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Bioenergy development in the UK & Nordic countries: A comparison of effectiveness of support policies for sustainable development of the bioenergy sector

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A R T I C L E I N F O

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A B S T R A C T

This paper uses both quantitative and qualitative analyses to evaluate the effectiveness of government policy and support mechanisms in the UK, Sweden, Denmark and Finland in promoting bioenergy – a key technology fundamental to each country's decarbonisation strategies. It is crucial that countries develop effective policies and support mechanisms to grow sustainable bioenergy sectors. This paper analyses the success of bioenergy policies within each country and evaluates the importance of wider independent variables that collectively characterise the background to energy sector, economic and environmental dynamics. Statistical correlation and regression analyses are applied to identify if the policy landscape has had an identifiable impact on actual bioenergy development. Furthermore, the outputs from a stakeholder workshop and expert interviews are analysed to identify drivers and barriers to bioenergy. The result is a comprehensive analysis of the successes and challenges in bioenergy development, and possible lessons that can be drawn for future promotion of the sector. The research finds that the UK and Nordic countries have had different yet equally successful approaches to promoting bio-power and bio-heat respectively. However, the influence of wider factors within different countries is found to have a potentially greater collective impact on bioenergy than any single policy mechanism. Thus there is credence in learning lessons from what does and does not work in different countries, but countries also need to develop their own brands of policy interventions that suit their country's unique challenges.

1. Introduction

Greenhouse gas (GHG) emissions from the provision of energy services are a fundamental contributor to global rising atmospheric GHG concentrations [1]. Low carbon renewable energy technology solutions are a cornerstone of many countries' energy strategies, providing a key mechanism for decarbonising their energy sectors [2]. Due to its high flexibility and potential for integration into wide ranging energy systems, bioenergy is a renewable energy option attractive to countries at all stages of economic development [3]. Initiating and sustaining the growth of any form renewable energy sector within a country is highly dependent on the design of support mechanisms framed within the energy policy landscape [4]. Within the EU the targets and commitments of the 2009 Renewable Energy Directive [5] (and the 2018 recast of the directive [6]) have provided a policy framework aimed at stimulating sustainable growth of the renewable energy sector, together with longer term political objectives such as the 2050 climate neutral economy target [7]. This research paper aims to evaluate the progress in development of the bioenergy sectors in both the UK and Nordic countries, with particular emphasis on identifying lessons of success and failures between the countries, and opportunities for each country going forward and more widely for different countries around the world.

The 'Renewable 2018 Global Status Report' [8] found that 179 countries have active policy measures aimed at supporting or removing the barriers to wider renewable energy deployment. With so many countries now developing and experimenting with their own brands of renewable energy support mechanisms, it is essential that lessons are learnt from both the successful and less successful initiatives [9]. There

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is likely no single solution or mix of policies uniformly suitable for all countries or regions, but successful policy experiences should be used to provide important lessons for other countries to decarbonise [10].

This paper focuses on analysing the successes and failures of renewable energy technology policy support mechanisms in the UK, Sweden, Denmark and Finland. These specific Nordic countries were chosen because they are representative of Northern Europe where there are comparably high levels of economic development, and strong climate change and renewable energy objectives [11]. All four countries have been subject to legally binding national targets under the EU Renewable Energy Directive [5] and have been subject to the EU Emissions Trading Scheme for reducing greenhouse gas emissions [12]. Each country has also gone further, developing ambitious national renewable energy and decarbonisation targets. At national level, the UK has domestic climate change legal commitments in the form of the 2008 Climate Change Act [9], amended in 2019 [10], requiring the UK to achieve a 100% reduction in GHG emissions by 2050. However, since the UK's decision to leave the EU, it finds itself at crossroads in terms of how to pursue its climate change and renewable energy commitments [13]. There may be lessons to be learnt from the Nordic countries, where their strong energy and climate policies are framed by their targets to reach carbon neutrality within a shorter timescale than the UK. Finland having pledged to reach carbon neutrality by 2035 [11] and Sweden having made a legally binding target for 2045 [12], whilst Denmark shares the UK's 2050 objective. The chosen decarbonisation strategies of the Nordic countries rely heavily on implementing intensive transition pathways based on renewable energy generation and increased energy efficiency [13].

The initial thesis of this article was developed from the outcomes of a stakeholder event held in Finland during March 2016 that brought together representatives from the UK, Sweden and Finland. Key organisers of this event are included in the authorship of this article, the event being held under the auspices of the Science and Innovation network under the UK Foreign & Commonwealth Office. This stakeholder event included a focus group session for developing the views of the stakeholders across the three countries on the primary successes and barriers to further development of the bioenergy sector in each country. We evaluated the extent to which trends in bioenergy heat and power generation may be attributed to the supportive policy landscape, in addition to evaluating the extent that wider country-specific factors may influence bioenergy. In doing so, we combine qualitative analysis, composed from the stakeholder event and in-depth interviews, together with quantitative analysis of bioenergy generation performance of each country to date, compared against the country's plans to reach their EU-defined national Renewables targets (as set out in 'National Renewable Energy Action Plans'). It is important to note that Denmark is absent from the qualitative analysis based on the stakeholder event, but was added as an additional country in the quantitative analysis to broaden the perspective. This was particularly to provide an additional comparator country for the UK which has more similarities to Denmark in biomass resources – unlike the reliance on domestic forestry resources in Sweden and Finland, both the UK and Denmark have more reliance on agricultural resources and imported biomass (mostly as wood pellets).

The analysis timeline spans from 1990 to 2019; 1990 marks the UK's support for renewable energy with the introduction of the 'Non-Fossil Fuel Obligation', whilst 2019 represents the latest year with complete published energy performance data. The research focuses on the generation of heat and power through bioenergy as these represent the largest sectors in terms of renewable energy deployment [14] and there is much existing research focusing on the success and impact of transport biofuel policy within different geographies [15–17].

2. UK & Nordic bioenergy through time

The following section aims to provide background information on the development of the bioenergy sectors in the UK, Sweden, Denmark and Finland. This includes an assessment of current levels of bioenergy generation in each country; the levels of bioenergy generation targeted by each country; and an overview of the key policy interventions and introducing major new bioenergy plants.

The renewable energy strategies of each country are significantly structured around the legally binding national renewables targets for 2020 which countries are required to meet under the EU's 2009 Renewable Energy Directive (RED) [5]. Member states were required to set out exacting plans for reaching their targets in subsequent national renewable energy action plans (NREAPs), based on a strict template. Table 1 combines the 2020 objectives for biomass heat and electricity from the NREAPs with the actual achieved final energy consumption data for 2018 [18]. An important point on data definitions is required here; whilst IEA data [19] was used for the main correlation analysis in this paper, the actual achieved consumption data for 2018 in Table 1 is based on Eurostat SHARES data, as this data matches the specific data definitions for showing compliance with the EU 2020 RES targets discussed in this section. This differential data approach was necessary as the IEA data is available for the longer time period of 1990–2019, allowing for a more comprehensive statistical analysis; in contrast, whilst the Eurostat SHARES data is needed for direct comparison to the RES targets, it is available only from 2004 to 2018.

Based on Table 1, a comparison can be made between the countries on two levels; firstly, the relative emphasis on bioenergy as a share of total power and heat; secondly the required progress in bioenergy between 2018 and 2020 to reach the 2020 objective. The text here also references the proportion of bioenergy as a share of the total 2020 Renewables objective (indicating how crucial bioenergy is to reaching the overall target). A key point in this data is that biomass heat and electricity should not be seen in isolation; in the Nordic countries at least, biomass electricity is generally delivered through combined heat and power (CHP), and therefore heat is produced concurrently with electricity. The UK differs here, where the lack of district heating grids restricts the development of large scale CHP. This difference is a common theme throughout this article.

2.1. Role of bioenergy in National renewable energy strategies to 2020

2.1.1. United Kingdom bioenergy targets & strategy

The RED set the UK a target of achieving 15% of total energy consumption from renewable sources by 2020, this being a large increase from the 1.5% achieved in 2005. The UK's strategy is to achieve this target through renewables providing 30% of electricity, 12% of heating and cooling and 10% of transport energy. Bioenergy fulfils a significant part of this, 22% of the 2020 RES-Electricity objective and 63% of that for heat. On the basis of the 2018 data, the UK has made good progress towards reaching its 2020 objectives, with an additional increase needed for both power and heat of 9% by 2020. However, it is notable that the UK's ambition level for biomass heat is much lower relative to the Nordic member states, with the 2020 objective only being for bioenergy to compose 8% of total heat consumption – compared to between 35% and 56% for the 3 Nordic member states. Whilst it can be argued that the UK started from a lower base than these countries, this is also true of Biomass electricity, where the UK 2020 objective is more comparable to the Nordic countries (7% of total electricity compared to between 11% & 23% for the Nordic countries). Thus the point is emphasised that the UK should particularly look to these countries' experience in the bio-heat sector.

