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Article

Benchmarking Environmental Impacts of Peat Use for Electricity Generation in Ireland—A Life Cycle Assessment

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Abstract: The combustion of peat for energy generation accounts for approximately 4.1% of Ireland's overall greenhouse gas (GHG) emissions, with current levels of combustion resulting in the emission of 2.8 Mt of CO_2 per annum. The aim of this research is to evaluate the life cycle environmental impacts of peat use for energy generation in Ireland, from peatland drainage and industrial extraction, to transportation, combustion, and subsequent after-use of the cutaway area, utilising Irish-specific emission factors. The environmental impacts considered are global warming potential, acidification potential, and eutrophication potential. In addition, the cumulative energy demand of the system is evaluated. Previous studies on the environmental impact of peat for energy in Ireland relied on default Intergovernmental Panel on Climate Change (IPCC) emission factors (EFs). This research utilises Irish-specific EFs and input data to reduce uncertainty associated with the use of default IPCC EFs, and finds that using default IPCC EFs overestimates the global warming potential when compared to Irish-specific EFs by approximately 2%. The greatest contribution to each of the environmental impacts considered arises from emissions generated during peat combustion, which accounts for approximately 95% of each of the environmental impact categories considered. Other stages of the life-cycle, such as impacts emanating from the peat extraction area, fossil fuel usage in harvesting and transportation machinery, and after-use of the cutaway area have much smaller effects on overall results. The transformation of cutaway peatlands to different after-use alternatives has the potential to mitigate some of the effects of peatland degradation and peat combustion.

Keywords: peat; energy; LCA; greenhouse gas emissions; environmental impacts; Ireland

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Highlights

- Environmental performance of peat energy generation in Ireland is analysed by LCA
- Peat combustion is the largest contributor to environmental impacts
- After-use of cutaway peatlands has potential to mitigate some of the impacts
- Use of default IPCC emission factors overestimates the global warming potential
- Peat energy generates higher GHG emissions over the life cycle than coal energy

1. Introduction

Ireland is one of the major producers of peat in the European Union, producing 2.8 Mt in 2009, second only to Finland with 9 Mt [1]. The combustion of peat for energy generation contributes significantly to Ireland's greenhouse gas (GHG) emissions, with current levels of combustion resulting in the emission of approximately 2.7 Mt of CO_2 per annum which is equivalent to 4.1% of Irelands overall GHG emissions [2]. The assessment of the environmental performance of the utilisation of peat for electricity generation in Ireland must be carried out from a life cycle perspective in order to achieve a number of aims: (1) to analyse the environmental performance of the utilisation of peat for energy generation in Ireland using country-specific emission factors and input data; (2) to assess the sensitivity of the results to these emission factors by comparison with default IPCC emission factors; (3) to compare the effects of the different after-use options for the cutaway peatland; and (4) to establish a reference scenario for the peat energy system to which other fossil fuel and bioenergy systems can be compared.

1.1. Peat Use for Energy in Ireland

In Ireland, peat is utilised in energy production and in the horticulture industry. There are currently three peat-fired power plants operating in Ireland: Edenderry, a 120 MWe rated bubbling fluidised bed plant, and two circulation fluidised bed plants, Lough Ree (100 MWe) and West Offaly (150 MWe). Together these power plants produce approximately 370 MWe which equates to 6.1% of Ireland's total primary energy requirements [3]. Bord na Móna (BNM), a semi-state company which was established in 1946 to manage the peat harvesting activities, is the only producer of peat for energy production in Ireland and supplies peat to the three peat-fired power plants. BNM harvest approximately 4 Mt of milled peat over 20,000 ha of peatland annually. Approximately 3.1 Mt of this is used for energy generation with Edenderry utilising 1.0 Mt, Lough Ree using 0.9 Mt and West Offaly burning 1.2 Mt. The remainder of peat is used for BNM's peat briquettes and garden compost which targets the domestic heating and horticultural sectors, respectively [2]. As of 2009, there were approximately 70 million tonnes of peat available for energy generation [4].

1.2. Peatlands and the Carbon Cycle

1.2.1. Pristine Peatlands

Peatlands in their natural state can act as a sink for atmospheric CO_2 and are classed as pristine peatlands [5]. Persistent carbon sequestration by peatlands over the past 10,000 years has resulted in the accumulation of a significant carbon store of 250–450 Gt in the northern peatlands [6]. Overall, the carbon content of the world's peatlands represents approximately one third of all terrestrial soil organic carbon (SOC), despite peatlands only covering 3% of the earth's surface [7]. This persistent carbon sequestration has contributed to global cooling on the millennium scale [8] and, the continued function of peatlands as a carbon sink has important implications for the global carbon cycle [7]. Approximately 17% of the Irish landscape is covered in peatlands. These peatlands contain a significant store of carbon, estimated at 1502.6 MT of SOC, this represents 36% of total SOC stock in Ireland [9].

While pristine peatlands are generally a net carbon sink, CO_2 emissions occur through root respiration and decomposition of both the acrotelm and catotelm [10]. In addition to this, pristine peatlands are a significant source of methane (CH_4), accounting for approximately 23% of global emissions [11–13]. Since the post-glacial development of northern peatlands, the sequestration of atmospheric CO_2 by these peatlands has been approximately balanced by the production of CH_4 in the same time period [10].

