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Decarbonizing Energy of a City: Identifying Barriers and Pathways

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Abstract: As researchers and ultimately deployers of energy decarbonisation solutions, we collectively see significant but often siloed efforts that in isolation may appear as an appropriate solution to an aspect of energy decarbonisation. However, when systemwide thinking is applied, a former attractive solution may become more challenging and, likewise, a less attractive silo may become more appropriate as part of an energy systemwide approach. Thus, the aim of this paper is to combine proposed energy decarbonisation concepts, e.g., electrification, hydrogen, biogas etc., with the status of the system in which they intend to operate, and then highlight the barriers, opportunities, and alternatives that may come into play when the whole system is taken into account. This is a hypothetical study using the city of Belfast, Northern Ireland, UK as an example and reflects, in part, the city's desire to decarbonise while enhancing its economic prosperity. The "system" is defined as the region boundaries, i.e., Northern Ireland will supply the energy (all or in part) to the city of Belfast. The methodology deployed here therefore is a framework of energy thinking that is the basis of such energy decarbonisation plans at a city-wide level.

Keywords: city-wide decarbonization; buildings; industry; transport

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1. Introduction

In the UK, the Climate Change Committee (CCC) in a recent report noted important challenges that the UK (England) must address if we are to successfully meet 2050 net zero targets [1]. These include resource efficiency and energy efficiency, e.g., heat [2] with the reduction in demands for energy across the economy. We must also make societal choices that lead to a lower demand for carbon-intensive activities, while technological solutions include extensive electrification, particularly of transport and heating, supported by a major expansion of renewable and other low-carbon power generation. We must consider the development of a hydrogen economy to service demands for some industrial processes, for energy-dense applications such as long-distance HGVs and ships, and for electricity and heating in peak periods. Carbon capture and storage (CCS) in industry, with bioenergy for greenhouse gas (GHG) removal from the atmosphere and very likely for hydrogen and electricity production, is being actively pursued. In terms of population and economy, England as part of the United Kingdom is the largest economy and the largest energy supplier/user and therefore, despite regional autonomy in energy policy, its actions and responses will likely influence regional responses to energy decarbonisation, through national policies and scale of economy.

The CCC has also recently examined Northern Ireland [3] as a devolved region in terms of its response to decarbonisation targets. Its conclusions are that Northern Ireland has some concepts as to how to decarbonize across seven identified areas, namely "Nature", "Working Lands & Seas", "Food Security", "Transport", "Towns & Cities", "Business", and "Community Preparedness & Response". The report notes that there has been limited or no progress in "Energy", "Health", "Water Supply", "Buildings", "Telecoms & IT", and "Finance". While this paper will focus on energy, other aspects will be drawn into the discussion as required to attempt to create a pathway, at least at a city level, for deployment of integrated energy approaches to decarbonisation.

Considering the decarbonisation challenges (and subsequent gas price rises due to international conflicts), UK energy policy has responded with "Powering up Britain" [4]. Supported aspects include Renewable Energy, an Insulation program, Electric Vehicles, Heat Pumps, Hydrogen, Nuclear power, and Carbon Capture and Storage (CCS) (i.e., continuing use of fossil fuel technology). Not obviously supported aspects in this document include Sustainable Transport, Business Energy, and Resource Efficiency. Therefore, this paper will attempt to bring forward relevant solutions that build on these recommendations, and the recommendations of the CCC, and consider how such approaches can be deployed in Northern Ireland and supply the city of Belfast.

Finally, the Belfast metropolitan area has a population of 643,000 but the actual city of Belfast has a population of 288,000 [5], which implies considerable movement in and out of the city for work, recreation, and education. Thus, while transport is of interest, Figure 1 reveals the energy used for the city.

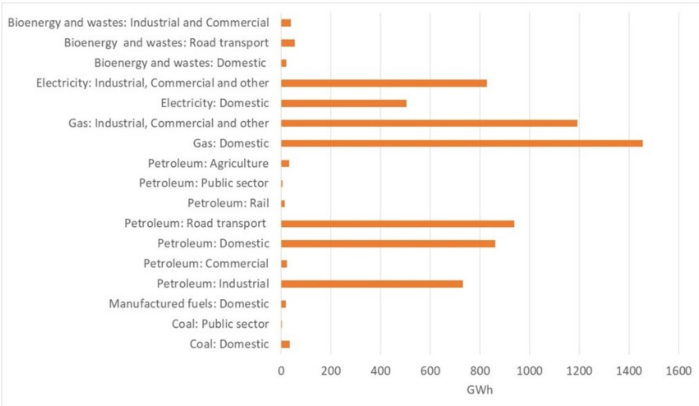

Figure 1. Detailed Breakdown of Belfast Annual Energy Data [5].

These data can be summarized into our three main silos as shown in Figure 2.

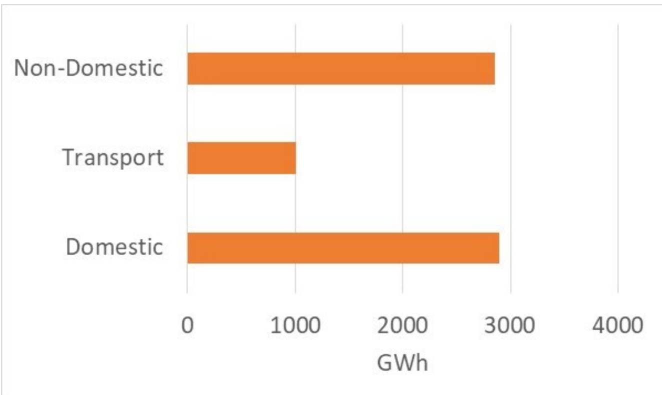

Figure 2. Summary of Belfast annual energy data [5].

In the context of Northern Ireland, the electricity mix [6] approaches 4000 GWh of renewable electricity (primarily from wind) which accounts for over half of our electricity consumption. This is not without its problems, and a stable electricity supply is maintained through wind curtailment and dispatching downwind-derived electricity supply. The System Operator of Northern Ireland (SONI) reports that "curtailment and constraint" is of the order of 300 GWh annually [7]. Therefore, it is recognized that extensive electrification, particularly of transport and heating, supported by a major expansion of renewable and other low-carbon power generation, will address aspects of curtailment and constraint if there is future investment in electricity networks, such as the current approaches to link Northern Ireland's extensive wind power (typically in its western counties) to the major conurbations of the eastern side [8]. However, across the UK in general, the CCC have noted a "lack of urgency" to address these issues [9].