The UK has principally supported bioenergy development through 'Renewable Obligation Certificates' (ROCs, for electricity), and the 'Renewable Heat Incentive' (RHI); indeed, the latter is perhaps the most developed and generous RES heat support scheme across the EU, and has been established in recognition of the low starting point of the UK in this sector [20,24]. Since 2015, the UK has shifted its support for Renewable Electricity from ROCs to "Contracts for difference" an auction-based system based on a "strike price" for Renewables (per MWh) and

Table 1
Comparison of bioenergy consumption for 2019 (achieved) and 2020 (objective).

Member State	Biomass-based energy, gross final energy consumption						Growth in Biomass-based energy from 2018 required to reach 2020 objective	
	2018 (achieved)		2020 (objective) (% of total projected power/heat)					
	Power	Heat	Power		Heat		Power	Heat
	GWh	GWh	GWh	%	GWh	%	%	%
UK	24,019	41,795	26,160	7%	45,520	8%	9%	9%
Finland	11,845	86,631	12,901	13%	76,874	43%	9%	−11%
Sweden	10,247	99,141	16,753	11%	110,308	56%	63%	11%
Denmark	4541	38,640	8846	23%	30,738	35%	95%	−20%

Note: Percentages of total power/heat refers to proportion of bioenergy within *all* sources of power/heat [18,20–23].

providing an effective subsidy by rewarding Renewables generators for the difference between the contemporary electricity market price ("reference price") and the strike price [25].

2.1.2. Finland bioenergy targets & strategy

The RED set Finland a target of achieving 38% of total energy consumption from renewable sources by 2020, rising from the 28.5% achieved in 2005. Finland's strategy is to achieve this target through renewables providing 33% of electricity, 47% of heating and cooling, and 20% of transport energy. Bioenergy plays a major role in this but unlike in the UK, it started from a relatively high base value, with the existence of a historically strong forestry sector. Although bioenergy fulfils a high proportion of Finland's overall RES objective for 2020, forming 39% of RES-Electricity and 91% of RES-Heat, it was already close to the 2020 biomass electricity objective in 2018 with a 9% increase needed in bio-power, whilst its bio-heat objective was already exceeded. Notably, Finland already reached in 2018 a share of 51% biomass in its overall heat sector, well in excess of the projected 43% share in 2020. Indeed, Finland made fast early progress on bioenergy objectives after the implementation of the Renewables Directive, exceeding interim objectives already in 2010 [26,27]. Finland's primary policies driving its 2010 'Climate and Energy Strategy' are subsidies under the 'Sustainable Forestry Financing Law' and the Feed-in Tariff Scheme [21].

2.1.3. Sweden bioenergy targets & strategy

Sweden's targets under the RED are to achieve 49% of total energy consumption from renewable sources by 2020, rising from the 39.8% achieved in 2005. However, Sweden put in place a national target of 50% of energy from renewable sources by 2020, whereby renewables provide 62.9% of electricity, 62.1% of heating and cooling and 13.8% of transport energy. In terms of biomass electricity, Sweden's objective under the RED for 2020 forms a relatively small 17% proportion of its overall RES-Electricity target, equating to an 11% share of total electricity consumption, although in absolute terms, the objective is the second highest of the countries considered here, at 16,753 GWh. Sweden also has some way to go to reach the latter, requiring a 63% increase between 2018 and 2020. For biomass heat, in keeping with the other Nordic countries, biomass forms a very high proportion (90%) of the 2020 RES-Heat objective, equating to 56% share in overall heat supply, and with only an 11% increase needed between 2018 and 2020 to reach its objective.

Sweden targets the use of forestry, agricultural residues and wastes as key bioenergy pathways, driven by support mechanisms such as those under the Electricity Certificates Act and Rural Development Programme [22].

2.1.4. Denmark bioenergy targets & strategy

Denmark's RED target is to achieve 30% of total energy consumption from renewable sources by 2020, increasing from the 17% achieved in 2005. The strategy to achieve this is for renewables to provide 51.9% of electricity, 39.8% of heating and cooling and 10.1% of transport energy. Denmark has the greatest focus on biomass electricity of all the countries considered here, at 45% of its overall RES-Electricity objective, constituting 23% of overall power supply. It appears unlikely to achieve this, as it would require almost doubling its 2018 output. However, in the heat sector, it has already significantly exceeded its 2020 objective, and was already sourcing 43% of overall heat from bioenergy in 2018, well in excess of its 35% objective for 2020.

On the domestic biomass resources side, Denmark's strategy emphasises waste and agricultural residue resources alongside the generation of biogas. Forestry biomass is largely imported as wood pellets. Denmark's policy landscape is defined by the Act on Sustainable Biofuels and The Biomass Agreement, which provide a series of support mechanisms to grow the bioenergy sector, whilst the Danish *Biogas Secretariat* has been established to support local authorities with the planning of biogas facilities and infrastructure [23].

2.2. Policy interventions & bioenergy generation trends

A timeline of total heat and power bioenergy generation [19] for each country between 1990 and 2019 is shown within Fig. 1, annotated to highlight where key policy interventions were introduced that were targeted at aiding the renewable energy sector. These include: Policy Interventions such as new tax mechanisms such as emission levies and financial and regulatory support packages such as a new Act of Parliament or Action Plan; and specific Bioenergy Support Schemes such as a feed-in-tariff or specific infrastructure support schemes. Fig. 1 also highlights where new Large Bioenergy Plant (>15 MW) started generating in each country. A full list of the specific policy interventions and major new bioenergy plant introduced in each country over the timeframe are included within Table 1 of the Supplementary Materials.

3. Research methodology

The following section describes the quantitative and qualitative methods applied within the research to evaluate how trends in bioenergy generation within the UK and Nordic Countries correlate with the timeline of policy interventions and wider independent variables.

3.1. Evaluating the relationships between bioenergy generation, policy interventions & wider variables

The energy sector is highly complex and influenced by a wide range of independent variables that may themselves be equally complex and reliant on further influences. As a result the development of new bioenergy infrastructure and sustainable supply chains will be reliant on a wide range of factors that may contrast significantly between different countries [28].

Statistical analyses are applied to evaluate the relationships between bioenergy generation trends within each of the countries and the timeline of policy interventions, whilst also assessing the potential influence of wider variables. This approach reflects that used by Kilinc-Ata (2016) [29], who applied Statistical Correlation and Multiple Regression

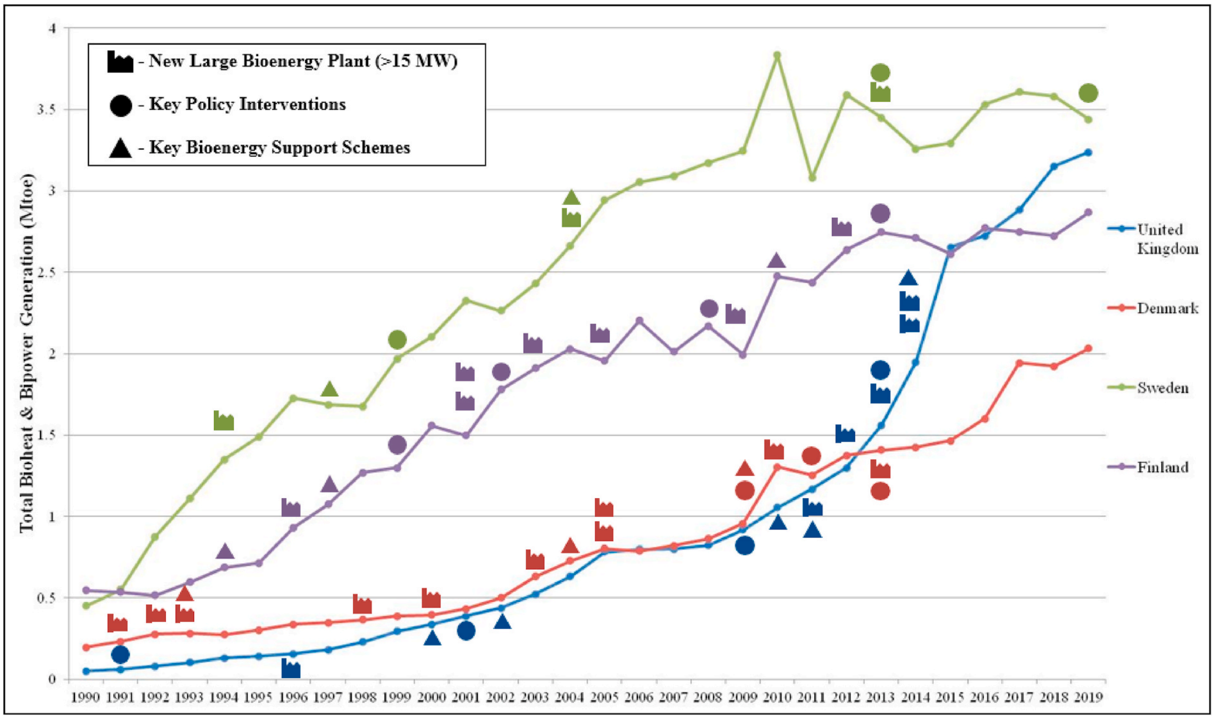

Fig. 1. Timeline of total bio-power & bio-heat generation & the key bioenergy sector interventions 1990–2019.