1.2.2. Disturbed Peatlands

As discussed previously, a large proportion of Ireland's land mass is covered by peatland. However, much of this peatland has been disturbed and degraded over the years due to land use change, with only 15% of peatland (approximately 180,000 hectares) remaining in its natural state [14]. The remainder has been subjected to large scale peat drainage and extraction for energy production and horticulture, severely degrading a large proportion of natural peatlands. The conversion of pristine peatland to a source of material for energy and horticulture alters the peat-forming function of the bog through drainage and removal of peat-forming vegetation [15]. These changes may have an impact on the natural position of peatland as a carbon sink in the global carbon cycle.

Peatlands have been drained for various uses including agriculture, forestry, and peat extraction for energy. CO_2 emissions from drained peatlands can increase by 100%–400% when compared to pristine peatlands due to drainage and removal of vegetation [16]. However, CH_4 emissions are subsequently reduced due to the reduction in the anoxic zone and the absence of peatland vegetation which can easily be degraded [17]. In fact, bare peatlands may result in a small uptake of CH_4 from the bare peat surface; however, remaining drainage ditches may continue to be a significant CH_4 source [18]. After harvesting of peat for energy ceases on a peatland, the remaining cutaway persists as a source of CO_2 to the atmosphere as the residual peat continues to decompose. A number of factors affect the release of emissions from peat harvesting fields including the quality of the residual peat, the moisture of the surface peat, and the relative area, along with the duration of time the peat stockpiles remain on site [19].

1.2.3. Restored Peatlands

After peat extraction from a peatland has ceased, there remain several potential after-uses for the remaining cutaway area such as afforestation, re-wetting, and natural regeneration. There is considerable variability in the capacity of these after-uses to reduce carbon emissions from cutaway peatland and indeed return to a carbon sequestering state. Cutaway peatland restoration has been shown to reduce CO_2 emissions [20], and even restore the carbon sequestration capacity compared to the original cutaway [21]. However, the return of anoxic conditions in the peatland results in an increase in CH_4 flux, with 100 ha of restored wetlands emitting CH_4 emissions of 105 tonnes of CO_2-equivalents (CO_2-eq) per year [22]. Restored peatlands are likely to contribute CH_4 emissions of the same magnitude as natural peatlands [20]. Afforestation of cutaway peatlands is a promising option to reduce the climate impact of the bare peatland [15]. Research shows that afforestation can reduce CO_2 emissions from the cutaway peatland, and in most cases can result in a return of the carbon sequestration function [15]. However, there can be considerable losses of soil carbon from the residual peat which continues to decompose [15,19]. In terms of CH_4, afforested peatlands are likely to be a modest sink; however, considerable emissions are more likely from drainage ditches [22].

1.3. Life Cycle Assessment of Peat Use for Energy Generation

The spatial and temporal variability of peatlands in both their natural and degraded states complicate their study through a life cycle perspective. The results of life cycle assessment (LCA) studies on peatlands therefore strongly depend on the variation and uncertainty in the input data which reflect the inherent heterogeneity of peatlands. Some important areas of variation in LCA studies include different assumptions about reference scenario, inclusion of the area surrounding the extraction site, emission factors for peatlands and combustion, and the time horizon considered; see Table 1.

1.3.1. Reference Scenario

The state of the peatland prior to drainage and peat extraction represents the reference scenario to which peat for energy utilisation is compared. In Finland and Sweden, peatlands which have previously been drained for forestry or agriculture have subsequently been used for peat extraction. Only pristine peatlands have been used for peat harvesting in Ireland [23]. Pristine peatlands can act as a carbon sink, and their disturbance for energy peat extraction can result in significant increases in GHG emissions to the atmosphere. As such, the use of pristine peatlands for energy peat extraction has the highest climate impact of the initial peatland condition types [24], and is comparable to, or higher than, the climate impact of coal energy [25–27]. Forestry-drained peatlands have higher levels of GHG emissions compared to pristine peatlands due to increased levels of peat decomposition. As such, the use of forestry-drained peatlands is more beneficial than the use of pristine peatlands, but the greenhouse gas impact is similar to that of coal energy [24–27]. The scenario with the lowest climate impact is the use of peatlands drained for agriculture, as these peatland have high levels of GHG emissions in their current state [24,25,27].

Table 1. Comparison of elements of LCA studies on peat use for energy generation.

