 166 KWh m^{-2} yr^{-1} and this figure was used as a guideline load for water and space heating from October to May with water heating only from June to September.

3. Results

In this study the optimal hybrid energy system is taken to be the most financially and environmentally efficient system for each region under the conditions analysed. The key features of the analysis are the total net present cost of the system (NPC), the levelised cost of energy (COE), the renewable fraction of the system, and the annual CO_2 emissions. Considering the energy resources potentially available in each region and the electricity demand scenarios under investigation (i.e. thermal energy demand met by an external fossil fuel source or by electrical energy through storage heater use), Table 3 shows the optimal stand-alone hybrid energy system for each region including fossil fuel generators and energy storage where necessary. Table 4 shows the optimal grid-connected hybrid energy system for each region when fossil fuel generators and energy storage are not included; the renewable fraction and annual CO_2 emissions of each system are also included.

4. Discussion

A wide range of NPC values were obtained from the model. It was observed that in 77% of the systems investigated, incorporating renewable energy into the grid-connected systems led to a lower NPC compared to stand-alone systems using fossil fuel energy production as a controlled

Table 3: Optimal stand-alone system for each region

Region	Energy demand	System components [a]	COE (€/kWh)	Renewable fraction (%)	CO_2 emissions (kg/yr)
NW rural	Electric + thermal	wind, generator, battery, converter	0.214	40	90,373
NW rural	Electric	wind, generator, battery, converter	0.207	92	53,067
W rural	Electric + thermal	wind, generator, battery, converter	0.273	34	166,972
W rural	Electric	wind, generator, battery, converter	0.254	82	96,091
W urban	Electric + thermal	hydro, generator, battery, converter	0.242	53	44,863
W urban	Electric	hydro, generator, battery, converter	0.254	70	98,063
SW rural	Electric + thermal	wind, generator, battery, converter	0.328	37	167,045
SW rural	Electric	wind, hydro, generator, battery, converter	0.167	90	81,011
S rural	Electric + thermal	wind, generator, battery, converter	0.316	42	88,005
S rural	Electric	wind, generator, battery, converter	0.311	81	115,449
S urban	Electric + thermal	wind, generator, battery, converter	0.208	32	89,613
S urban	Electric	wind, generator, battery, converter	0.195	70	90,517
SE rural	Electric + thermal	wind, generator, battery, converter	0.323	42	89,551
SE rural	Electric	solar, wind, generator, battery, converter	0.322	76	117,024
E rural	Electric + thermal	wind, generator, battery, converter	0.370	34	95,574
E rural	Electric	solar, wind, generator, battery, converter	0.376	64	159,289
E urban	Electric + thermal	wind, generator, battery, converter	0.178	24	91,236
E urban	Electric	wind, generator, battery, converter	0.259	41	161,343
Midlands N rural	Electric + thermal	biomass, generator, battery, converter	0.559	10	115,607
Midlands N rural	Electric	generator, battery, converter	0.613	0	408,325
Midlands S rural	Electric + thermal	biomass, generator, battery, converter	0.534	8	174,747
Midlands S rural	Electric	solar, generator, battery, converter	0.585	16	317,858

[a] (wind icon) = wind; (generator icon) = generator; (battery icon) = battery; (converter icon) = converter; (hydro icon) = hydro; (solar icon) = solar; (biomass icon) = biomass

Table 4: Optimal grid-connected system for each region

Region	Energy demand	System components [a]	COE (€/kWh)	Renewable fraction (%)	CO_2 emissions (kg/yr)
NW rural	Electric + thermal	grid, wind	0.065	49	-33,208
NW rural	Electric	grid, wind	0.045	92	-218,070
W rural	Electric + thermal	grid, wind	0.106	33	135,313
W rural	Electric	grid, wind	0.092	83	-98,403
W urban	Electric + thermal	grid, hydro	0.117	57	-18,071
W urban	Electric	grid	0.133	0	169,165
SW rural	Electric + thermal	grid, wind	0.135	15	187,729
SW rural	Electric	grid, wind, hydro	0.094	73	-3,1895
S rural	Electric + thermal	grid, wind	0.137	23	106,382
S rural	Electric	grid, wind	0.105	67	27,554
S urban	Electric + thermal	grid, wind	0.129	35	89,252
S urban	Electric	grid, wind	0.084	77	-20,947
SE rural	Electric + thermal	grid, wind	0.131	24	104,053
SE rural	Electric	grid, wind	0.100	81	-79,190
E rural	Electric + thermal	grid, wind	0.150	19	111,891
E rural	Electric	grid, wind	0.120	60	57,843
E urban	Electric + thermal	grid, wind	0.106	47	59,143
E urban	Electric	grid, wind	0.127	30	118,301
Midlands N rural	Electric + thermal	grid	0.160	0	137,324
Midlands N rural	Electric	grid	0.140	0	212,735
Midlands S rural	Electric + thermal	grid	0.160	0	219,534
Midlands S rural	Electric	grid	0.140	0	212,735