It is now established that Northern Ireland has significant wind power integration challenges, currently being addressed by electricity network constraints and wind power curtailment [10]. There are plans to strengthen the electricity network, and storage has been muted, e.g., batteries, etc. as well as hydrogen as part of transport and energy supply for high-temperature heat sources for manufacturing and possibly part of the power generation mix. This is in addition to biogas (given the agricultural strength of Northern Ireland) and Northern Ireland's new gas network, which at the distribution level at least consists of high-density polyethylene pipes, are being considered for the possibility of carrying hydrogen [11]. Therefore, Northern Ireland has a mix of options, and it may be the additionalities that govern the ultimate deployment of technologies.

2. Energy Options

Referring again to the Climate Change Committee and is March 2023 report to the UK Parliament "Progress in Adapting to Climate Change" [12], the following aspects were noted:

- resource and energy efficiency that reduce demand for energy across the economy.
- societal choices that lead to a lower demand for carbon-intensive activities.
- extensive electrification, particularly of transport and heating, supported by a major expansion of renewable and other low-carbon power generation.
- development of a hydrogen economy to service demands for some industrial processes, for energy-dense applications in long-distance HGVs and ships, and for electricity and heating in peak periods.
- carbon capture and storage (CCS) in industry, with bioenergy (for GHG removal from the atmosphere), and very likely for hydrogen and electricity production.

Again, referring to the CCC in "Determining a Pathway to Net Zero" [12], the following points are noted:

- Demand reduction—can we engage in less carbon-intensive activity without making people worse off?
- Improved efficiency—can we maintain the same level of activity with less waste?
- Electrification—can we use low-carbon electricity instead of fossil fuels to power the activity?
- Hydrogen—if the energy use cannot be electrified, can we use low-carbon hydrogen instead?
- Carbon capture—if we can't avoid emissions, can we capture them and store them safely?
- Removals—for any remaining emissions, we need to remove an equivalent amount from the atmosphere to meet Net Zero.

Finally, the CCC refers to these (and other) actions as a "moving towards a circular economy" [13], and a circular economy approach will be addressed in this study through looking at linking energy supplied, e.g., renewable energy, waste heat etc., to energy required, e.g., electricity, heat etc. Figure 3 summarizes the suggested options for the decarbonisation of Belfast, or at least its starting point.

For domestic applications, the domestic heat demand is 2393 GWh in Belfast, and the average UK heating season is 5.6 months. With approximately 140,000 households and a price range for cavity wall insulation being £520 to £2300 per home [14], the costs range from £72,000,000 to £320,000,000 for the housing stock. With savings equating to £300 to £600/year/home, an annual saving of £42,000,000 to £84,000,000 could be achieved. In addition, extrapolating the data from De Urquia [15] regarding UK home insulation retrofit jobs, such home insulation employment, can create 7000 jobs in Belfast alone at a sustainable, secure rate when aiming for 2050 net zero targets. With an average of £50,000 Gross Value Added per job as a guide [16], this is a considerable opportunity to become a major employer and influence in a regional city.

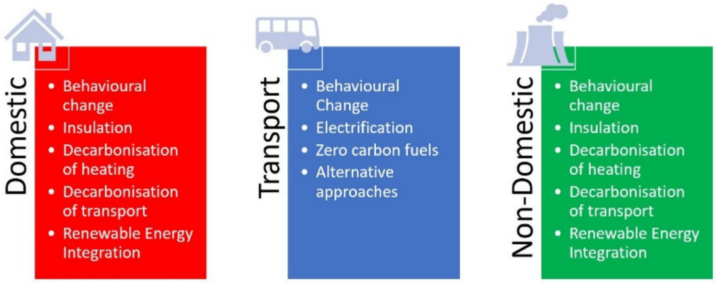

Figure 3. An options summary for city decarbonisation.

Decarbonisation of heating has several options. UK heat pump policy is focused on 600,000 heat pump installations per year by 2028 [17], but this does not appear to align with a strong policy and support for insulation. The "Great British Insulation Scheme" [18] provides £1 billion for 300,000+ homes, which may act as a stimulus package and a route to best practice and "hard to treat" properties but is insufficient for the entire building stock of approximately 25 million properties.

Therefore, a heat pump target that does not engage with a home insulation policy may oversize heating systems if an insulation plan develops later. However, current climate trends (predicted by the UK's Met Office) see Northern Ireland's mean winter temperature rising by up to 2.6 °C [19]. Therefore, with overheating in summer (where a rise of up to 3 °C is predicted), there may not be a strong case for deep insulation, but rather some intermediate pathway. In such an envisioned pathway, a currently correctly sized heating system would suffice for the duration of its lifetime and the emphasis would be on reducing the curtailment and constraint of wind power and increasing heat pump performance, i.e., when coupled with thermal storage and future heat networks. If future electricity market structures could reflect uses of curtailed and constrained wind power in a form of "social tariff" and reduced electricity pricing to manage the variability of wind power (and other renewables), a dynamic tariff as suggested by, e.g., Freier and von Loessl [20] can be designed that overcomes cost barriers for technology adoption. For the 600,000 heat pumps proposed per year by 2028, the benefit to the UK economy is estimated to be £5.5 billion [21].

A current air-source and ground-source domestic heat pump field trial carried out by UK Catapult illustrates performances across a sample of 750 homes and indicates a strong likelihood that with appropriate measures, e.g., larger hydronic radiators, etc., all homes in the UK have the possibility of successfully deploying a heat pump. Figure 4 is a snapshot of the 2-min data taken from one of these homes [22]. Assuming a Seasonal Performance Factor of 2.5 (ratio of annual heat required versus annual electricity required), displacing the 1400 GWh of domestic gas required by Belfast with air-source heat pumps would lead to an increased demand for electricity consumption of approximately 560 GWh. Thus, a review of the local electricity distribution network would be required.