statistical analyses to evaluate the correlation between both policy and wider factors on the uptake on renewable energy over time.

A series of dependent and independent variables were identified and a database was developed to record how each variable changed within the research countries over the timeline 1990 to 2019. The dependent variables characterise the levels of bioenergy generated, whilst the independent variables characterise changing dynamics of the policy landscape, total energy supply and consumption, energy security trends, wider economics and environmental factors. The choice of independent variables used within this research were identified drawing influence from previous research [29–31].

A database was developed to map how each variable changed within each country over the analysis timeframe. The aim of this exercise was to create a data framework for each country that would enable statistical analyses to evaluate the relationships between bioenergy generation and a series of independent variables. An overview of the chosen variables analysed are presented in Table 2 and Table 3, and the full database is included in the accompanying Supplementary Materials document.

3.1.1. Relationship between the policy landscape and bioenergy generation

The number, design, and focus of regulations and policies aimed at increasing the uptake of renewables will be fundamental to increasing generation over time. To analyse the collective influences of such interventions in each country a database was developed drawing on the IEA IRENA data [35], to record the changing characteristics of the policy landscape between 1990 and 2019. Building on the approaches utilized in similar research previously [36–38], a tally system was used to give each country a score for each year depending on the number of relevant renewable energy and bioenergy specific policies in force at any given time. For example, if a country had a feed-in-tariff and grant scheme in place for the years 2009–2011, each of these years are allocated a 'support scheme score' of '2', and so on. The analysis methodology provides a process for evaluating how the changing number of supportive policies over time may influence the bioenergy sector. The research relies on the qualitative analyses presented later in this paper to evaluate the specific successes and failures of individual policy interventions.

Table 2
Country specific dependent variables.

Dependent Variables	Data Source	Measurement Unit
Total Heat & Power Bioenergy Generation	[19]	*GWh*
Total Bio-power Generation	[19]	*GWh*
Total Bio-heat Generation	[19]	*GWh*

3.1.2. Relationship between total energy supply & consumption variables and bioenergy generation

The trends and dynamics of alternative energy sources may have a direct impact on the uptake of renewable technologies. For example nuclear and gas are considered to be cleaner energy alternatives that may be used as stepping stones to move away from CO_2 intensive energy sources such as coal [39], thus pursuit of these energy technologies may influence focus on bioenergy. The research uses IEA data [19] to characterise changing trends in oil, coal, nuclear, gas and power within each country.

3.1.3. Relationship between energy security variables and bioenergy generation

Energy security is a crucial policy concern for any government. Research such as that by Johansson, 2013 [40] demonstrated that factors influencing energy security will have an influence on the uptake on renewable technologies. For example, a country highly reliant on imported energy sources may be more likely to pursue options for renewables and thus increase their energy security. This can then have a negative feedback impact, whereby increasing renewable energy generation may reduce the demand for imported energy or fuels [41]. The research uses IEA data [19] to characterise changing trends of total energy and power imports within each country.

3.1.4. Relationship between the economic variables and bioenergy generation

It is a plausible argument that countries' wealth will determine the extent to which they will be able to develop and sustain growth of their

Table 3
Country specific independent variables influencing bioenergy generation.

Independent Variables		Unit	Source	Variable's Relationship with Bioenergy
Policy Landscape	Bioenergy Support Schemes Renewable Energy Policy Climate Change Policy	*No. in Force*	[19]	*Designed to support the bioenergy sector, renewable generation and transition towards low and zero carbon*
Total Energy Supply	Natural Gas	*Mtoe*	[19]	*Total energy supply and consumption dynamics, bioenergy potentially replacing fossil fuel energy technologies and balancing changing energy consumption trends*
	Oil	*Mtoe*	[19]	
	Coal	*Mtoe*	[19]	
	Nuclear	*Mtoe*	[19]	
Energy Consumption	Power	*TWh*	[19]	
	Gas	*PJ-gross*	[19]	
Energy Security	Net Energy Import	*Mtoe*	[19]	*Bioenergy generation may reduce need to import energy*
	Net Natural Gas Import	*PJ-gross*	[19]	
	Oil Product Import	*kt*	[19]	
	Power Import	*Mtoe*	[19]	
Economic	GDP	*Billion US$*	[32]	*Increases opportunities for bioenergy support*
	Oil Price	*Index Price*	[33]	*Substitute for bioenergy generation*
	Coal Price	*Index Price*	[33]	
	Natural Gas Price	*Index Price*	[33]	
Environment	CO_2 Emissions	*CO_2 metric tons per capita*	[32]	*Pressure to reduce CO_2, increases focus on bioenergy*
	Heating Degree Days	*Actual Heating Degree-Days*	[34]	*Drives the demand for energy*

renewable technology sectors. The relationships between a country's renewable energy uptake and different economic variables have been extensively tested in the literature. Previous studies both agree [36,42] and disagree [43,44] with the notion that economic wealth measures such as GDP influence the deployment and capacity of renewable energy generation. Further economic variables such as the price of conventional fuels have also been shown [42] to influence the extent of that country's switch to renewable technologies – renewable technologies becoming more economically viable as the price of fuels such as coal and gas increase [45]. Research [46,47] has also demonstrated that energy costs are reduced as deployment of renewables increase. This research uses World Bank Development Indicator data [32] to evaluate whether increasing wealth and changing fuel prices have influenced the levels of bioenergy generated.

3.1.5. Relationship between the environmental variables and bioenergy generation

GHG emission measures such as CO_2 emissions *per capita* are variables intrinsically linked to the uptake on renewable technologies. GHG emissions and the desire to reduce them are themselves a fundamental driver for countries developing strategies and policies aimed at decarbonising their energy sectors through increased renewable energy generation. Likewise trends of increased renewable energy generation will result in inverse trends on GHG emissions [48]. The research uses World Bank Development Indicator data [49] to characterise changing trends in CO_2 emissions for each country.

The inclusion of further environmental variables within the analyses, such as heating degree days is easily justified, as variables such as changing environmental conditions have been proven [50] to influence energy use regardless of wider macro-level influences – if it is cold more energy (and bioenergy) will likely have be used. EU Eurostat data [34] is used to characterise the recorded heating degree days' conditions for each country.

3.2. Quantitative analyses – measuring the relationships between variables & bioenergy generation

The database of country-specific dependent variables (Table 2) and independent variables (Table 3) was analysed applying two statistical tests:

- Pearson Correlation statistical analyses are undertaken to measure the strength of the relationships between bioenergy generation and each of the independent variables. The research applies '2-tailed' correlation analyses to also evaluate the directional relationship between bioenergy generation and the independent variables.
- Multiple Regression statistical analysis are undertaken to evaluate the combined influence of the independent variables on the levels of bioenergy generated. This is carried out to help develop a wider understanding of the interactions that may influence changing trends in bioenergy generation.

The statistical analyses was carried out using IBM SPSS Statistics 25 software [51].

3.3. Qualitative analyses - understanding the changes in bioenergy generation through time

To provide a broader understanding and evaluation of how specific interventions may have influenced bioenergy generation, qualitative analysis is undertaken on the outputs of a UK-Nordic bioenergy roundtable event. This analysis aims to identify the key drivers of and barriers to bioenergy sector within the United Kingdom and Nordic Region based on the experiences of key bioenergy stakeholders.