	Lappi & Byrne [23]	**Grönroos *et al.* [26]**	**Hagberg & Holmgren [24]**	**Kirkinen & Minkinnen [25]**	**Nilsson & Nilsson [28]**
Reference scenarios	Not considered	Pristine, forestry-drained, cultivated peatland	Pristine, forestry-drained, cultivated peatland	Pristine, forestry-drained, cultivated peatland	Pristine, forestry-drained, cultivated peatland
Surrounding area	Not considered	Minor for previously drained, 50% of extraction area for pristine	Minor for previously drained, 50% of extraction area for pristine	Not considered	Equal to extraction area
Peat extraction	IPCC default emission factors (2004) -200 kg C $ha^{-1} \cdot a^{-1}$, 0.1 kg N_2O-N $ha^{-1} \cdot a^{-1}$	CO_2: Extraction area: +960 g CO_2 $m^{-2} \cdot a^{-1}$; surrounding area: +629 g CO_2 $m^{-2} \cdot a^{-1}$ CH_4: Extraction and surrounding area: +2.25 g CH_4 $m^{-2} \cdot a^{-1}$, N_2O: Extraction and surrounding area: +0.06 g N_2O $m^{-2} \cdot a^{-1}$	CO_2: Extraction and surrounding areas: Rise to +980 g CO_2 $m^{-2} \cdot a^{-1}$ over 2 years until end of extraction. CH_4: Extraction and surrounding areas: +3.7 g CH_4 $m^{-2} \cdot a^{-1}$ throughout. N_2O: Extraction area: Decrease to +0.1 g N_2O $m^{-2} \cdot a^{-1}$ by year 10 of extraction and increase again to +0.15 g $m^{-2} \cdot a^{-1}$ by end of extraction. Surrounding area: decrease linearly during the first 5 years of extraction to +0.08 g N_2O $m^{-2} \cdot a^{-1}$.	CO_2: Extraction area: +6.84 g CO_2 MJ^{-1}; stockpile: 1.48 g CO_2 MJ^{-1} CH_4: +0.0039 g CH_4 MJ^{-1}	CO_2: Extraction area: +1000 g CO_2 $m^{-2} \cdot a^{-1}$. Surrounding area: +1000 g CO_2 $m^{-2} \cdot a^{-1}$ during drainage, 300 g CO_2 $m^{-2} \cdot a^{-1}$ during extraction. CH_4: 10% of the CH_4 emissions for pristine peatlands in extraction area, 25% in the surrounding area (falling to zero by year 8 of extraction). N_2O: Extraction area: Decrease to +0.1 g N_2O $m^{-2} \cdot a^{-1}$ by 10 year of extraction, increase again to +0.15 g $m^{-2} \cdot a^{-1}$ by end. Surrounding area: decrease linearly during first 5 years of extraction to +0.08 g N_2O $m^{-2} \cdot a^{-1}$.
Combustion	114940 kg CO_2 TJ^{-1}, 3 kg CH_4 TJ^{-1}, 7 kg N_2O TJ^{-1}	105.9 g CO_2 MJ^{-1}, 0.0085 g CH_4 MJ^{-1}, 0.0128 g N_2O MJ^{-1}	105.2 g CO_2 MJ^{-1} with 99% oxidation factor 104.1 g CO_2 MJ^{-1}, 5 mg CH_4 MJ^{-1}, 6 mg N_2O MJ^{-1}	105.9 g CO_2 MJ^{-1}, 8.5 mg CH_4 MJ^{-1}, 12.8 mg N_2O MJ^{-1}	105.2 g CO_2 MJ^{-1} with 99% oxidation factor 104.1 g CO_2 MJ^{-1}, 5 mg CH_4 MJ^{-1}, 6 mg N_2O MJ^{-1}

Table 1. *Cont.*

	Lappi & Byrne [23]	**Grönroos *et al.* [26]**	**Hagberg & Holmgren [24]**	**Kirkinen & Minkinnen [25]**	**Nilsson & Nilsson [28]**
Restoration	Not considered	CO_2: $-112\ CO_2\ m^{-2}\cdot a^{-1}$, CH_4: $17\ g\ CH_4\ m^{-2}\cdot a^{-1}$	CO_2: increases to $-120\ g\ CO_2\ m^{-2}\cdot a^{-1}$ in 5 years after restoration and remains at this level thereafter CH_4: $+17\ g\ CH_4\ m^{-2}\cdot a^{-1}$ N_2O: insignificant	CO_2: $-121.6\ g\ CO_2\ m^{-2}\cdot a^{-1}$, CH_4: $+22.6\ g\ CH_4\ m^{-2}\cdot a^{-1}$, N_2O: insignificant	CO_2: $-363\ g\ CO_2\ m^{-2}\cdot a^{-1}$ CH_4: rise from zero to the emission rate of pristine mire during first 20 years of restoration. N_2O: $+20\ mg\ N_2O\ m^{-2}\cdot a^{-1}$.
Residual peat	Not considered	CO_2: begins at $+1000\ g\ CO_2\ m^{-2}\cdot a^{-1}$, exponentially decreases during first 85 years after which 50% of residual peat has decomposed. Slow release to $1200\ g\ C\ m^{-2}$ at the end of period.	CO_2: begins at $+1100\ g\ CO_2\ m^{-2}\cdot a^{-1}$, exponentially decreases during first rotation, after which 50% of the residual peat has decomposed. Remaining peat decomposes slowly over the remaining period.	Carbon content of $15{,}000\ g\ C\ m^{-2}$ decreases to $1200\ g\ C\ m^{-2}$ within 300 years.	Extraction area: $+1000\ g\ CO_2\ m^{-2}\cdot a^{-1}$ for 22 years after extraction ceases then stops. Surrounding area: decomposition continues at $1000\ g\ CO_2\ m^{-2}\cdot a^{-1}$ for first 5 years of afforestation and decreases to $367\ g\ CO_2\ m^{-2}\cdot a^{-1}$ after 15 years.
Afforestation	Not considered	CO_2: (over 45 years) $-413\ g\ CO_2\ m^{-2}\cdot a^{-1}$ for forestry-drained peatlands, $-716\ g\ CO_2\ m^{-2}\cdot a^{-1}$ for cultivated peatlands and pristine fens. Carbon accumulation in soil: 0–45 years: $-297\ g\ CO_2\ m^{-2}\cdot a^{-1}$ 46–90 years: $-149\ g\ CO_2\ m^{-2}\cdot a^{-1}$ 91–180 years: $-59\ g\ CO_2\ m^{-2}\cdot a^{-1}$ 181–280 years: $-20\ g\ CO_2\ m^{-2}\cdot a^{-1}$ CH4: $-0.05\ g\ CH_4\ m^{-2}\cdot a^{-1}$	CO_2: (over 85 years) $-820\ g\ CO_2\ m^{-2}\cdot a^{-1}$ in biomass. At end of rotation, 80% of carbon in biomass is emitted immediately, the remaining 20% decomposes on site over next rotation period. Carbon accumulation in humus: $-3.5\ kg\ C\ m^{-2}$ by end of rotation period. CH_4 emissions negligible as for forestry-drained peatlands N_2O: decreases from $+0.15\ g\ N_2O\ m^{-2}\cdot a^{-1}$ to $+0.06\ g\ N_2O\ m^{-2}\cdot a^{-1}$ after 45 years, remaining at this level for rest of period.	CO_2: $-448\ g\ CO_2\ m^{-2}\cdot a^{-1}$ in biomass, $-147\ g\ CO_2\ m^{-2}\cdot a^{-1}$ in aboveground forest litter, $-15\ g\ CO_2\ m^{-2}\cdot a^{-1}$ belowground forest litter.	CO_2: $-979\ g\ m^{-2}\cdot a^{-1}$ in biomass. Carbon accumulation in humus: $-183\ g\ m^{-2}\cdot a^{-1}$ in nutrient rich areas (70 year rotation), and $81\ g\ m^{-2}\cdot a^{-1}$ in nutrient poor sites (90 year rotation) N_2O: $+0.08\ g\ N_2O\ m^{-2}\cdot a^{-1}$ for afforested area. For surrounding areas emissions decrease from +0.15 to $+0.08\ g\ N_2O\ m^{-2}\cdot a^{-1}$ in 5 years after afforestation, falling to $+0.06\ g\ N_2O\ m^{-2}\cdot a^{-1}$ after 22 years. CH_4 emissions are assumed to be negligible as for forestry-drained peatlands.