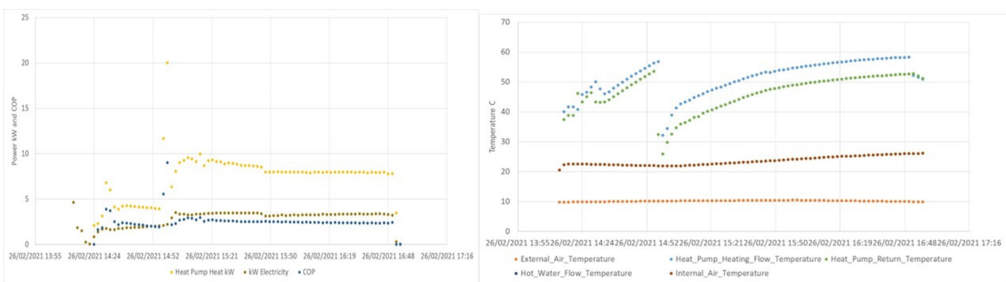

Figure 4. Heat performance (**Left**) and operating conditions (**Right**) for an example UK house trial [22].

For the decarbonisation of transport, Figure 5 illustrates the annual journey by type of vehicle taken in Belfast [23]. As a major employment hub (with two universities), there is a significant commuter profile to these journeys, primarily by car and over 20 million bus passenger journeys per year. The public bus network (under the banner of Translink and directly controlled by the Northern Ireland regional government), has begun a trial of electric and hydrogen buses with double-decked commuter buses. The electric and hydrogen (fuel cell) versions carry up to 64 passengers for a range of about 200 miles. With an average bus use of 180 miles per day within the Northern Ireland Translink bus fleet, this seems reasonable. The hydrogen bus at a typical hydrogen price of £3 per kg would cost approximately £180 per refueling and can be refueled in 7 min. The electric version has a fast charge time of 2.5 h and would cost £133 per charge. Therefore, for both options, effectively acting as a form of electricity storage, there would be a need to bring the electricity from the curtailed and constrained parts of western Northern Ireland to the demand center of the east (Belfast).

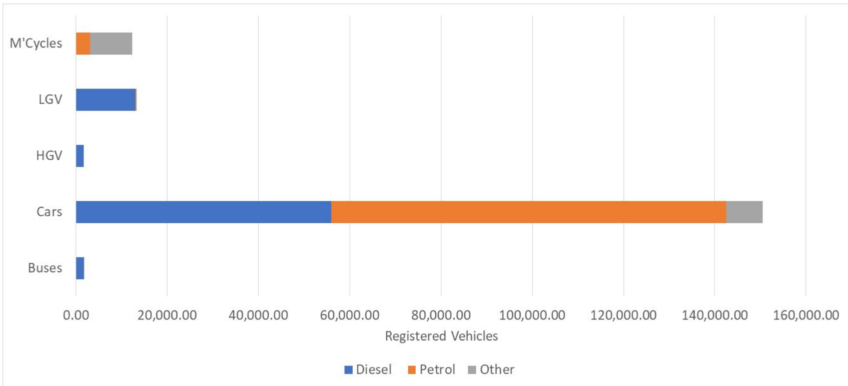

Figure 5. Belfast transport statistics [23].

Figure 6 illustrates the capacities of the primary electricity substations in Northern Ireland [24]. While Belfast has additional capacity for larger-scale connections (green points) for battery charging points and, for example, proton exchange membrane electrolyzers for hydrogen production, the west of Northern Ireland (i.e., the left-hand side of the figure) has a higher proportion of "red" sub-stations with capacity limitations. This is of course a contributor to wind curtailment and constraint in that there is not the ability to move this electricity to the demand centers.

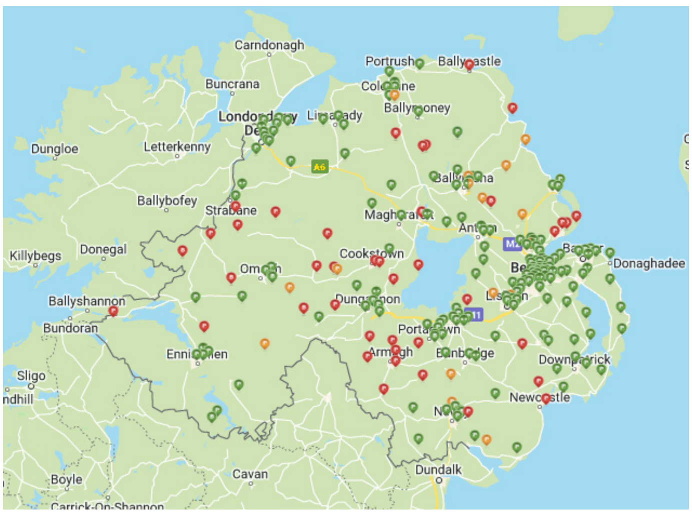

Figure 6. Substation capacity map with red indicating a lack of capacity and green indicating headroom for electricity demand growth [24].

Electrification of transport (particularly private vehicles) is an option for decarbonisation (as well as improved air quality) in our cities. Newbuilt homes (in England) must have a charge point incorporated in them as of June 2022. All new nonresidential buildings with more than 10 parking spaces must have a minimum of one charge point and cable routes for one in five (20%) of the total number of spaces. All nonresidential buildings undergoing a major renovation that will have more than 10 parking spaces must have a minimum of one charge point, along with cable routes for one in five spaces [25]. But how many public charge points does Belfast require?