3.3.1. UK-Nordic bioenergy roundtable event

The analysis focuses on the outputs from a 'UK-Nordic Bioenergy Forum' engagement event held in Espoo, Finland in March 2016. The event's theme was: 'the role of biomass related combustion technology, heat and gas networks', and was attended by over 40 bioenergy stakeholders from the UK, Finland, and Sweden, which represented a balance of government, academic, and industry sectors. The composition of the participants is set out in Table 4 below. This event was jointly organised by the Science and Innovation Network of the UK Foreign and Commonwealth, The University of Manchester, UK Supergen Bioenergy Hub network, Aalto University, Knowledge Transfer Networks (UK), VTT (Finland) and Spinverse (as co-ordinators of the Finnish BEST Bioenergy Programme).

As can be seen from Table 4, the number of Finnish and UK participants at the event was quite equally matched, with a smaller Swedish contingent. However, many Finnish participants were involved in the

Table 4
Breakdown of Bioenergy stakeholders Attending the "UK-Nordic Bioenergy Forum" Event.

	Industry & Industry Associations	Academia & Research Organisations	Government & State Agencies	TOTAL
UK	11	3	4	18
Finland	11	10	2	23
Sweden	3	2	0	5
TOTAL	25	15	6	46

Swedish market. They could thus contribute an informed view on the barriers and drivers in the Swedish bioenergy sector. The outputs from the event's focus group session are the key materials analysed in this research, as explained in the following section.

3.3.2. Stakeholder analysis approach – focus groups

During the focus group session, stakeholders were asked to discuss two key aspects of expanding the bioenergy sector in each country: what are the barriers to bioenergy and positive drivers of the development of the sector. Each focus group was composed of, as far as possible a mix of the different country representatives, with a total of five focus groups. The focus groups were facilitated in their discussions by the co-authors of this article. This empirical data was recorded and collated into a database for analysis. Adopting the method developed by Röder 2016 [52], a tally system was used to account every time different individuals highlighted specific perceived drivers and barriers of the bioenergy sector in each country. This resulted in the development of a comprehensive list of the different perceived drivers, barriers, and the frequency at which each was mentioned.

3.3.3. In-depth interviews (UK only)

The above stakeholder analysis revealed that UK stakeholders identified a disproportionate range of barriers to bioenergy development compared to the Nordic countries. In order to investigate this further, three in-depth interviews were carried out with representatives of each of the following key stakeholder groups: UK Government; Consultancy – Project development and implementation consultancy; Industry association.

It was agreed that the identities of the interviewees would remain anonymous. These in-depth interviews were based on a set of guiding questions on issues in bioenergy development in the UK, but were generally allowed to be rather free-form to focus best on the area of expertise of the interviewee, and their insights into the sector from their own working experience.

4. Research results

4.1. Evaluation of the relationships between variables and bioenergy generation through time

4.1.1. Relationship between bioenergy generation and specific independent variables

Results of the Pearson Correlation analysis are presented within Fig. 2 which is supported by the data listed in Table 5. Fig. 2 maps the specific relationship between total bioenergy generation and each of the independent variables. Each marker is located on a scale between 1.0 and −1.0, reflecting the directional characteristics of the relationship. For example markers for independent variables located close to 1.0 are variables that have a positive relationship with total bioenergy generation – as the value of the variable increases, total bioenergy generation increases accordingly. In contrast, markers for independent variables

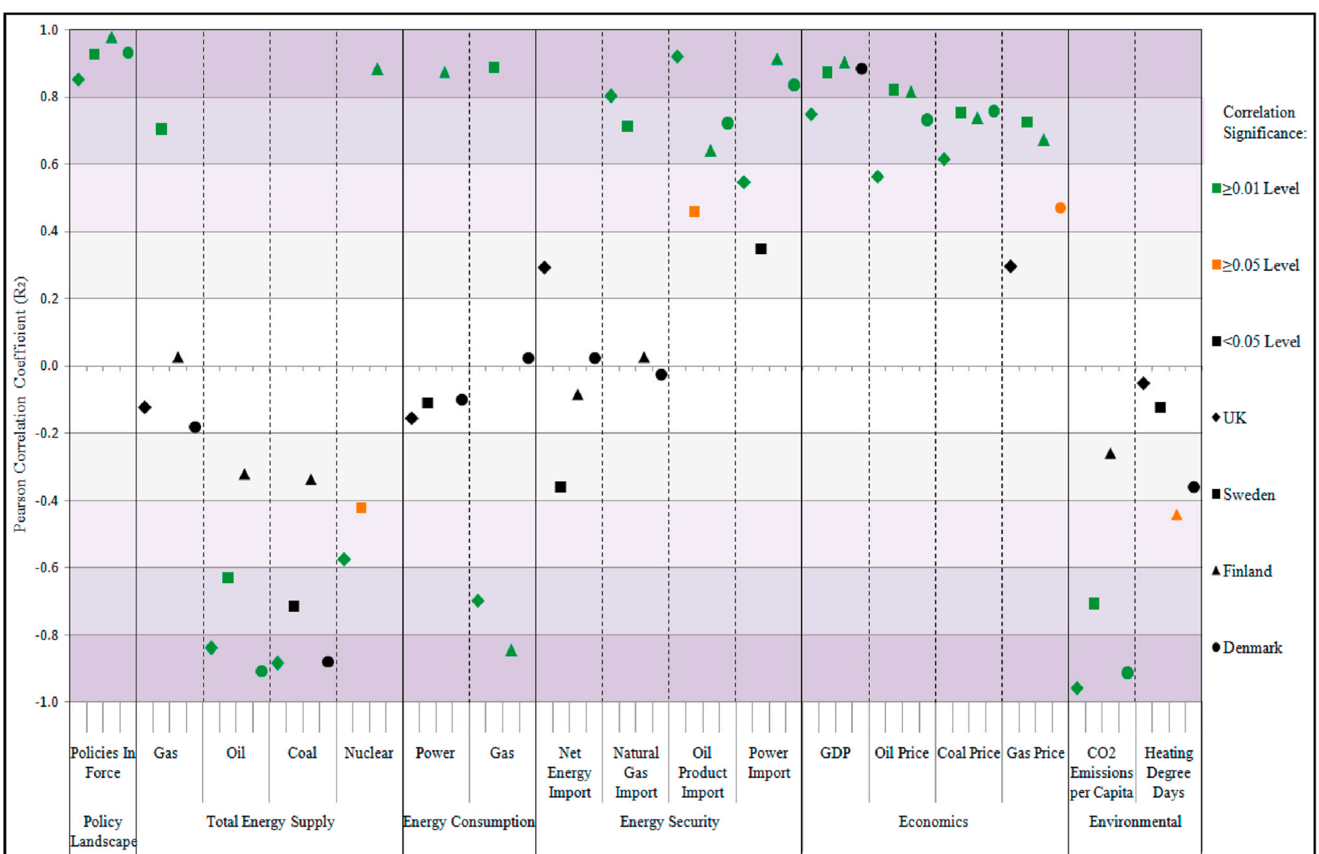

Fig. 2. Mapping Pearson Correlation Outputs, analysing the relationship between Total Bioenergy Generation with the Policy Landscape, Energy Supply, Consumption & Security Dynamics, and with Economic and Environmental variables over the timeline 1990 to 2019.

Table 5
Results of Pearson correlation analysis between bioenergy generation & the independent variables within the UK, Denmark, Sweden and Finland 1990 to 2019.

