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Review

Energy Supply Potentials in the Northern Counties of Finland, Norway and Sweden towards Sustainable Nordic Electricity and Heating Sectors: A Review

Robert Fischer * , **Erik Elfgren and Andrea Toffolo**

Energy Engineering, Luleå University of Technology, SE-97187 Luleå, Sweden; erik.elfgren@ltu.se (E.E.); andrea.toffolo@ltu.se (A.T.)

* Correspondence: robert.fischer@ltu.se; Tel.: +46-920-49-1454

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Abstract: The lands in the northernmost corner of Europe present contradictory aspects in their social and economic development. Urban settlements are relatively few and small-sized, but rich natural resources (minerals, forests, rivers) attract energy-intensive industries. Energy demand is increasing as a result of new investments in mining and industries, while reliable energy supply is threatened by the planned phase out of Swedish nuclear power, the growth of intermittent power supplies and the need to reduce fossil fuel consumption, especially in the Finnish and Norwegian energy sectors. Given these challenges, this paper investigates the potentials of so far unexploited energy resources in the northern counties of Finland, Norway and Sweden by comparing and critically analyzing data from statistic databases, governmental reports, official websites, research projects and academic publications. The criteria for the technical and economic definition of potentials are discussed separately for each resource. It is concluded that, despite the factors that reduce the theoretical potentials, significant sustainable techno-economic potentials exist for most of the resources, providing important insights about the possible strategies to contribute to a positive socio-economic development in the considered regions.

Keywords: potentials; energy supply; renewable sources; Nordic countries

1. Introduction

The northern counties of Finland (“Lapland”), Norway (“Finnmark”, “Troms” and “Nordland”) and Sweden (“Norrbotten”) have some very distinctive features, among which sub-arctic climate, low population density and small municipalities and settlements that are separated by long distances are prominent (see Figure 1). The main economic activities are forestry industries, pulp and paper and related chemical industries, mining and ore processing, iron and steel industries, reindeer herding, fishing and tourism. The climatic conditions and the energy intensive industries make the energy consumption in the electricity and heating sectors higher than the national averages. For instance, the heating demand of a standard residential home and the electricity demand per capita are about double of those in the southern regions of these Nordic countries [1,2].

Future trends for the demand in the electricity and heating sectors present some challenging aspects as well. The development of unexplored mineral resources and the implementation of the expressed political will to re-industrialize the Nordic countries will increase electricity demand (e.g., the expected establishment of new datacenters in Norrbotten will increase the annual Swedish electricity demand by 4–5 TWh or 3%) [3–5]. The vision of developing strong bio-based economies will require additional biomass resources from forests to be utilized for bio-based products including transport fuels, chemicals, construction materials, iron and steel and other materials such as textiles and plastics [6]. The recent hydrogen-based research in low- or zero-emission iron production has the potential to increase electricity demand from the iron and steel industry by a factor of 15, from 235 kWh/ton crude steel to 3488 kWh/ton [7], while about 50% of the Swedish crude steel production (4962 ktons in 2017) is located in Norrbotten [8]. The other low-emission alternative, i.e., bio-based iron and steel production, would increase the demand of biomass [9]. Municipalities in these counties are also pro-active in attracting people and industries to move to the North in order to counteract the demographic situation of ageing and decreasing population.

Figure 1. Map including the northern counties of Finland ("Lapland"), Norway ("Finnmark", "Troms" and "Nordland") and Sweden ("Norrbotten") and cities of the counties with a population >10,000. (• Administrative centre; ° city). Source: Google Earth. US Dept of State Geographer © Google Earth. Image IBCAO. Image Landsat/Copernicus. Adapted by authors.