Assuming an average commute for the metropolitan area to Belfast's city center of approximately 20 min per journey [23], a typical electric car would use approximately 5 kWh in one day. This is cross-referenced with an average of 270 Wh/mile for a typical electric car and an average daily commute of approximately 19 miles. With 150,000 private car vehicles registered in Belfast, and with electric cars with ranges from 150 to 250 miles, charging would need to occur at least every 7 to 12 days. Therefore, using 10 days as a form of electricity network diversity factor, it could be assumed that 15,000 cars would require charging in any one day. Northern Ireland has typically 7 kW chargers at home, 22 kW public chargers, some 50 kW (Rapid) public chargers and 26 ultra rapid chargers (up to 180 kW). Typical driving experiences sees EV charging starting at 20% state-of-charge (SOC) of the battery of the car and ending at 80% SOC [26]. If home charging were used, 15,000 cars achieving 80% SOC from 20% SOC, an additional 364 MW to 607 MW instantaneous power would be required, if all this happened at a particular moment. Smart tariffs and charging are required so that, for example, utilizing a 7-h evening/night tariff with off-peak electricity supply would reduce this instantaneous demand to 52 MW to 87 MW for the smaller-to-larger electric cars charged across the city. This becomes possible when noting the available capacities of the distributed primary substations.

3. Northern Ireland and Renewable Energy

Given that Northern Ireland has a significant renewable electricity resource in wind that also suffers both constraint and curtailment to maintain a stable electricity supply, constraint (limitation in electricity network capacity) and curtailment (excess power) occurs the west of Northern Ireland.

3.1. Wind Power in the West

Our studies [27,28] realise that local storage adjacent to the wind resource will reduce fluctuations in wind electricity production. These have been carried out with NEPLAN 360 Cloud software (referred to in [27,28]), which facilitated modelling of electricity network constraints noted in [24]. NEPLAN has extensive libraries of network components, namely transmission and distribution circuits based on common international standards. Thus, the data provided in reference [24] coupled with wind farm capacities in the region and their performance profiles allowed the generation of Figure 7. Figure 7 illustrates the darker green challenging areas, where wind power is typically generated, but is consumed in the major centers of the eastern part of Northern Ireland.

Northern Ireland Electricity Networks and the Northern Ireland Utility Regulator have published outline concepts for upgrading the electricity network to meet 70% flexible renewable electricity inputs without passing on excessive costs to electricity customers up until 2030 [29,30]. However, other proposals including adjacent wind power generation with novel offshore floating wind technology are being considered. It is proposed that that may be up to 1 GW of offshore wind power in Northern Ireland, with initial production starting in the mid-2030s. For wind power in Northern Ireland, an approximation of 1 GW peak capacity may generate up to 1700 GWh annually [31]. There are challenges for landfall, but an existing connection where the Moyle Interconnector from Scotland makes landfall could be a possibility. Two proposed sites under active consideration in the first phase are North Channel Wind 1 and 2, which have a 400 MW capacity and will generate 700 GWh annually. The Moyle Interconnector now shows a considerable export aspect, where it is now used to ease Northern Ireland curtailment (Figure 8) [32].

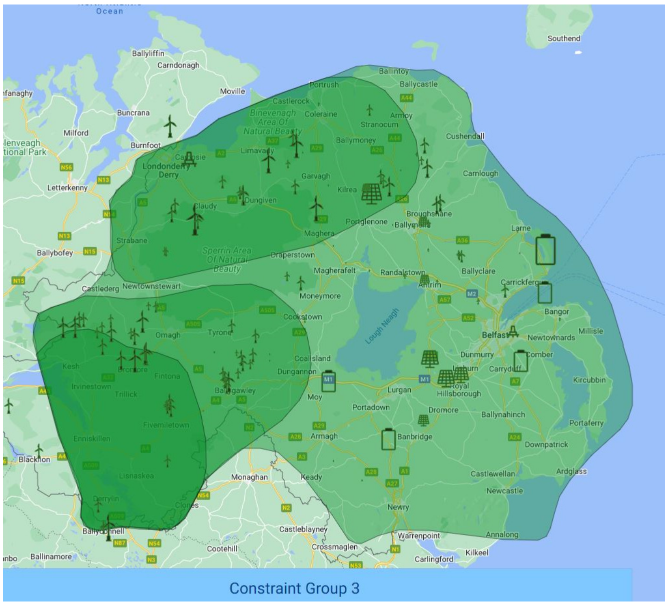

Figure 7. Northern Ireland areas of highest electricity network constraint with wind turbine and photovoltaic symbols representing wind and PV "farms" that are connected to the electricity network, and battery symbols indicating electricity storage (batteries).

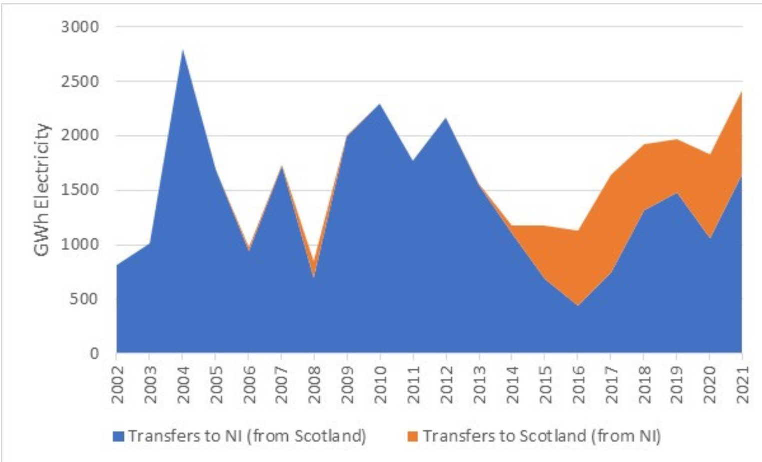

Figure 8. Performance of the Moyle Electricity Interconnector to Scotland [31].

3.2. Hydrogen Belfast

Several options are being considered for hydrogen supply and usage in addition to transport. The Northern Ireland gas network is one of the most recently constructed gas networks in Europe and is illustrated in Figure 9. Polyethylene pipes are considered suitable for hydrogen transport up to 2 bar [33]; this may only facilitate hydrogen use in the local distribution network (<7 bar) and not the intermediate pressure network (7 bar) or the transmission network (55 bar). Therefore, there is a concern that, for example, local electrolyzers can only serve local needs and pressure and leakage will become a concern at higher pressures. If we also exclude hydrogen for domestic heating purposes [34], transport and industrial process heating may be of interest. If the gas network pressures reduce the likelihood of its use, local production will be required.