"–" sign indicates sink; "+" sign indicates source.

1.3.2. System Boundary

The delineation of the system boundary is crucial in the comprehensiveness of LCA studies of peat energy systems, and the main consideration is whether to extend the boundary to the surrounding areas which are affected by peatland drainage but not part of the extraction area. LCA studies differ on the criteria for including the surrounding area, determining its spatial footprint, and the GHG flux in the area. Table 1 shows details regarding the differences between these LCA studies and contains information relevant to the following sections.

1.3.3. Peatland Emissions Factors

Greenhouse gas fluxes from peatlands across the various stages of peat extraction can vary depending on spatial and temporal variability, in addition to the nutrient status of the peatland. GHG fluxes occur from the peat fuel extraction area, stockpiles of harvested peat, and the surrounding peat area which has been affected by drainage. Emission factors are used to estimate the GHG fluxes from these peatland areas, with differing factors having an effect on overall LCA results. Previous research on peat use for energy in Ireland relies on general emissions factors from the IPCC to evaluate the climate impact of peat use for energy [23], due to a lack of Irish-specific emission factors available at the time. Similar research carried out in Finland and Sweden used country specific emission factors; see Table 1.

1.3.4. Combustion Emission Factors

Peat is the least carbon efficient fuel source when compared to other fossil fuels such as oil, natural gas or coal [23], and its combustion can emit over 90% of total CO_2 emissions of the full peat energy chain [25]. As such, the accurate quantification of GHG emissions from peat combustion is important in achieving precise LCA results. The use of different combustion emission factors in different LCA studies can produce diverse results [23,25,28].

1.3.5. After-Use Options

Consideration of the GHG fluxes associated with different after-treatments of cutaway peatland areas is important in understanding the full impact of the entire peat-for-energy chain.

1.3.5.1. Restoration

Restoration of the cutaway peatland to a peat-forming system can result in the cessation of CO_2 emissions from residual peat decomposition and can also reinstate the carbon sink function of the system. However, the reinstatement of a high water table in the restored peatland increases CH_4 emissions. LCA studies make different assumptions on the rate of CO_2 uptake and CH_4 emission of the restored peatland; see Table 1.

1.3.5.2. Afforestation

Similarly to rewetted cutaway peatlands, afforested cutaways both emit and absorb greenhouse gases. GHG emissions from afforested cutaways primarily arise from decomposition of residual peat and soil emissions of N_2O [24]. On the other hand, afforestation leads to carbon accumulation through growing biomass and results in carbon input to the soil both above and below ground. The consideration of both factors is an important factor in LCA studies of afforested cutaway peatlands; see Table 1.

1.3.6. Time Horizon

The time horizon over which the peat energy system is evaluated is important in determining the global warming potential of the system where the effects of long-term land-use change are considered [26]. A 300-year time period has been considered in some LCA studies [24,25,28]. However, Groonroos *et al.* (2012) noted that it may be misleading to use a time perspective longer than 100 years, as climate mitigation action is required in the near future, in less than 300 years. In addition to this, choosing a long time period is complicated by the fluxes to and from the system, which are dynamic and change further during a longer time span, and results therefore become increasingly uncertain over time. In practice, a time perspective over 100 years includes a great deal of uncertainty and the results are not recommended for decision making [27]. A 100-year time period is also used for GHG accounting under the Kyoto Protocol to the United Nations Framework Convention on Climate Change [29].

2. Materials and Methods

Life cycle assessment (LCA) is a tool which can be used to assess the environmental impacts and energy requirements of peat energy systems over the entire life cycle, from peat drainage and harvesting to combustion and subsequent after-use of degraded peatlands. The holistic nature of LCA allows the identification of points in the system of critical contributions to key environmental impacts.