In addition to such envisioned economic developments the electricity and heat supply situation in Finland is already under pressure due to the large dependency on imported electricity [10], and due to the need of replacing the shares of energy peat and other fossil fuels used in these sectors in order to fulfill the country's emission reduction commitments. In Norway, increased export of electricity to the rest of Europe is an opportunity to counterbalance a potential decline of oil and gas revenues and requires investments in new generation capacity from hydropower and wind [11]. Sweden faces the potential shutdown of three out of nine nuclear reactors by 2020 and a total nuclear phase out by 2045 according to current policies [12]. These base load capacities will have to be replaced and, in addition, peak and load balancing capacities will have to be installed to ensure a reliable electricity supply, which is also challenged by the increase of intermittent electricity generation. Finally, all three countries have the ambition to reduce fossil fuels in the transport sector, where electricity, biogas and biofuels are the possible substitutes.

Although an overall picture has not been provided yet on how these challenges and possible developments will affect the energy demand in the future, the motivation is strong to explore the additional energy supply potentials in the northern counties of Finland, Norway and Sweden. These counties play an important role in securing the energy supply of their respective countries with the currently exploited hydropower, biomass and wind resources. Compared to similar studies in the literature, this paper provides a comprehensive investigation in the selected counties on the energy supply alternatives that are currently most relevant, including an overview of the energy integration potential between industries and municipal energy utilities. Accordingly, insights are offered about the possible strategies to both expand current energy supply and to retain or improve energy security in a sustainable manner.

This paper explores technical energy supply potentials, which are also economically feasible under current and near-future market conditions. Providing a definition for technically and economically feasible "potential" that is consistent for different energy resources is, however, a difficult exercise. In the studies from the open literature, the factors applied by the authors to limit the theoretical potential of a given energy resource depend on the scope of the study and the nature of the specific resource. More details on the criteria applied here to limit the theoretical potential of a specific energy resource are given in the corresponding dedicated subsections of this paper. As the paper is focused on the counties of Lapland (Finland), Finnmark, Troms and Nordland (Norway) and Norrbotten (Sweden), the intention is to present information on such potentials in these counties only if sufficient data are available.

Sections 2 and 3 provide a background of the current energy supply situation in the electricity and heating sectors and an overview of the national energy and climate policies in the three Nordic countries, respectively. Data on energy demand and supply, installed capacities and utilized resources are derived from official reports from national energy agencies and statistic databases at national (STAT.FI, SSB.NO, SCB.SE) and European (Eurostat, ENTSO-E) level. Section 4 presents the analysis of the available energy supply potentials, with separate subsections dedicated to hydropower, wind and solar energy, biomass from forestry, energy peat, waste incineration, integration with industrial energy systems and ocean energy. The analysis relies on data from academic publications, international organizations (e.g., IEA Biomass), research projects (e.g., Biomass Energy Europe (EU-BEE)), national energy agencies and other governmental authorities, industrial branch organizations. Finally, given the above mentioned peculiar distribution of urban settlements in the territory of these northern counties, Section 5 gives a brief account of the energy supply situation from the point of view of the local municipalities, derived from the information available on the official websites of municipalities and municipal energy utilities.

2. Status of Energy Supply in the Electricity and Heating Sectors

The gross final energy consumption (GFEC) and the electricity and the heating and cooling sectors in Finland, Norway and Sweden all feature renewable energy shares above the EU28 averages in 2015 (see Table 1 [13,14]).

Table 1. Shares of renewable energy in the gross final energy consumption (GFEC) and in the electricity and the heating and cooling sectors in 2015 [13,14].

Country	RE % in GFEC (%)	Electricity (%)	Heating & Cooling (%)
EU28	16.7	28.8	18.6
Finland	39.3	32.5	52.8
Norway	69.4	106.4 *	33.8
Sweden	53.9	65.8	68.6

* Norway: higher renewable electricity production than final consumption; excess is exported.

Electricity sector

Finland, Norway and Sweden together had a total net electricity generation capacity of 88.3 GW installed in 2016, which generated 363 TWh (Table 2). Transmission capacities between these Nordic countries and to all neighboring countries allow significant energy exchanges and contribute to security of supply within the Nordic area [15].

Table 2. Installed capacity, electricity generation and %—shares in Finland, Norway, Sweden in 2016 [15].