Pearson Correlation			Policy in Force	Total Energy Supply				Energy Consumption		Energy Security				Economics				Environmental	
				Natural Gas	Oil	Coal	Nuclear	Power	Natural Gas	Net Energy Import	Natural Gas Import	Oil Product Import	Power Import	GDP	Oil Price	Coal Price	Natural Gas Price	CO2 Emissions per Capita	Heating Degree Days
UK	Total Bioenergy	Coefficient R^2	0.853**	−0.123	−0.839**	−0.885**	−0.574**	−0.154	−0.699**	0.293	0.802**	0.920**	0.548**	0.748**	0.562**	0.616**	0.299	−0.959**	−0.050
		Significance.	0.000	0.516	0.000	0.000	0.001	0.417	0.000	0.116	0.000	0.000	0.002	0.000	0.002	0.000	0.122	0.000	0.793
	Total Bio-Power	Coefficient R^2	0.858**	−0.119	−0.843**	−0.885**	−0.578**	−0.147	−0.698**	0.299	0.805**	0.923**	0.545**	0.754**	0.569**	0.619**	0.308	−0.959**	−0.052
		Sig. (2-tailed)	0.000	0.530	0.000	0.000	0.001	0.437	0.000	0.108	0.000	0.000	0.002	0.000	0.001	0.000	0.111	0.000	0.786
	Total Bio-Heat	Coefficient R^2	0.644**	−0.229	−0.634**	−0.808**	−0.413*	−0.339	−0.650**	0.074	0.622**	0.739**	0.584**	0.495**	0.291	0.451*	0.009	−0.760**	0.010
		Sig. (2-tailed)	0.000	0.223	0.000	0.000	0.023	0.067	0.000	0.698	0.000	0.000	0.001	0.005	0.126	0.012	0.963	0.000	0.958
Denmark	Total Bioenergy	Coefficient R^2	0.932**	−0.180	−0.908**	−0.877**	–	−0.099	0.025	0.026	−0.021	0.723**	0.835**	0.889**	0.733**	0.759**	0.470*	−0.913**	−0.359
		Sig. (2-tailed)	0.000	0.340	0.000	0.000	–	0.604	0.898	0.892	0.953	0.000	0.000	0.000	0.000	0.000	0.012	0.000	0.052
	Total Bio-Power	Coefficient R^2	0.940**	−0.017	−0.867**	−0.888**	.-	0.063	0.148	−0.149	−0.157	0.701**	0.827**	0.925**	0.778**	0.788**	0.567**	−0.869**	−0.359
		Sig. (2-tailed)	0.000	0.928	0.000	0.000	–	0.740	0.444	0.431	0.665	0.000	0.000	0.000	0.000	0.000	0.002	0.000	0.052
	Total Bio-Heat	Coefficient R^2	0.919**	−0.242	−0.915**	−0.864**	.-	−0.160	−0.024	0.093	0.022	0.724**	0.830**	0.866**	0.708**	0.740**	0.428*	−0.918**	−0.355
		Sig. (2-tailed)	0.000	0.199	0.000	0.000	–	0.398	0.901	0.624	0.953	0.000	0.000	0.000	0.000	0.000	0.023	0.000	0.054
Sweden	Total Bioenergy	Coefficient R^2	0.928**	0.704**	−0.630**	−0.713**	−0.423*	−0.109	0.888**	−0.360	0.713**	0.458*	0.350	0.873**	0.821**	0.753**	0.726**	−0.706**	−0.123
		Sig. (2-tailed)	0.000	0.000	0.000	0.000	0.020	0.568	0.000	0.051	0.000	0.011	0.058	0.000	0.000	0.000	0.000	0.000	0.518
	Total Bio-Power	Coefficient R^2	0.822**	0.658**	−0.727**	−0.767**	−0.516**	−0.294	0.883**	−0.514**	0.669**	0.508**	0.218	0.960**	0.889**	0.869**	0.741**	−0.800**	−0.225
		Sig. (2-tailed)	0.000	0.000	0.000	0.000	0.004	0.114	0.000	0.004	0.000	0.004	0.248	0.000	0.000	0.000	0.000	0.000	0.231
	Total Bio-Heat	Coefficient R^2	0.940**	0.694**	−0.548**	−0.649**	−0.352	−0.004	0.847**	−0.260	0.702**	0.409*	0.404*	0.783**	0.742**	0.654**	0.684**	−0.619**	−0.062
		Sig. (2-tailed)	0.000	0.000	0.002	0.000	0.056	0.984	0.000	0.165	0.000	0.025	0.027	0.000	0.000	0.000	0.000	0.001	0.746
Finland	Total Bioenergy	Coefficient R^2	0.980**	0.030	−0.319	−0.334	0.884**	0.876**	−0.845**	−0.084	0.030	0.640**	0.915**	0.903**	0.816**	0.738**	0.673**	−0.257	−0.440*
		Sig. (2-tailed)	0.000	0.875	0.086	0.071	0.000	0.000	0.000	0.661	0.874	0.000	0.000	0.000	0.000	0.000	0.000	0.196	0.015
	Total Bio-Power	Coefficient R^2	0.943**	0.043	−0.294	−0.319	0.876**	0.884**	−0.737**	−0.068	0.043	0.576**	0.879**	0.856**	0.762**	0.704**	0.609**	−0.187	−0.406*
		Sig. (2-tailed)	0.000	0.822	0.114	0.086	0.000	0.000	0.000	0.721	0.820	0.001	0.000	0.000	0.000	0.000	0.001	0.351	0.026
	Total Bio-Heat	Coefficient R^2	0.979**	0.025	−0.323	−0.335	0.876**	0.862**	−0.870**	−0.088	0.025	0.653**	0.915**	0.907**	0.822**	0.740**	0.685**	−0.277	−0.446*
		Sig. (2-tailed)	0.000	0.895	0.082	0.070	0.000	0.000	0.000	0.645	0.895	0.000	0.000	0.000	0.000	0.000	0.000	0.163	0.014
Key		** Correlation is significant at the 0.01 level (2-tailed). * Correlation is significant at the 0.05 level (2-tailed).																	

located close to −1.0 demonstrate an inverse relationship with total bioenergy generation – as the value of the variable decreases, total bioenergy generation increases. The colour coding of the markers within Fig. 2 is designed to highlight the strength of the relationship (R^2 correlation coefficient) between the independent variables and total bioenergy generation. For example markers located towards 1.0 and coloured green are found to have a significant ($p > 0.01$) positive relationship with total bioenergy generation.

The data presented within Table 5 also provides outputs of Pearson Correlation statistical tests where the relationship between the independent variables and total bio-power and total bio-heat generation are analysed for each country. This allows assessment of potential variations in the relationships between the policy landscape and wider independent variables within bio-power and bio-heat generation.

The results of the Pearson Correlation statistics mapped in Fig. 2 highlight both similarities and differences in the relationships between the independent variables and bioenergy within each country. Significant positive correlations are shown for each country between the *Policy in Force* variable and bioenergy - generation increasing as the policy landscape develops and new policies are implemented.

There are largely inverse relationships between the total energy supply variables and bioenergy generation. Significant inverse correlations are shown between bioenergy generation and *Oil Supply* in the UK, Sweden and Denmark, with *Coal Supply* in the UK and with *Nuclear* in the UK and Sweden – as total supply of these alternative energy sources decreases, bioenergy generation increases. In contrast significant positive correlation is shown between *Gas Supply* in Sweden and *Nuclear* in Finland – bioenergy also increasing as each of these variables increase over the timeline. Significant positive correlations are also shown between *Power Consumption* in Finland and *Gas Consumption* in Sweden with bioenergy. In contrast significant inverse correlations are shown between *Gas Consumption* in the UK and Finland.

A number of contrasts can be seen between the characteristics of the relationships between the energy security variables and bioenergy generation. *Net Energy Import* is shown to have no significant correlation with bioenergy generation. In the UK a significant positive relationship is shown between *Gas, Oil* and *Power Imports*. There is a similar relationship in Sweden for *Gas* and *Oil Imports*, and for both Finland and Denmark for *Oil* and *Power Imports*.

Significant positive correlations are shown between bioenergy and the majority of the economic variables, aside from in UK and Denmark where the correlations with *GDP* and *Gas Price* respectively are shown to not be significant. *CO_2 Emissions per Capita* are shown to have a significant inverse relationship with bioenergy generation within the UK, Sweden and Denmark – CO_2 emissions reducing over the timeline as bioenergy increases. The strength of this correlation is less for Finland. There are also inverse relationships between the *Heating Degree Day* variables and bioenergy for each country, although this correlation is only shown to be significant in Finland.

4.1.2. Relationship between bioenergy generation and wider country specific variables

Outputs from the Multiple Regression statistical analyses are presented within Table 6, and may be evaluated to provide a deeper understanding of how the independent variables for each country may collectively influence bioenergy generation. The complete output tables from the Multiple Regression analyses are presented within the Supplementary Materials.

Within Table 6 the coefficient determination (R^2) values provide an overall measure of the strength of association across the variables – the proportion of variance within the Total Bioenergy Generation (dependent variable) that may be explained by the independent variables. Presented on a scale between 0 and 1, an R^2 value of 1 would indicate that 100% of variance could be explained by the independent variables. The significance (ANOVA $p < 0.05$) of the R^2 values are also presented, documenting whether the independent variables are found to be significant predictors of bioenergy generation over the timeline.