2.1. Goal and Scope

The goal of this study is to evaluate the environmental impacts of the use of peat for energy generation in Ireland using Irish-specific emission factors. The research aims to improve on previous research on the greenhouse gas emissions of peat use for energy in Ireland, which used general IPCC emission factors, by utilising recently developed Irish-specific emission factors. In addition to this, other impact categories are assessed including acidification potential, eutrophication potential, and the energy requirements of the system. The reference scenario is peat conservation. The study represents a reference scenario of peat-fired power plants which can be compared to other fossil power plants and biomass co-firing systems in Ireland.

The functional unit of the system is defined as ‘1MWh of power produced at the power plant’. However, it is also important to compare the use of peatlands for energy production to the reference scenario, which is peatland conservation. In this case it is useful to compare based on area of peatland (ha).

2.1.1. System Description

2.1.1.1. Industrial Peat Extraction

The system diagram is outlined in Figure 1.

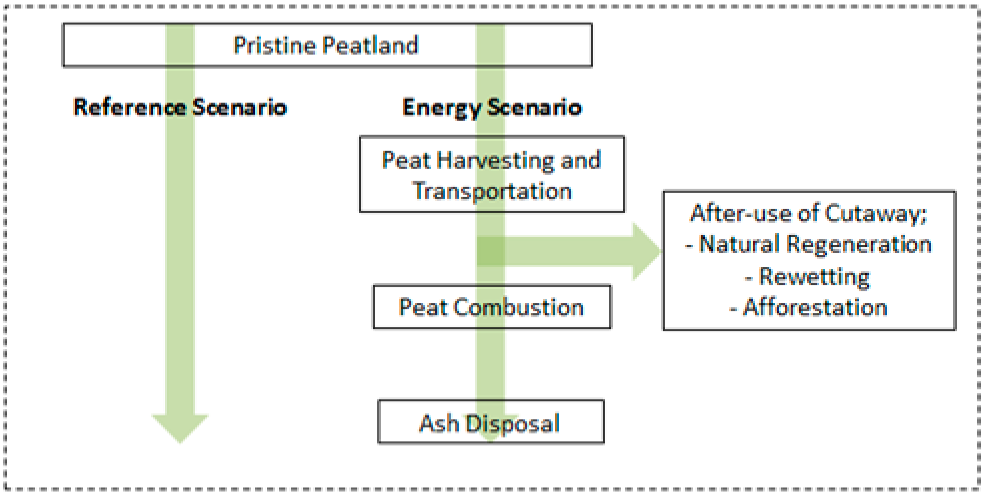

Figure 1. System diagram.

In Ireland, only pristine peatlands have been used for industrial peat extraction. As a result, this study considers pristine peatland conservation the reference scenario to which the peat-for-energy chain is compared. The first step in the peat for energy chain is peatland drainage and preparation. Peat in an un-drained peatland has very high moisture content (MC), approximately 95%. In order to facilitate the use of heavy machinery during industrial peat extraction, drainage ditches are installed to reduce the MC to approximately 80% [18]. The drainage ditches are installed at 15 m intervals, each approximately 1 km in length. Depending on the hydrological status of the bog, the drainage period can last from 5 to 7 years [30]. Once the bog has been drained to the required moisture content, the surface layer of vegetation is removed and peat extraction can begin. Milling is the peat harvesting method carried out in Ireland, in which the top 10–15 cm of peat is broken into crumbs or "milled" using industrial machinery. The milled peat layer is inverted and dried on the surface to a moisture content of 45%–55% (with a corresponding energy content of approximately 7 $GJ \cdot t^{-1}$), before being harvested and formed into stockpiles which hold the peat from 10 peat harvesting fields [31]. The length of the harvesting period depends on the initial depth of the bog, the peat type and annual harvest rate, the presence or absence of timber, and the bog floor contours and the degree to which they may cause an early cessation of harvesting operations. It is assumed that an average Irish peatland used for industrial peat extraction has a depth of 6 m and MC of 94%. In this case, 1 ha of peatland contains 3600 dry tonnes of peat. It is assumed that 0.5 m of peat with an average MC of 90% will be remaining after peat extraction has ceased, which equates to 500 dry tonnes of peat left in the cutover. As such, 3100 dry tonnes of peat can be harvested from 1 ha of peatland. If an average of 180 tonnes at 55% MC is harvested per annum, the harvest period will be approximately 38 years. The peat is loaded from the stockpiles into narrow gauge railway wagons and transported to the power station, over a distance of 16 km, where it is combusted for electricity generation [31]. The ash remaining after peat combustion is transported approximately 4 km by train to landfill.

After harvesting has ceased, there are a number of after-treatment options which have the potential to be applied to the remaining cutaway area. The after-treatment options considered in this study include: 11,136 ha rewetted (nutrient poor), 10,320 rewetted (nutrient rich), 3356 ha afforested, and 11,114 naturally regenerated.

The time period considered in this study is 100 years. Peatland drainage and extraction lasts for approximately 44 years, as such after-use treatments have been applied for 56 years.

2.1.1.2. Peat Combustion

This study considers two peat-fired circulation fluidised bed power plants with a capacity of 100 MWe and 150 MWe, hereafter referred to as "plant 1" and "plant 2", respectively. In 2013, plant 1 combusted approximately 18,620 dry tonnes of peat with a power plant output of 754,570 MWh and a cycle efficiency of 36.82%. Plant 2 combusted approximately 24,057 dry tonnes of peat and produced 1,010,179 MWh with a cycle efficiency of 35.99%.