Country	Hydro		Wind		Biomass		Nuclear		Fossil Fuels		Total
Finland	3.2 GW	(19.1%)	1.4 GW	(8.5%)	1.7 GW	(9.9%)	2.8 GW	(16.6%)	7.7 GW	(45.9%)	16.8 GW
	15.8 TWh	(24.2%)	3.1 TWh	(4.7%)	10.8 TWh	(16.5%)	22.3 TWh	(34.1%)	13.4 TWh	(20.5%)	65.4 TWh
Norway	30.8 GW	(95.9%)	0.87 GW	(2.7%)	0.002 GW	(0.0%)	-	-	0.45 GW	(1.4%)	32.1 GW
	143.4 TWh	(96.5%)	2.1 TWh	(1.4%)	-	-	-	-	3.1 TWh	(2.1%)	148.6 TWh
Sweden	16.2 GW	(41.1%)	6.03 GW	(15.3%)	2.98 GW	(7.6%)	9.7 GW	(24.7%)	4.5 GW	(11.4%)	39.4 GW
	61.2 TWh	(41.0%)	15.4 TWh	(10.3%)	9.0 TWh	(6.0%)	60.5 TWh	(40.5%)	3.3 TWh	(2.2%)	149.4 TWh

Hydropower dominates electricity generation in Norway. In Sweden hydropower and nuclear power play an equally important role, complemented by a fast-growing wind sector and a relatively constant energy generation share from biomass in district heating (DH) and industrial combined heat and power plants (CHP) in 2016. In Finland, nuclear power provides a third of electrical energy, followed by hydropower, fossil fuels, biomass and wind. While Norway and Sweden were net exporters of electrical energy, Finland imported almost 20% of its final electricity consumption in 2015 [10,15].

Electricity generation shares in the selected northern counties of our focus are detailed in Table 3. Hydropower dominates in all of them (except Finnmark) and contributes with high shares to the electricity generation in the respective countries. Norrbotten and Finnmark have also significant shares from thermal electricity production. Generation from wind power was still relatively small in 2014 but shows a growing trend in Finland and Sweden [16–19].

Table 3. Electricity generation in the northern counties of Finland, Norway and Sweden in 2014, and %—shares of the national electricity generation.

Northern County	Hydro		Wind		Thermal *		Total	
Lapland	4.4 TWh	(33.2%)	0.37 TWh	(33.5%)	1.4 TWh	(4.8%)	6.1 TWh	(9.4%)
Finnmark	1.3 TWh	(1.0%)	0.28 TWh	(12.5%)	1.50 TWh	(41.9%)	3.1 TWh	(2.2%)
Troms	3.0 TWh	(2.2%)	0.12 TWh	(5.6%)	0.15 TWh	(4.3%)	3.3 TWh	(2.3%)
Nordland	14.8 TWh	(10.9%)	0.10 TWh	(4.5%)	-	(0.0%)	14.9 TWh	(10.5%)
Norrbotten	13.9 TWh	(22.7%)	0.7 TWh	(4.5%)	1.3 TWh	(10.6%)	15.9 TWh	(10.6%)

* Bio, fossil, CHP and thermal power (no CHP) combined.

Heating sector

In 2015 the building heating demands in these three Nordic countries were 40.8 TWh in Finland, 76.4 TWh in Sweden and 41.7 TWh in Norway. The DH shares were 31.2% in Finland, 58.4% in Sweden and 12.5% in Norway. Biomass resources from forestry industry, biodegradable shares in waste incineration, waste heat as well as (non-renewable) waste gases from industries and electricity contribute to an increasing share from renewable energy resources and from recyclable waste streams to the DH systems (Table 4). Heating supply, when not connected to DH, is dominated by electricity in Norway, electricity and biomass in Sweden and Finland, the fossil fuel shares were 7.9% in Finland, 5% in Norway and 2.7% in Sweden [16,20–23].

As mentioned above, Finland, Norway and Sweden have renewable energy shares in the electricity and heating sectors well above the EU28 average. While fossil fuels in DH in Norway and Sweden remain dominant for peak demand only and as a share of waste incineration, Finland still had a high share of 16% of energy peat, which is classified as a fossil fuel. The share of energy peat in Lapland DH was 40% in 2015 [24].