For each independent variable within Table 6, standardised coefficient β values are also presented, highlighting the characteristics of the relationship between each independent variable with total bioenergy generation. For example if an independent variable has a β value of 0.8, this means that as bioenergy generation increase by 1 unit over a timeframe the independent variable will have also increased by 0.8 units over the same timeframe. The β values are highlighted where the independent variables are found to demonstrate a significant ($p < 0.05$) degree of unique variance on the bioenergy generation that is not explained by any of the other variables. Where there are no significant β values for a country there is potentially a high degree of collinearity across the independent variables – there is high correlation across the independent variables [53].

For each of the countries the overall regression models were significant, >98.5% of the variances in total bioenergy generation over the

Table 6
Results of the multiple regression statistical analysis between bioenergy generation & the independent variables 1990 to 2019.

Independent Variables		United Kingdom		Denmark		Finland		Sweden	
		R^2	β	R^2	B	R^2	β	R^2	β
Policy Landscape	Policies in Force	0.997*	0.072	0.996*	0.229	0.989*	0.703	0.985*	0.307
Total Energy Supply	Natural Gas		−0.441		−0.013*		*excl.*		*excl*
	Oil		0.493		−0.568		−0.132		0.242
	Coal		0.106		−0.358		−0.443		0.039
	Nuclear		−0.084		N/A		−0.075		0.155
Energy Consumption	Power		0.268		0.283		0.506		0.008
	Natural Gas		0.428*		−0.100		−0.109		0.112
Energy Security	Net Energy Import		−0.012		0.137		0.182		−0.126
	Net Gas Import		−0.360		−0.029		−0.396		0.264
	Oil Product Import		0.199		0.136		−0.052		0.108
	Power Import		−0.036		0.201*		−0.286		0.153
Economic	GDP		0.221		0.327*		0.020		−0.009
	Oil Price		−0.166		0.389		0.433		−0.232
	Coal Price		−0.024		−0.071		−0.063		0.093
	Natural Gas Price		0.084		−0.450*		−0.160		0.302
Environment	CO_2 Emissions		−1.703*		0.541		0.366		−0.633
	HDD		0.124		0.110		0.089		0.089

Key:	excl.	Predictor variables are excluded within the SPSS software where their trend over the timeline can be perfectly predicted from one or more of the other independent variables.
	*	Denotes independent variables where the coefficient is $p < 0.05$, therefore contribute unique variance on the bioenergy generation that is not explained by the wider variables.

timeline 1990 to 2019 can be predicted by the independent variables with a high degree of significance (ANOVA $p = <0.01$).

Evaluation of the coefficient β values for each country highlights there are several independent variables that potentially result in unique influences on bioenergy generation that may not be explained by the other variables. In the UK this includes *Natural Gas Consumption* and *CO_2 Emissions per Capita*, and in Denmark *Power Import*, *GDP*, *Natural Gas Supply & Natural Gas Price*. These are trends specific to these countries, as the coefficient β values for the independent variables for both Sweden and Finland are not shown to be significant, suggesting there are no specific independent variables that have a strong unique relationship with total bioenergy generation. There is also potentially a high degree of collinearity between the independent variable datasets – they can be linearly predicted from the others with a high level of accuracy. This doesn't reduce the reliability of the regression models but is a phenomenon that affects the coefficient β values of the individual independent variables [54].

In summary the multiple regression analyses highlights that increases in levels of bioenergy generation within each of the countries may be predicted with high degrees of accuracy from the independent variables. There are only a limited number of independent of variables that have unique influences on bioenergy generation. Given the high overall R^2 values and potential of collinearity across some of the independent variables, it suggests there are many interactions and linkages between many of the independent variables that collectively have a significant influence on bioenergy generation trends.

4.2. *Understanding changes in bioenergy generation*

The empirical data of the bioenergy stakeholder's perceived drivers of and barriers to the bioenergy sector have been mapped within a venn diagram within Fig. 3. Each segment of the venn diagrams represent one of the three countries involved in the stakeholder event: UK, Sweden, and Finland. The items listed within the segments are issues identified by stakeholders as being either drivers or barriers to the bioenergy sector. Where listed issues overlap segments, this indicates the issue is relevant to more than one of the countries. The respective size of the text used for each issue represents the frequency that each item was mentioned by different stakeholders – the larger the text the more stakeholder perceive the items to be a driver or barrier.

Within Venn Diagram A, bioenergy stakeholders perceive the most important issue driving the bioenergy sector across all three countries to be the EU Renewables directive and its inherent targets. Thus the role of the EU targets in setting the agenda for the sector is well recognised. Considering the stakeholder feedback, it was possible to build upon the positive correlations between the implementation of support schemes and bioenergy sector development as shown in Fig. 3 by identifying more explicitly which support schemes have been most critical to the bioenergy sector. A feed-in-tariff/premium was implemented in both UK and Finland and was considered to be a key driver of bioenergy in both countries. Whilst the feed-in tariff premium implemented in Finland has covered many types of bioenergy plant (since 2010), the primary role of that put in place in the UK has been in supporting the development of anaerobic digestion. Thus it is notable in the UK case that this is recognised as a key driver in view of its limited remit (pointing out the relative success of the AD sector in the UK) [55].

The most important support scheme identified in the UK and Sweden was the Renewables Quota System (Renewables Obligation in the UK). For all countries the importance of carbon taxes/price floors was highlighted, suggesting a real impact of carbon policies on the sector as experienced by stakeholders. The Renewables Heat incentive – a form of feed-in tariff for heat was also positively identified for the UK, but not by all focus groups (some issues concerning this scheme are further considered in 4.2.1). A notable absence from Fig. 3 is any mention of some of the support schemes listed in Supplementary Materials - indicating that some schemes have had very limited perceived impact. For example there is no reference to the VAT reduction scheme for bioenergy in Finland, the Energy Aid/Investment aid in Sweden and Finland, or the Bioenergy Infrastructure scheme in the UK. A key conclusion from this discussion can be that two types of support scheme have the greatest impacts – price support schemes and carbon incentives. The role of supplementary tax and investment-based incentives appears weak and the extent to which government should focus efforts and financing on such schemes is somewhat questionable.

The stakeholder's perceived barriers mapped within Venn Diagram B of Fig. 3 highlight an interesting picture, particularly for the UK where

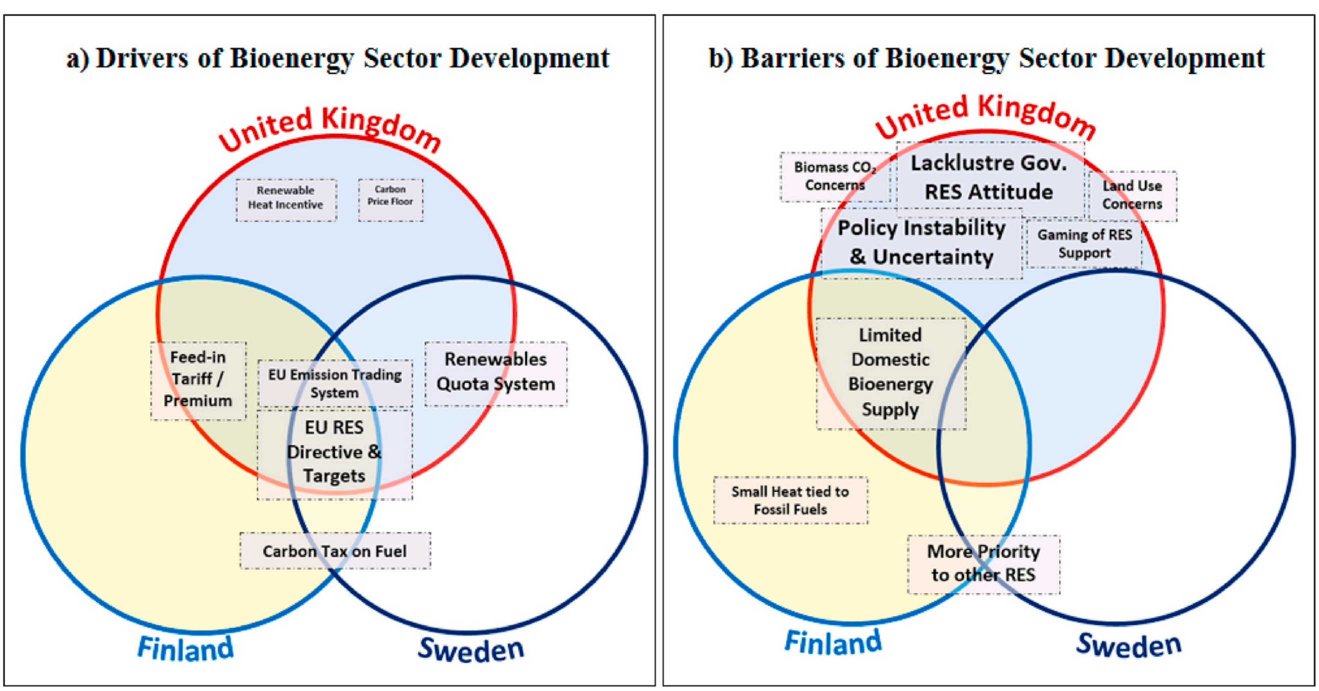

Fig. 3. Bioenergy stakeholder perceived drivers & barriers of the bioenergy sector development & increased bioenergy generation in the UK, Finland & Sweden.