2.2. Data Inventory

The input data for the LCA study is mainly composed of data specific to Irish conditions. Emission factors for peatlands in all stages of the life-cycle (pristine peatland, industrial extraction, and after-use) specific to Ireland are obtained from Wilson *et al.* [15], see Table 2. Wilson *et al.* [15] estimated emissions factors for Irish conditions based on carbon studies for the major peatland land uses in Ireland, and where Irish data was unavailable they utilised data from peatland carbon studies located within the temperate climate zone. Emission factors for dissolved organic carbon (DOC) were unavailable for Irish conditions, with the exception of natural peatlands, so default IPCC factors were used. The emission factors were applied for the different periods of the peatland life cycle, e.g. the emission factors for production fields (given in Table 2) were applied for the period of drainage and peat extraction, and the emission factors for the different after-uses were applied for the period after peat extraction had ceased, as described in the system description. Emission factors for peat combustion are obtained from the National Inventory Report for Ireland 2014 [32].

Table 2. Emission factors for different peat land use categories in Ireland [15,33].

Land Use Category	**CO_2 Flux Rates (tonnes CO_2 $ha^{-1}\cdot year^{-1}$)**	**CH_4 Flux Rates (tonnes CH_4 $ha^{-1}\cdot year^{-1}$)**	**DOC flux Rates (tonnes C $ha^{-1}\cdot year^{-1}$)**
Natural peatlands	−0.42	0.05	0.26
	Industrial peat extraction		
Production fields	2.09	0.004	0.31[a]
Naturally regenerated cutaway	3.22	−0.007	0.24[a]
Rewetted cutaway, nutrient poor	−0.4	0.03	0.24[a]
Rewetted cutaway, nutrient rich	1.57	0.22	0.24[a]

[a] IPCC default emission factors due to lack of Irish data available.

Default emission factors from IPCC were used in the sensitivity analysis to determine the effects of different emission factors for peatlands on the overall results; see Table 3.

Table 3. IPCC Tier 2 default emission factors [33].

Land Use Category	CO_2 Flux Rates (tonnes CO_2 $ha^{-1}\cdot year^{-1}$)	CH_4 Flux Rates (tonnes CH_4 $ha^{-1}\cdot year^{-1}$)	DOC Flux Rates (tonnes C $ha^{-1}\cdot year^{-1}$)	N_2O-N Flux Rates (tonnes N_2O-N $ha^{-1}\cdot year^{-1}$)
		Industrial peat extraction		
Production fields	2.8	0.0061	0.31	0.0003
Rewetted cutaway, nutrient poor	−0.23	0.092	0.24	-
Rewetted cutaway, nutrient rich	0.5	0.216	0.24	-

Afforestation of cutaway peatlands has reached 3356 ha to date. Insufficient data is available to derive an Ireland-specific emission factor for the afforested peatlands [15]. Wilson, Müller *et al.* [15] adapted values from Duffy *et al.* [3] to estimate a carbon sink for afforested peatlands of 1.9 t $C\cdot ha^{-1}\cdot a^{-1}$. In this study the carbon balance of the afforested cutaway peatland area was estimated using CO2FIX [34,35]. CO2FIX is a stand-level modelling tool which quantifies the carbon stocks and fluxes in the forest biomass and soil. The model calculates the carbon balance with a time-step of one year and allows the long-term carbon balance of a forest ecosystem to be evaluated. The initial soil organic carbon content of the cutaway peatland is estimated to be 250 $t\cdot C\cdot ha^{-1}$ based on the assumptions described previously that 0.5 m of peat with an average MC of 90% will be remaining after peat extraction has ceased, which equates to 500 t of peat left in the cutover. With a peat carbon content of 50%, this equates to 250 t C in the soil. The model is dependent on data from afforested sites in the Carbifor project [36]. The stand is harvested after 41 years, with thinning occurring every 4 years after the stand has reached the age of 19. The harvest produces three assortments: sawlog (>20 cm diameter), stakewood/palletwood (13–20 cm diameter), and pulpwood (7–13 cm diameter). It is assumed that pulpwood will be used for energy generation, and as such that carbon contained in the pulpwood is released to atmosphere in the same year as harvest. The sawlog and stakewood assortments are used in sawnwood production and represent a long term carbon store. One hundred years after afforestation, the soil carbon content has been reduced to approximately 186 t C ha^{-1}, but carbon stored in standing biomass has reached approximately 183 t $C\cdot ha^{-1}$. Taking into consideration the quantity of carbon stored in long term products, and the carbon released from the utilisation of pulpwood for bioenergy, the afforested cutaway peatland has accumulated 180 tonnes t C ha^{-1} over 100 years. This represents an annual carbon sink of 1.8 t $C\cdot ha^{-1}\cdot a^{-1}$. This value corresponds well with the carbon sink estimation of 1.9 t $C\cdot ha^{-1}\cdot a^{-1}$ for forested peatlands specified by Wilson, Müller *et al.* [15].

Data on the industrial peat harvesting process and peat reserves in Ireland was obtained from Bord na Mona [31].

Data concerning the emission of GHGs from diesel combustion in industrial peat extraction machinery and during transportation is based on Nilsson & Nilsson [28] and Uppenberg *et al.* [37]. The quantity of diesel is estimated to be 1.3% of the energy in extracted peat, and subsequent CO_2 emissions are estimated as 1 g $CO_2{\cdot}MJ^{-1}$ of peat extracted [37]. CH_4 emissions are estimated as 0.7 mg $CH_4{\cdot}MJ^{-1}$ of peat extracted, and N_2O emissions are estimated as 0.025 mg $N_2O{\cdot}MJ^{-1}$ of peat extracted [28].