One such solution is related to Wastewater Treatment Works (WwTW). The Belfast WwTW currently treats effluent for 400,000 population equivalent and would be an example of "Sector Coupling". According to the Urban Wastewater Treatment Directive [35], one population equivalent (PE) requires 60 g of oxygen per day, and at 200 L/person/day this leads to 400,000 PE and therefore 24,000 kg Oxygen/day. Using the following expression:

$2H_2O \rightarrow 2H_2 + O_2$ e.g., 36 g of H_2O gives 4 g of H_2 and 32 g of O_2, 3000 kg of hydrogen will be produced per day. With each bus requiring 60 kg/bus/day, it leads to the fueling of 50 buses per day. However, the electrolyzers will require 120,000 kWh of electricity, which would need to be from renewable sources to call this "green" hydrogen. Therefore, use of the Moyle Interconnector and ultimately offshore floating wind power, both with their proximity to Belfast, may prove an option for the necessary electricity supply.

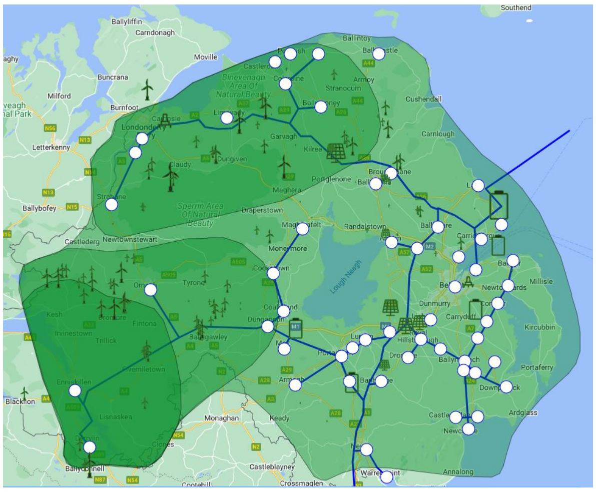

Figure 9. The Northern Ireland Gas Network with gas distribution hubs noted as white circles.

Industrial energy use in the Belfast area is significant. Two aspects where hydrogen has been considered are aircraft manufacture (e.g., carbon fiber) and cruise liner visits (as Belfast is the birthplace of the infamous and ill-fated RMS Titanic). With 170 cruise liner calls in 2023 [36], there will be a need for greater onshore power as cruise liners presents significant fossil fuel based GHG emissions when operating in port to support their on-board activities. Shipping traditionally utilizes heavy fuel oil (HFO), and its combustion leads to sulphur oxides (SOx), nitrogen oxides (NOx), heavy metals, and polycyclic aromatic hydrocarbons (PAHs). Average fuel in port per hour per ship = 677 kg HFO [37]. Assuming a marine engine efficiency at 30% and 40.9 MJ/kg for HFO, a demand of 180 MWh over a 24 h stay is anticipated. This equates to 7.5 MVA of average instantaneous power, and when addressing the available capacity of the local primary substation adjacent to the mooring points, this appears feasible. However, the challenge remains of how to bring our renewable wind-derived electricity from the west of Northern Ireland without significant electricity upgrades.

When considering aircraft manufacturing at present, the energy consumption in carbon fiber manufacturing is in the range of 100–900 MJ per 1 kg of fibers produced. This is significantly higher in comparison to some other energy-intensive industries such as steel production, which is in the vicinity of 20–30 MJ/kg. Again, taking the adjacent WwTW as a hydrogen supply, 3000 kg of Hydrogen (WwTW) and a boiler efficiency of 90%, 3000×33.33 kWh $\times 0.9 = 89{,}991$ kWh is equivalent to 323,967 MJ. This leads to 300 kg to 3000 kg carbon fiber/day (process dependent). With, for example, "each Boeing 787 aircraft contains approximately 32,000 kg", this may be a useful resource for smaller aircraft production. However, while the combustion of hydrogen does not release CO_2 into the atmosphere, the higher-temperature combustion will lead to higher levels of NOx (ultimately leading to acid rain) unless, for example, selective catalytic reduction (SCR) and selective noncatalytic reduction (SNCR) are included. Process heat recovery is possible, as many of these processes occur at over 200 °C.

Therefore, waste heat as a valuable resource must be considered. If the replacement of natural gas is considered (typically used for heating applications), a domestic annual heat demand of 1400 GWh in Belfast would be required. Given that the average UK heating season is 5.6 months and that central heating in the UK was operated typically 7.5 h per day, and adopting the Danish best practice in district heating networks of this type where a heat network will have a diversity factor of 0.6, the average instantaneous heat demand is 0.65 GW. Assuming a 70% efficient electrolyser meeting all bus fleet needs in Belfast, it will deliver approximately 1.77 GWh/day, which would in turn deliver approximately 1/3rd of the heat required. Other waste heat or heat pump sources are needed.

3.3. Renewable Belfast

The final analysis is based on renewable energy deployment to and within the city of Belfast. One technology under consideration is biogas. Biogas will be derived from the significant agriculture industry of Northern Ireland, which typically produces 11 million tonnes of manures annually [38]. In addition, Northern Ireland produces 8 million tonnes of silage annually, primarily to feed the 1.7 million cows that underpin the major meat and dairy industries. With an "average" cow consuming over one tonne of silage per month across winter period, most silage is consumed. With Northern Ireland consuming about 6000 GWh of natural gas per year, i.e., 21,600,000,000 MJ, most manures in Northern Ireland are derived from cattle [39]. With cattle manure delivering 22 m^3/tonne (fresh weight) of biogas, our cattle will produce 22 m^3 times 11,000,000 tonnes, leading to 242,000,000 m^3 of gas. With a typical calorific value 20 MJ/kg and density 0.6 kg/m^3, this will lead to 2,904,000,000 MJ of biogas, i.e., 13% of Northern Ireland's needs, or over half of the natural gas needs of Belfast, when such gases are injected into local gas infrastructure. Poultry waste will provide a further 4% of Northern Ireland's needs, while food waste will provide a further 1%. Therefore, such biogas may be a useful resource but is reliant on current farming practices. A future vegetarian society would facilitate silage use in anaerobic digestion, realizing up to 6 times increase in gas production without significant change to land use (although natural fertilizer sources would need to be applied).