by far the greatest number of perceived barriers are mentioned. The greatest bioenergy barriers in the UK are shown to be the instability of the policy landscape, the perceived lacklustre attitude of the Government to renewables, and concerns shared with Finnish stakeholders and to lesser extent Swedish stakeholders about availability of domestic resource supply. The latter is perhaps surprising in the Swedish and Finnish case given the predominance of domestic forestry resources in the bioenergy supply [56]. For Sweden and Finland it is primarily indicative of issues related to the mobilisation and reliable supply of forestry biomass from many small landowners, and the link between bioenergy and the pulp and paper sector; the decline of the latter has given rise to concern about the availability of secondary biomass (i.e. material considered waste products from the pulp and paper sector but used for bioenergy production e.g. bark, branches, stumps). Both Swedish and Finnish stakeholders perceived their Governments' prioritisation of alternative renewables to be the key barrier to both their bioenergy sectors (this principally refers to promotion of wind energy). Furthermore, Finnish stakeholders highlighted specific concerns about how their small-scale heat installations are intrinsically tied to fossil fuels, representing a key barrier to a widespread shift to bioenergy.

4.2.1. *Understanding of barriers gained through UK expert interviews*

Further in-depth interviews were conducted to provide insights to factors in the UK concerning bioenergy development, particularly the barriers to development and the challenges of the UK bioenergy sector which were so evident in the stakeholder focus groups discussed above. The outputs of the in-depth interviews are summarised in Table 7, which provides input to the discussion in section 5.

5. Bioenergy lessons from the UK & Nordic Countries

5.1. *Understanding the varying influences of bioenergy in different countries*

This research set out to evaluate the relationship between bioenergy generation and policy/regulatory interventions within the focus countries, whilst also investigating the potential influence of wider variables. The Pearson Correlation statistical analyses highlight the importance of the policy landscape in supporting bioenergy deployment – the increasing number of relevant policies in force over the timeline having significant positive correlation with levels of bioenergy generated. This is supported by the stakeholder perception analyses where policy interventions such as EU Directives and feed-in-tariffs were the predominant factors items identified as being drivers of bioenergy within the UK, Sweden and Finland. This aligns with the conclusions of similar research [29] where statistically significant relationships were found between national policies and renewable energy deployment, and thus provides further evidence that policy interventions can and do influence the renewable energy sector. However, the outputs from the research's Multiple Regression statistical analyses demonstrated that the number of related policies in force within each country do not have any unique significant correlation with bioenergy. This suggests that policy alone does not drive increased generation, thus highlighting the importance of the relationship between bioenergy generation and wider independent variables that collectively characterise the energy, economic and environmental landscape of the countries.

There are limitations of this methodology for evaluating the effectiveness of government policy and support mechanisms for promoting

Table 7
Quotes and Paraphrases taken from In-depth UK Bioenergy Expert Interviews.

Key Theme	Stakeholder Interview Quotes & Paraphrases			Common Concerns
	Consultancy – Project Development & Implementation	Industry Association	UK Government stakeholder	
Support of biomass electricity-only sector	*"Ultimately believe biomass should not be used for electricity, but only for heat and transport"*	*"Essential problem is political. Lot of debate on the conversion of coal plants"* *"criticism saying biomass for converted coal plants being dirtier than coal"*		• Doubts over compatibility of sustainability of support of electricity-only biomass generation (though not mentioned by government stakeholder)
Are the challenges of heat being correctly addressed?	*"CHP is a challenge as there are not very many large loads at 1 MW+"* *"RHI consultation on CHP has caused problems. The closure of the Renewables Obligation has made this problem worse"* *"Preoccupation with electrification of heat [i.e. heat pumps], is misguided as will not develop at the scale foreseen … …as problematic implications for distribution grid"* *"RHI is [generally] very good [for bio-heat]"*	*"RHI only to 2021 as funded from general taxation …. so have to commission before then".* *"Need both CFD and RHI to make a biomass CHP project survive" [adds complexity]* *"Very high tariff digression in RHI has destroyed industry created; automatic digression was necessary but was too rigid."*	*"Heat is a challenge"* *"Heat networks are not really on house developer's radar, would need state intervention."* *"The UK has a housing shortage so putting in additional requirement on housebuilding is not practical."* *"District heating has an undeserved negative reputation in the UK."*	• Positive view on RHI. • Concerns on support scheme timescales and tariff changes. • Heat networks extremely challenging for UK and do not seem realistic.
Biogas (Anaerobic digestion) and Biomethane (latter can be direct input to gas grid)	*"think biomethane tariff is good, and that it has been successful …. .are some issues on feedstock sustainability"* *"Renewable gas sector has a promising future"*	*"Biomethane has been good because of extensive gas grid; so very popular. But government is very concerned about amount of energy crops being used."*	*"Biogas (anaerobic digestion) is fine for the 2020 targets but is not a good solution for longer run decarbonisation."* *"We need improve gasification to produce clean enough output to go directly into gas network."*	• Biomethane has promising future if technical barriers can be overcome. • Biomethane will fit well within existing gas energy infrastructure. • May provide good pathway for decarbonising heating.
Future of bioenergy support	*"Instability has been the problem!"* *"Consider role of biomethane with CCS"*	*"Tariff changes thus far have been too extreme to develop viable supply chains."* *"A tariff guarantee could avoid rush, and allow full commissioning time."*	*"New Contracts for Difference scheme is an interesting economic case study to get an efficient result"* *"But do already have some negative feedback from smaller operators who consider administration too much."* *"Bio-CCS could be important for negative emissions; recognised in Paris climate agreement."*	• Need for stability and simplicity in support schemes. • Recognition of a role for bio-CCS.

bioenergy. The correlation methodology presented in this research is somewhat novel compared to existing approaches in literature, though the positive correlation between support schemes and bioenergy development in the countries does seem significant and supportive of the general approach. Further investigation might be warranted on why similar policy interventions do not appear to have the same direction and effects in different countries.

The Pearson Correlation outputs presented within Fig. 2 highlight trends where the relationship between bioenergy and specific variables are similar, but also instances where the opposite relationships can be observed. For example all the results for the economic independent variables for each country demonstrate a positive 'unidirectional relationships' with bioenergy generation. As GDP increases, it will provide countries with the means to grow and sustain a sustainable growth of a bioenergy sector. Likewise as the prices of alternative fuels such as oil, coal and gas increase, there will be greater incentive to shift towards bioenergy as an alternative option, thus bioenergy generation will increase in accordingly.

Difficulties arise when trying to explain the influence of different independent variables on bioenergy generation when the relationships are shown to have contrasting effect from country to country. For example, increasing natural gas consumption is shown to have a significant positive relationship with bioenergy generation in Sweden, but a significant negative relationship with bioenergy in the UK and Finland. This may be explained through considering that different countries have different strategies to developing their energy sectors, prioritise and incentive different technologies and renewable energy generation may itself impact multiple issues in different ways - renewables may varyingly impact a country's energy security, industrial and economic growth, environment and climate change performance. Given that different countries have unique policy landscapes and market contexts, the changing dynamics of the energy landscape in one country may have a different collective impact on the renewable sector compared to a similar change in another country [57].

This research may be interpreted as providing contrasting messages about how countries should best support their renewable sectors. There is both credence in learning lessons from the success or otherwise of policies in different countries but ultimately each country should develop their own brand of policies and combinations of interventions to suit their country's unique challenges [58]. However there is great value in supporting quantitative and modelling assessment with qualitative analyses.

5.2. The influence of changing fossil fuel demand dynamics

The close links between the bioenergy sector with fossil fuels and wider energy demand dynamics were highlighted within the stakeholder perceptions analyses, where mechanisms for taxing fuel carbon emissions and the embedded fossil fuel infrastructure were identified as both drivers and barriers to bioenergy respectively. These linkages are reaffirmed through the correlation analysis results, where the country specific variables linked to fossil fuels (Supply, Consumption, Imports, Prices) are shown in many cases to have significant correlations with bioenergy generation trends.