Data concerning peat combustion and additional resources required for power plant operation was sourced from the annual environmental reports of the plants included in the analysis [38,39].

2.3. Life Cycle Impact Assessment

The attributional LCA for peat use for energy generation in this case was carried out using the CML 2001 [40] method and ecoinvent [41] database. Several impacts important in the evaluation of energy systems were considered: acidification potential (AP), eutrophication potential (EP), and global warming potential (GWP). The cumulative energy demand (CED) is also evaluated, allowing the energy ratio (energy out *versus* energy in) of the system to be calculated. The term "energy ratio" is used to characterize relations between the energy input and output. Energy ratio is a ratio between the energy output and energy input according to the following equation;

$$ER = Eo/Ei$$

where,

Eo—energy output,
Ei—energy input,
ER—energy ratio [42].

3. Results

The life cycle impacts of the use of peat for energy generation in Ireland are outlined in Table 4.

Table 4. Life cycle impacts of electricity production from peat combustion (per MWh).

Impact Category	Unit	Power Plant 1 (100 MWe)	Power Plant 2 (150 MWe)	Average
Global warming potential	t CO_2-eq	1.15	1.10	1.12
Acidification potential	g SO_2-eq	278	268	273
Eutrophication potential	g PO_4-eq	21	21	21
Cumulative energy demand	MJ	227	219	223

The life cycle includes impacts from peatland drainage and harvesting, transportation, peat combustion in the power plant, and after-use of the cutaway peatland. Emissions from the combustion of both peat and light fuel oil, which is used during start-up, account for approximately 95% of impacts contributing to GWP, AP and EP for both power plants. Industrial peat extraction, including emissions from harvesting and transportation machinery, and from the disturbed peatlands, accounts for approximately 3% of all environmental impacts considered. Emissions from the after-use of cutaway peatlands account for 2% of each of the environmental impacts considered. The use of light fuel oil in start-up accounts for 11% of overall energy demand in both cases, with peat harvesting and transportation accounting for approximately 89% of energy requirements. The global warming potential of peat use for energy generation ranges from 1.1–1.15 t CO_2-eq MWh^{-1} depending on the power plant.

Limestone is used to reduce sulphur oxides (SO_x) emissions from peat combustion, with the quantity of limestone required depending on fuel quality. The production of limestone is an energy and GHG emission intensive process. Power plant 2 did not require the use of any limestone in 2013, thus lowering the global warming potential compared to power plant 1, which utilised approximately 157 t of limestone.

The average energy ratio of the peat-fired power plants considered is 16, *i.e.*, for each MJ required to fuel the power plant, 16 MJ of energy is produced by the plant.

The global warming potential of the different after-use options considered for cutaway peatlands is shown in Figure 2.

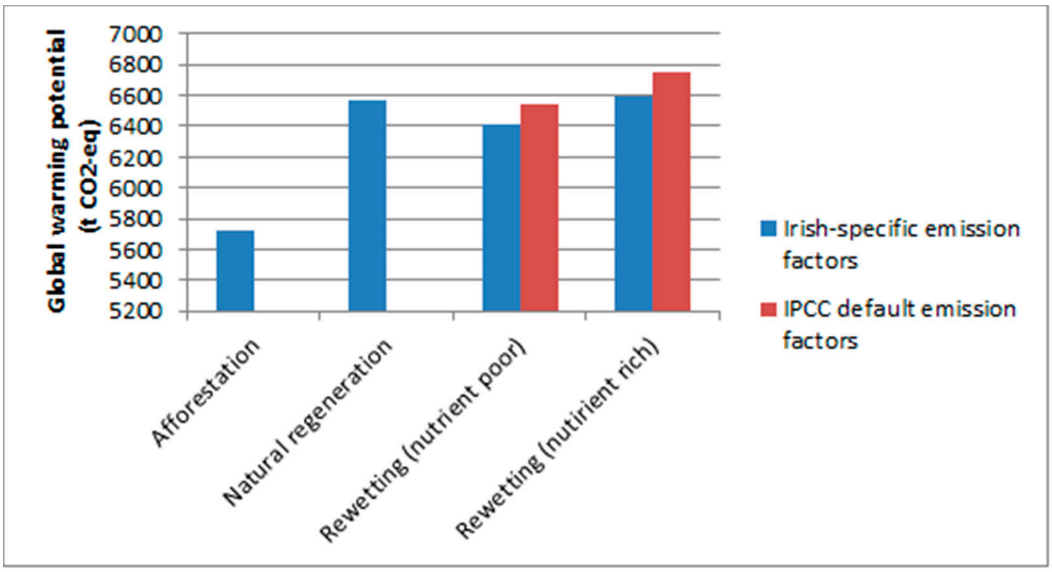

Figure 2. Global warming potential of 1 hectare of peatland subjected to peat removal (and combustion) and subsequently treated to different after-use treatments.