Finally, many cities should deploy photovoltaic (PV) panels. The city of Leeds (UK) was used as an example of wide-scale, rapid assessment using LIDAR [40]. The population of Leeds is approximately double that of Belfast, and the potential for PV assessed through LIDAR has been noted, with an accuracy of 81%. Using a simple assumption that Belfast will be half this power as it has approximately half the population of Leeds, Belfast could deliver 500 GWh annually. This appears almost to meet the domestic electricity demand of Belfast, but the role of energy storage would require full exploration, both locally for diurnal use (e.g., batteries) and for seasonal use (hydrogen, compressed air, etc.).

Considering domestic battery storage, the maximum solar array permitted is 3.96 kW peak solar array. Assuming an average 3.5 h of solar energy per day in the UK, approximately 14 kWh of electricity can be stored. If appliances can be operated during periods when the PV array is in use, a battery size of between 6 kWh and 8 kWh would be required for non-solar times. At approximately £11,000 for a PV/Battery arrangement such as this, the paybacks are for those householders who are occupying their "forever" home.

3.4. Decarbonisation Cost Esitimates

The pathways explored in the preceding analysis have realized potential solutions to decarbonizing a city, and there now follows a summary of the possible costs involved in achieving this. This analysis has considered aspects of energy efficiency and renewable energy, leading to electrification, hydrogen production, and biogas as potential energy vectors within the city. This analysis has considered aspects of domestic, transport, and nondomestic energy use.

For household insulation, the cost of insulating 140,000 houses would range between £73 M and £320 M. Savings would range from £42 M to £84 M annually, so simple payback is very favorable, ranging from 1.7 years to 4 years. The approximate 7000 jobs required to implement such a program also contribute over £350,000 per year, but the challenge is that of the affordability of finance. At a 6% interest rate, this appears to add one extra year to the simple payback analysis.

The electrification of heating with, for example, air-source heat pumps with current electricity prices does not deliver cost savings. They do however, deliver significant carbon reductions (over 180,000 tonnes of CO_2 if deployed across the whole housing stock when compared to natural gas boilers), but such a deployment would require a substantial capital cost of over £420 M. Such funding may require heat (air source heat pumps in this case) being delivered as a service style contract where carbon savings and demand side response for wind power are costed benefits.

District heating (e.g., lower-temperature fourth- and fifth-generation approaches) may realize space heating needs. Such a network requires areas of heat density above 150 TJ/km^2 [41] in the first instance, and areas of Belfast within that category are noted in Figure 10, (derived from [42]).

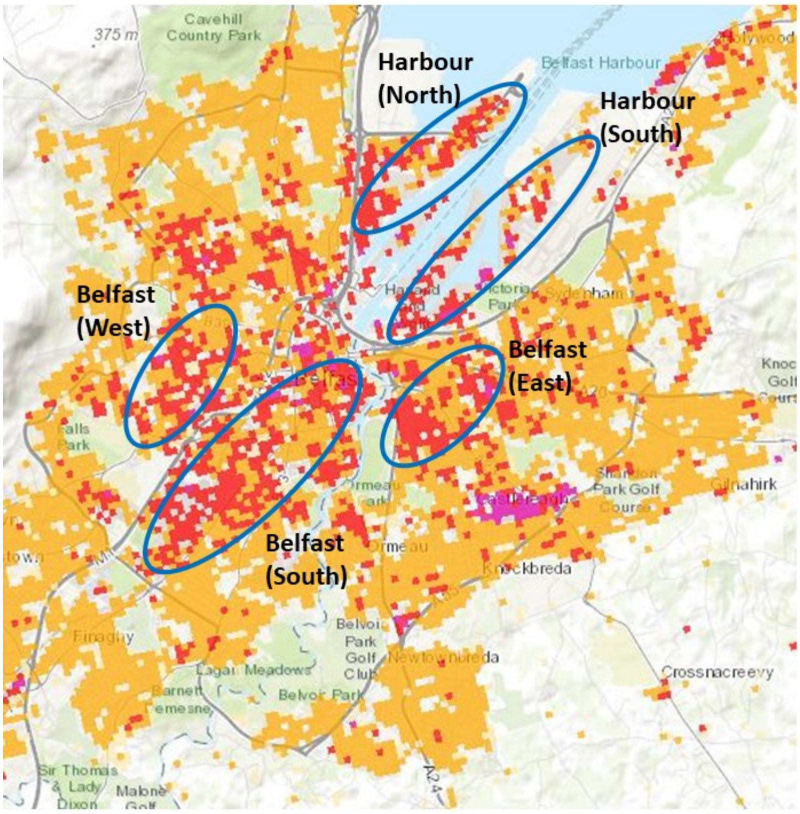

Figure 10. Proposed heat network areas of interest (adapted from [42]).

Table 1 illustrates the likely costs of such installations, based on costs derived from the Sustainable Energy Authority of Ireland [43], illustrating a two-pipe system (running into each building for heating and domestic hot water) or a four-pipe system (two pipes for heating and two pipes for domestic hot water).

Table 1. Capital cost estimations of heat networks [43].

			2 Pipe	4 Pipe
Heat Network	**km^2**	**Length km**	**Capital Lo £**	**Capital Hi £**
Harbour North	1.91	3.247	£1,623,500.00	£4,870,500.00
Harbour South	3.41	5.797	£2,898,500.00	£8,695,500.00
Belfast West	4.75	8.075	£4,037,500.00	£12,112,500.00
Belfast South	5.24	8.908	£4,454,000.00	£13,362,000.00
Belfast East	2.51	4.267	£2,133,500.00	£6,400,500.00
Totals	**17.82**	**30.294**	**£15,147,000.00**	**£45,441,000.00**

Finally, the electrolyser for green hydrogen could be a proton exchange membrane type (80 °C hot water as waste heat) or a solid oxide type (400 °C as waste heat). The latter would be useful for the process-heating applications noted previously, would be of the order of 10 MW in capacity, and would be of the order of £10 M in capital costs.