These linkages can be explained by further understanding the many challenges facing countries trying to transition away from fossil fuels to renewables – for bioenergy, the fundamental barriers being cost competitiveness and established fossil fuel infrastructure. But unlike other renewables, bioenergy can often constitute a direct "drop-in" replacement for fossil-fuels - e.g. in co-firing, and does not face the problem of intermittency faced by other forms of renewables [59]. It is thus notable that stakeholders strongly identified the role of carbon price/tax mechanisms as positive drivers for bioenergy development since they can potentially level the cost comparison between biomass-based and fossil fuels.

5.3. The UK & Nordic case studies – different strategies for promoting bioenergy

An interesting contradiction between the findings of the research's correlation statistical analyses (Fig. 2) and the qualitative analyses is that for each country a significant correlation was found between the policies in force over the timeline and bioenergy generation, yet policy issues were widely reported by stakeholders as being perceived barriers to development of the bioenergy sector – particularly for the UK. This issue is reaffirmed through closer inspection of the statistic outputs listed in Table 5 where the positive correlation between the policy landscape and bioenergy generation in the Nordic countries is greater than for the UK. The outputs within Table 5 also highlight a contrast in how the policy landscape has influenced the generation of bio-power vs. bio-heat. The bioenergy policy interventions of the Nordic countries are shown to have much greater correlation with the levels of bio-heat generated, whilst the UK's policy interventions document higher correlation with bio-power generation.

The reasons for this difference can be at least partly understood by the advantageous background for bio-heat in the Nordic countries, whereby relative modest policy adjustments can result in significant changes, in contrast to the weak background in the UK. A key factor here is the existence of large district heating networks; whilst these have historically been supplied by fossil fuel plants, it is relatively easy to convert or replace these installations by bioenergy-based facilities. In the UK, the situation is much more challenging, given the lack of such networks and thus the need to replace individual household heating systems, implying much greater expense and complexity. In certain cases Nordic countries may be able to switch to bioenergy-based heat by switching fields in existing plants with relatively low conversion costs - as the UK has been able to do for biomass based electricity. There are however other factors in explaining this difference. Sweden was particularly early in its implementation of a carbon tax, (since 1991), which has influenced a shift from fossil-based to biomass-fired heating not only in large installation connected to district heating but also at the level of individual households [60]. Sweden's early progress in this sector has enabled through the establishment of extensive domestic feedstock supply chains using forestry resources [61] which imply that further bioenergy development is made easier – a form of "snowball effect". As discussed in 2.1.1, whilst the UK is making good progress to reaching its 2020 bio-heat target, its target is very modest compared to the Nordic countries, and the UK sees the decarbonisation of its heating sector as 'the biggest challenge' [62] – reflecting very similar sentiments from the expert interviews summarised in 4.2.1. Furthermore, making this progress has only been possible through the implementation of the Renewable Heat Incentive (RHI), which is much more generous than equivalent schemes for the bio-heating sector in the Nordic countries. Indeed, the cost effectiveness of the UK's RHI has been questioned - but for the reasons explained is likely to meet with less success than if a similar scheme were implemented in Nordic countries [63].

Therefore, the question remains of what the UK could learn from the approach of the Nordic countries in the heating sector. It could of course attempt to develop district heating networks. However, as pointed out during the in-depth interviews, heat networks are extremely challenging to develop in the UK. Furthermore, the Nordic countries are also facing a difficult situation for heat networks, where low electricity market prices, especially during periods of high generation from intermittent generation have damaged the competitive situation of district heating [64]. The impact of this has been twofold – with the low market prices for electricity decreasing the revenues of CHP plants and the making operating costs of electrical heat pumps lower than using district heat. Thus it is clear that while it is a struggle to maintain the competitiveness of district heat in Nordic countries, it is unlikely to be a realistic choice for the UK to any significant extent.

Somewhat in contrast to bio-heat, the UK appears to present a successful case for cost-effective development of bio-power with wider applicability. Over recent years the UK has achieved large step changes in generation driven by support schemes such as the Feed-in-Tariff and Renewable Obligation, that enabled the establishment of large scale bio-power facilities predominantly fuelled by imported feedstocks to be co-fired with coal [65]. This strategy of establishing international feedstock supply chains to fuel large scale facilities may represent an option attractive to similar countries with limited domestic resource availability and bioenergy aspirations [66]. However, both existing literature [67,68] and the stakeholder analysis in this paper has questioned the long run sustainability and resource efficiency of focusing on electricity-only biomass as opposed to use of biomass in CHP and heat-only plants (the latter can be up to 90% efficient, in contrast to electricity-only biomass plant with an efficiency typically under 30%). Furthermore, at European level, the bioenergy GHG savings thresholds and other bioenergy sustainability criteria introduced as part of the 2018 recast of the 2009 Renewables Directive will limit new electricity-only biomass installations being counted as Renewables or provided with subsidies. Whilst the latter may never be implemented in the UK in view of Brexit, it does imply that strong policies for electricity-only biomass have limited applicability to other countries in the European context [6].

5.4. Future pathways for bioenergy in the UK and Nordic Region, and wider global lessons

The UK, Nordic and many other countries are likely to face many of the same bioenergy challenges over the coming years as they face up to their respective renewable energy and climate change targets. The Nordic countries each have world leading decarbonisation targets with aspirations to become virtually fossil fuel free by 2050 or before. Although in many respects they are well on their way to achieving these, there will need to be continual step changes in renewable energy generation driven by technological innovation and strong political commitments [13]. The UK also has strong renewable energy and climate change legal commitments [10], although it is at a cross-roads in many respects as the UK decides on its post-Brexit roadmap and all countries have to navigate through potential known and unforeseen circumstances such as those presented by Covid-19.

Both the UK and Nordic countries will need to increase the development of their bioenergy sectors to meet their policy targets, and will likely look at each other and around the world for inspiration. There are already mechanisms in place that should influence how Governments develop, evaluate and appraise policies, including assessing international case studies; for example the UK Government's Green Book [69] confirms that policy options should be considered as "informed by stakeholder consultation or engagement, lessons learned from previous interventions, international best practice and the wider evidence base." It is important that these evaluations do take place, because as highlighted by UK bioenergy stakeholders analysed within this research (Fig. 3) and by much literature [70], uncertainty and instability of UK Government policy is perceived as major barrier for the bioenergy sector. This an area where great lessons can be learnt from the Nordic countries. In addition to policy stability, perhaps the most positive examples from Sweden and Finland are their apparent effectiveness of developing their bioenergy heating sector.

6. Policy conclusions

We undertook correlation statistical analyses to evaluate the influence of policy interventions on bioenergy generation in the UK, Sweden Denmark and Finland between 1990 and 2019. Further regression statistical analyses were carried out to evaluate the influence of wider country specific factors such as GDP, changing fossil fuel, and energy demand dynamics. This was complemented by qualitative analyses evaluating the outputs from a focus group event where bioenergy stakeholders identified their perceived drivers of and barriers to bioenergy sector development.

The research finds that bioenergy is influenced by multiple factors specific to different countries. Policy interventions are not found to have any unique significant correlation with bioenergy generation, highlighting the importance of the relationship between bioenergy generation with wider independent variables that collectively characterise the energy, economic and environmental landscape of the countries. Therefore, it can be difficult to identify the successes and failures of different policy interventions in isolation without considering the wider influences. There is both credence in learning lessons from what does and does not work in different countries, but ultimately each country ought to develop their own brand of policies and combinations of interventions to suit their country's unique challenges.

Both the UK and Nordic countries will need to increase the development of their bioenergy sectors to meet their policy targets, and will likely look at each other and around the world for inspiration. The UK's approach to promoting bio-power generation represents a successful strategy in producing a step change in generation and in creating a regime for sustainable imported biomass. Use of biomass in CHP and heat-only plants could be preferable from a resource efficiency point of view to electricity-only plant, but the possibilities for this are more limited in the UK market. The success of the bio-heat sector in the Nordic countries may have limited transferability to countries such as the UK which lack district heating infrastructure. However, the Nordic example of the success in sustained long-term policy does sit in contrast to the instability of the policy regimes such as that in the UK – political will to maintain support policies is critical.

Disclaimer

The views expressed in this paper are those of the authors and external stakeholders consulted for this work and do not reflect the official policy or position of the UK Science & Innovation Network or the wider UK Government.

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Appendix A. Supplementary data

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