The results include emissions from the drainage and harvest of one hectare of peatland, with the harvested peat subsequently combusted for energy generation, and the remaining cutaway subject to after-use. Afforestation of the cutaway peatland results in a reduction in the soil carbon content of the remaining peatland due to decomposition; however, the increase in biomass results in a net carbon sink over a 100 year time horizon. Depending on the nutrient status of the cutaway, rewetting can result in a return in the carbon sink capacity of the bog, as in the case of the nutrient poor cutaway, or remain a carbon source as in the case of the nutrient-rich cutaway. Natural regeneration of the cutaway peatland results in a carbon source. Afforestation has the lowest global warming potential, followed by rewetting of nutrient poor cutaway, with natural regeneration and rewetting of nutrient-rich cutaway resulting in similar GHG emissions.

Figure 2 also shows the GWP of the rewetting scenarios when using default IPCC emission factors (given in Table 3) in place of the Irish-specific emission factors. The results show that using IPCC emission factors overestimates the GWP of both rewetting scenarios compared to the Irish-specific emission factors. When analysing the peat extraction phase in isolation, the use of default IPCC emission factors overestimates the global warming potential by 2% compared to the use of Irish-specific emission factors.

The conservation of pristine peatland results in GHG emissions of approximately 90 t CO_2-eq·ha^{-1} over a 100 year time horizon. The utilisation of 1 ha of peatland for industrial peat extraction and subsequent energy generation results in GHG emissions of 980,189 t CO_2-eq over the same period including emissions from the peatland harvesting and after-use as well as combustion.

4. Discussion and Conclusions

The greatest contribution to each of the environmental impacts considered is from the emissions generated during peat combustion. Other stages of the life-cycle, such as emissions emanating from the peat extraction area and fossil fuel usage in harvesting and transportation machinery, have much smaller impacts. After-use treatments of the industrial cutaway areas also make a small contribution to overall impacts. The emission factors for the various states of peatland—pristine, managed for extraction, and subject to after-use—contain a large level of uncertainty [15]. However, the level of uncertainty relating to the emissions from peat combustion is low, and as combustion is the main contributor to each of the environmental impacts considered the overall uncertainty is low.

Consideration must be given to the reference land use; in this study it is considered to be pristine peatland, as this is the only type of peatland which has been used for peat extraction in Ireland. In this analysis the conservation of pristine peatland over a 100-year time period results in a small positive global warming potential. The peatland in its pristine state acts as a sink of atmospheric CO_2, but the peatland is also a source of CH_4. The global warming potential of CH_4 is 21 times that of CO_2 [43], and as such CH_4 emissions from the peatland outweigh the benefits resulting from CO_2 accumulation from the atmosphere. Drainage of pristine peatlands and extraction of peat for energy generation causes direct emissions from the degraded peatland but also indirect emissions from peat combustion. In this case, the small net GHG emissions from a pristine peatland are replaced with much larger emissions from both the peatland and from peat combustion.

The transformation of cutaway peatlands to different after-use alternatives has the potential to mitigate some of the effects of peatland degradation and peat combustion. The results show that afforestation of the cutaway results in the lowest global warming potential per hectare of peatland, as carbon accumulated in growing biomass compensates for the carbon lost from peat decomposition. Natural regeneration of the cutaway area results in the area remaining a source of carbon emissions over the time period considered. Rewetting nutrient-poor cutaway areas establishes a carbon sink, while rewetting nutrient rich cutaways results in a source of carbon to the atmosphere. The differences in the carbon sequestration ability of these two land uses can be attributed to differences in microsite composition following rewetting, hydrological conditions and time since rewetting. [15]

A sensitivity analysis was carried out to determine the effects of different emission factors for peatlands on the overall results. The results of this study show that using the default IPCC emission factors in place of Irish-specific emission factors results in an overestimation of the global warming potential. Similarly, Lappi and Byrne [23] estimated GHG emissions of 1.1 t CO_2-eq·MWh^{-1} over the life cycle of peat combustion using default IPCC emission factors, similar to the results of this study. However, they did not include emissions from the after-use of the cutaway peatlands.

This study represents a reference scenario to which other energy systems may be compared. The use of peat for energy generates more emissions than electricity generation from coal, estimated at 0.99 t CO_2-eq·MWh^{-1} for Irish conditions [44]. The global warming potential of electricity production from natural gas was estimated for conditions in Great Britain, as data is unavailable for Ireland [45]. The global warming potential of electricity produced from natural gas is 0.484 t CO_2-eq·MWh^{-1}, considerably lower than the impacts estimated for peat electricity estimated in this study.

It should be noted that this study considers a time horizon of 100 years, and since it uses the CML (2001) method, it does not consider temporal variation in the inventory of emissions. Future research on the peat-for-energy system could make use of dynamic LCA methodology to determine the effects of the temporal variation of emissions in the peat for energy scenario and the peat conservation (reference) scenario. In addition, further research on peat for energy in Ireland should focus on the environmental impacts of the implementation of co-firing targets at the three peat-fired power plants, using indigenous biomass sources such as energy crops [46,47], forest residues [48], and co-products from the wood processing industry [49].

In conclusion, the aim of this study was to analyse the environmental impacts of peat utilisation for energy generation in Ireland using country-specific emission factors and input data. The different after-uses of cutaway peatlands in Ireland are compared to determine the global warming potentials of each alternative. The impacts on overall results of using Irish-specific emission factors to evaluate the global warming potential of the system is compared to the use of default IPCC emission factors. This research establishes a reference scenario for the peat energy chain to which other fossil fuel and bioenergy chains can be compared.

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Author Contributions

Fionnuala Murphy designed, conducted and analysed all research work presented in this paper. Kevin McDonnell and Ger Devlin provided structured oversight and direction to the research work.

Conflicts of Interest

The authors declare no conflict of interest.

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