4. Discussion

In attempting to decarbonise a city, the view has been taken that:

1. Local energy resources are used, i.e., those in Northern Ireland. Northern Ireland has an immense wind resource and an emerging solar resource, but the electricity network requires (and is getting) upgrading to deliver this electricity.
2. Energy efficiency is ultimately very important but may not be applied as it is very cost dependent. However, long-term sustainable employment and relatively short paybacks are overlooked as a future investment possibility. In considering the whole energy package for a city, energy-systems thinking is often not considered, i.e., reductions in heat demand due to increased insulation leading to less decarbonized heat in the future.
3. Hydrogen is a possibility, but often analysts do not consider the green (renewably derived) electricity required to deliver "green" hydrogen. Furthermore, if hydrogen is used in a combustion process, the NOx emissions arising from high-temperature combustion will ultimately add to the acid rain phenomenon. Capital cost, safety, and reliability also remain serious questions.
4. Heat pumps need a stronger electricity network and may require some building upgrading. They can decarbonise both process and space heating. However, while natural gas remains relatively inexpensive (which is a current need to combat fuel poverty, etc.), the efficiency of a heat pump and its emissions savings will be partially overshadowed by operating costs and capital costs. Electricity tariffs (derived from variable wind power and to manage wind-derived electricity curtailment and constraint) and thermal storage would deliver lower operating costs and possibly a lesser electricity network upgrading requirement.
5. Biogas from cattle and other farm animals and silage is useful, but there may not be enough. Farming practice and responses to dietary changes, e.g., vegetarianism, may change the fuel mix (i.e., allow more silage and fewer manures). More silage would increase the gas volume available, as would tighter controls of the diet of cows. However, biogas is a useful resource for both direct use, stored via line-pack storage for example, and use in the existing gas electricity generating plant when renewable energy such as wind and solar is not available.
6. Photovoltaics (and batteries or other forms of storage) need full economic costings.
7. Wind power was heavily subsidized without taking into consideration what happens when the power is not required i.e., we turn off wind electricity (curtailment). Electricity storage (whether short term, e.g., batteries or long-term, e.g., compressed air, hydrogen, etc.)
8. Electric vehicles will need a smart charging infrastructure and local distribution analysis to facilitate operation. This could be part of the short-term electricity storage capacity we need, if vehicle electrification continues to grow.
9. Heat recovery and heat networks may prove very useful but will need optimized routes, core customers, and cooperation with other heat sources, such as the emerging geothermal resource.

Therefore, to conclude, linking technologies to decarbonise a city has many gaps, and while it is possible to perform individual technology analyses, the science of system integration is still in its infancy, at least in the UK sense.

5. Conclusions

The decarbonisation pathway of a city such as Belfast has only been started. The largest challenge is to integrate individual approaches into a systemwide approach. Supporting funding from local and national levels encourages a siloed approach due to lack of systemwide thinking. It may be up to the local city and community planners to develop such thinking on behalf of the government. However, the levels of funding required are significant, and the inclusion of new jobs in manufacture and deployment of such a system may be aligned to future "green growth" strategies.

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References

1. Climate Change Committee. *Progress in Adapting to Climate Change, 2023 Report to Parliament*; Climate Change Committee: London, UK, 2023.
2. Rosenow, J.; Guertler, P.; Sorrell, S.; Eyre, N. The remaining potential for energy savings in UK households. *Energy Policy* **2018**, *121*, 542–552. [CrossRef]
3. Climate Change Committee. *Adapting to Climate Change-Progress in Northern Ireland*; Climate Change Committee: London, UK, 2023.
4. Powering Up Britain, ISBN 978-1-5286-4017-6, March 2023, 30 Pages. Available online: https://assets.publishing.service.gov.uk/media/642468ff2fa8480013ec0f39/powering-up-britain-joint-overview.pdf (accessed on 20 April 2023).
5. Energy Statistics. Available online: https://www.nisra.gov.uk/ (accessed on 20 April 2023).
6. Energy in Northern Ireland. Available online: https://www.economy-ni.gov.uk/sites/default/files/publications/economy/Energy-in-Northern-Ireland-2022.pdf (accessed on 20 April 2023).
7. Wind Historical Curtailment. Available online: https://www.soni.ltd.uk/media/documents/Wind-DD-Historical-Jul-2023.png (accessed on 20 April 2023).
8. SONI Launch Mid-Antrim Upgrade Project to Strengthen the Electricity Grid. Available online: https://www.soni.ltd.uk/newsroom/press-releases/soni-launch-mid-antrim-up/ (accessed on 20 April 2023).
9. Available online: https://www.theccc.org.uk/publication/2023-progress-report-to-parliament/ (accessed on 20 April 2023).
10. Agbonaye, O.; Keatley, P.; Huang, Y.; Odiase, F.O.; Hewitt, N. Value of demand flexibility for managing wind energy constraint and curtailment. *Renew. Energy* **2022**, *190*, 487–500. [CrossRef]
11. Clean Hydrogen Development. Available online: https://sibni.org/project/clean-hydrogen-development/ (accessed on 20 April 2023).
12. Reducing UK Emissions: 2020 Progress Report to Parliament. Available online: https://www.theccc.org.uk/publication/reducing-uk-emissions-2020-progress-report-to-parliament/ (accessed on 20 April 2023).
13. CCC Insights: Determining a Pathway to Net Zero. Available online: https://www.theccc.org.uk/wp-content/uploads/2023/01/CCC-Insights-Briefing-Determining-a-pathway-to-Net-Zero.pdf (accessed on 20 April 2023).
14. Cavity Wall Insulation. Available online: https://energysavingtrust.org.uk/advice/cavity-wall-insulation/ (accessed on 20 April 2023).
15. De Urquia, B.V. Insulating UK homes could save the country 'billions' assessments show. *Eng. Technol.* **2022**, *17*, 10. [CrossRef]
16. Creating a Good-Jobs Economy in the UK. Available online: https://economy2030.resolutionfoundation.org/wp-content/uploads/2023/07/Creating-a-good-jobs-economy-1.pdf (accessed on 20 April 2023).
17. Energy Security Bill Factsheet: Low-Carbon Heat Scheme. Available online: https://www.gov.uk/government/publications/energy-security-bill-factsheets/energy-security-bill-factsheet-low-carbon-heat-scheme#:~:text=Why%20is%20a%20scheme%20like,transition%20to%20low-carbon%20heat (accessed on 20 April 2023).
18. Apply for Support from the Great British Insulation Scheme. Available online: https://www.gov.uk/government/publications/more-help-to-improve-the-energy-efficiency-of-your-home-through-the-great-british-insulation-scheme/great-british-insulation-scheme#:~:text=The%20Great%20British%20Insulation%20Scheme%20is%20a%20new%20government%20scheme,and%20run%20until%20March%202026 (accessed on 20 April 2023).
19. UK Climate Projections (UKCP). Available online: https://www.metoffice.gov.uk/research/approach/collaboration/ukcp (accessed on 20 April 2023).
20. Freier, J.; von Loessl, V. Dynamic electricity tariffs: Designing reasonable pricing schemes for private households. *Energy Econ.* **2022**, *112*, 106146. [CrossRef]
21. O'Regan, N. Supply Change. Seizing Opportunity in the UK Heat Pump Supply Chain. The Social Market Foundation. 2023. Available online: https://www.smf.co.uk/publications/uk-heat-pump-supply-chain/ (accessed on 10 September 2023).
22. Electrification of Heat UK Demonstration Project. Available online: https://es.catapult.org.uk/project/electrification-of-heat-demonstration/ (accessed on 20 April 2023).
23. Northern Ireland Transport Statistics. Available online: https://www.infrastructure-ni.gov.uk/system/files/publications/infrastructure/ni-transport-statistics-2020-2021.pdf (accessed on 20 April 2023).