[a]  = grid;  = wind;  = hydro

source of energy (data not shown). Many of the grid-connected systems, including those that incorporated wind energy, also demonstrated negative annual CO_2 emissions due to the offsetting of emissions related to the electricity grid by the renewable energy component (Table 4). According to the Kyoto Protocol Ireland is required to restrict carbon emissions to 62.8 million tonnes of CO_{2e} per annum. The annual emissions for 2008, 2009, and 2010 have all been below this limit due to the trading of carbon credits [34]. The wind turbine installed in Dundalk Institute of Technology offset the emission of almost 1000 tonnes of CO_2 in 2007 and 2008 [7], indicating the potential environmental savings achievable from community-based wind energy systems. Increased penetration of renewable energy components could therefore contribute to meeting future CO_2 emissions limits without requiring trading of carbon credits.

It was observed generally that grid-connected systems have a lower COE than stand-alone systems (Table 3 and Table 4). This is considered to be due to the injection of excess electricity produced into the national grid which offers a source of income to offset the costs of implementing renewable energy generation in Ireland.

It should be noted that for systems with a separate thermal energy source, HOMER does not consider the capital, maintenance, or replacement costs of the boiler system; only the boiler fuel costs are included. This leads to under-estimation of the system costs and makes it difficult to draw comparisons between the two load types. The nature of the electrical thermal system, which incorporates a high night-time consumption rate, means the generation output for solar-based energy systems for example tend not to coincide with the demand, meaning more energy storage is required in a stand-alone system either by incorporating hydrogen production or the use of battery storage (Table 3).

Overall, the results obtained are consistent with those reported by Connolly et al [4] in that wind energy features strongly in comparison to any other specified resource: the vast majority of hybrid systems both in stand-alone and grid-connected systems feature wind energy to some degree. Although wind energy displays potential in such a large proportion of hybrid decentralised energy systems, it is probable that obtaining planning permission to erect wind turbines in urban areas will prove difficult due to negative public opinion and site impracticality, however.

With regard to energy production with biogas harvesting, it is considered that the initial costs associated with establishing a small-scale biogas facility would be widely unfeasibly under the conditions investigated. It would be more cost-efficient to model a larger anaerobic digestor to serve a larger community than was modelled here, however this does not correspond with the energy demands analysed in this research. The biogas applications were found generally to have the highest NPC and COE values of all the systems investigated due to the large financial input required (Table 3).

Hydropower was included in the optimal hybrid energy system for the Southwest rural community in both the stand-alone and grid-connected systems. A potential constraint to hydropower in Ireland is site inaccessibility: the optimal locations for hydropower stations in Ireland are mountainous regions which often fall in National Heritage Areas [35] and may therefore be deemed unsuitable for resource exploitation. Almost 500 sites were identified as having potential for hydropower generation in Ireland, however making this resource one which warrants complete examination to highlight sites that are not restricted by location within NHAs.

5. Conclusion

Although Ireland potentially has access to a number of renewable energy resources, the feasibility of each option must be examined thoroughly. Ireland has great potential to generate electricity from wind energy, particularly along western coastlines. Indeed, wind energy was a component of the majority of the optimal hybrid energy systems investigated. In 2010, almost 10% of Ireland's gross electricity consumption was met by wind. Despite an extensive list of possible generation sites, hydropower generation contributed just over 2% of the gross electricity consumption in 2010. Wind energy has been the focus of a number of feasibility studies for renewable energy in Ireland, however it is considered that a thorough examination of the hydropower potential will reveal a number of locations which could increase hydropower's contribution to electricity generation in Ireland.

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