24. Network Capacity Map. Available online: https://www.nienetworks.co.uk/connections/capacity-map (accessed on 20 April 2023).
25. Approved Document S: Infrastructure for Charging Electric Vehicles, Frequently Asked Questions. Available online: https://www.gov.uk/guidance/approved-document-s-infrastructure-for-charging-electric-vehicles-frequently-asked-questions (accessed on 20 April 2023).
26. Kostopoulos, E.D.; Spyropoulos, G.C.; Kaldellis, J.K. Real-world study for the optimal charging of electric vehicles. *Energy Rep.* **2020**, *6*, 418–426. [CrossRef]
27. Ademulegun, O.O.; Keatley, P.; Hewitt, N.J. Techno-economic analysis of energy storage within network constraint groups for increasing the share of variable renewable energy. *Electr. J.* **2021**, *34*, 106974. [CrossRef]
28. Agbonaye, O.; Keatley, P.; Huang, Y.; Ademulegun, O.O.; Hewitt, N. Mapping demand flexibility: A spatio-temporal assessment of flexibility needs, opportunities and response potential. *Appl. Energy* **2021**, *295*, 117015. [CrossRef]
29. A Future Network for All. Available online: https://www.nienetworks.co.uk/documents/future_plans/rp7-business-plan-summary-april-2023.aspx (accessed on 20 April 2023).
30. NIE Networks RP7 Price Control: Our Approach. Available online: https://www.uregni.gov.uk/files/uregni/documents/2022-07/2022-07-06%20RP7%20final%20Approach%20Document%20final.pdf (accessed on 20 April 2023).
31. Department for the Economy and The Crown Estate publish a Statement of Intent. Available online: https://www.economy-ni.gov.uk/news/department-economy-and-crown-estate-publish-statement-intent (accessed on 20 April 2023).
32. Mutual Energy: Annual Report 2023. Available online: https://www.mutual-energy.com/wp-content/uploads/2023/08/3119-Mutual-Energy-Annual-Report-2023-D5-FINAL.pdf (accessed on 20 April 2023).
33. Hermkens, R.J.M.; Colmer, H.; Ophoff, H.A. Modern PE Pipe Enables the Transport of Hydrogen. In Proceedings of the 19th Plastic Pipes Conference PPXIX, Las Vegas, NV, USA, 24–26 September 2018.
34. Rosenow, J. Is heating homes with hydrogen all but a pipe dream? An evidence review. *Joule* **2022**, *6*, 2225–2228. [CrossRef]
35. Urban Wastewater. Available online: https://environment.ec.europa.eu/topics/water/urban-wastewater_en (accessed on 20 April 2023).
36. Belfast Harbour to Welcome 170 Cruise Calls in 2023. Available online: https://www.belfast-harbour.co.uk/news/belfast-harbour-cruise-2023/ (accessed on 20 April 2023).
37. Simonsen, M.; Gössling, S.; Walnum, H.J. Cruise ship emissions in Norwegian waters: A geographical analysis. *J. Transp. Geogr.* **2019**, *78*, 87–97. [CrossRef]
38. Mehta, N.; Anderson, A.; Johnston, C.R.; Rooney, D.W. Evaluating the opportunity for utilising anaerobic digestion and pyrolysis of livestock manure and grass silage to decarbonise gas infrastructure: A Northern Ireland case study. *Renew. Energy* **2022**, *196*, 343–357. [CrossRef]
39. Smith, K.A.; Williams, A.G. Production and management of cattle manure in the UK and implications for land application practice. *Soil Use Manag.* **2016**, *32*, 73–82. [CrossRef]
40. Jacques, D.A.; Gooding, J.; Giesekam, J.J.; Tomlin, A.S.; Crook, R. Methodology for the assessment of PV capacity over a city region using low-resolution LiDAR data and application to the City of Leeds (UK). *Appl. Energy* **2014**, *124*, 28–34. [CrossRef]
41. O'Shea, J.; Gartland, D.; Hayden, J. Transition Roadmap for Developing District Heating in South Dublin, Interreg NWE HeatNet NWE Report. 2019. Available online: https://www.codema.ie/images/uploads/docs/HeatNet_NWE_Transition_Roadmap_Report_Final_-_Digital.pdf (accessed on 10 September 2023).
42. Irish Heat Atlas Version 2.1. Available online: https://euf.maps.arcgis.com/apps/webappviewer/index.html?id=101b7da79a7d4e09a92402bd4ce8384c (accessed on 20 April 2023).
43. National Heat Study. Available online: https://www.seai.ie/data-and-insights/national-heat-study/ (accessed on 20 April 2023).