Table 4. Building heating demand (TWh), %—shares of renewable energy (RE) in heating and cooling (H&C) [13,14]. %—shares of DH and energy resources in DH in 2015 [16,20–23].

Country	Building Heating Demand (TWh)	RE in H&C (Eurostat) (%)	DH (%)	Renewables in DH, Excluding Electricity (%)	Recyclables * in DH (%)	Electricity in DH (%)	Fossil Fuels in DH (%)
Finland	40.8 TWh	52.8%	31.2%	37.0%	-	-	58.4%
Norway	41.7 TWh	33.8%	12.5%	29.1%	52.6%	13.0%	5.3%
Sweden	76.4 TWh	68.6%	58.4%	35.6%	50.7%	4.9%	7.0%

* Recyclables include: solid wastes, flue gas condensation, waste heat and waste gases from industries.

3. National Energy and Climate Policies

Finland and Sweden are obliged as EU member states to contribute to the key targets of the EU 2030 climate and energy framework, i.e., a binding target to cut at least 40% of greenhouse gas (GHG) emissions in EU territory (from 1990 levels) and to achieve a share of renewable energy of at least 27% and an improvement in energy efficiency of at least 27%. In January 2018, in order to ensure that the declared climate goals in the UNFCCC Paris Agreement, the European Parliament voted for more ambitious and binding EU targets at 35% renewable energy and 35% energy efficiency, allowing Member States to set indicative national targets [25,26]. The EU proposed in [27] binding GHG emission reductions to be achieved by EU member states in 2030 (from 2005 levels), which are 39% for Finland and 40% for Sweden.

Ambitions for longer term perspectives in the EU are set out in the 2050 low-carbon economy roadmap, including 80% GHG emission cuts by 2050. The EUs Energy Roadmap 2050 explores the transition for the energy system. Norway, through its EEA membership, has committed itself to similar obligations. The three countries participate in the EU Emissions Trading System (ETS) and carbon taxes are applied on non-ETS sectors [28].

Finland's National Energy and Climate Strategy from 2017 targets an 80−95% reduction in greenhouse gas emissions by 2050 [29]. Continued efforts aim to reduce coal and other fossil fuels from the energy sectors, building on the commitments from the Finnish National Renewable Energy Action Plan (NREAP) [30] and National Energy Efficiency Action Plan (NEEAP) [31]. Increased shares of nuclear and renewables will reduce emissions in the electricity and heating sectors. Efficient energy use in all sectors shall contribute to reduce energy and carbon intensity of the Finnish economy and increase self-sufficiency of the Finnish energy supply. In addition to these domestic measures a better integration of Finnish gas and electricity systems in the Nordic region are needed to consolidate Finnish energy security [29,32,33].

Norway adopted a new energy policy in 2015 with a timeframe up to the year 2030 under the premises of strengthened security of supply considering future transformations of the international energy market and especially the electricity market. This policy—"Power for change"—envisions more efficient consumption of energy and further expansion of renewable energy generation from hydro, wind, solar, biomass and waste. The target for improvements in energy intensity (energy use/BNP) is set to 25% from 2016 to 2030, the GHG-emission reduction target is 40% by 2030 with 1990 as base-year. A specific target for overall renewable energy share was not defined in this new policy, but it had exceeded already in 2014 the 67.5% target set for 2020 in the NREAP [34–36].

Sweden had an energy commission in place, which submitted its final report in January 2017 [12]. The commission proposed a 100% renewable energy target for 2040, which is complemented with an increased end-use efficiency target of 50% by 2030 as compared to 2005 levels. In the newly adopted climate policy framework for Sweden the GHG emission targets are detailed as follows: By 2030 Swedish emissions shall be by at least 65% lower as compared to 1990 levels, 75% lower by 2040 and by 2045 emissions from activities on the Swedish territories shall be reduced by 85% as compared to 1990 levels [37]. The current Swedish target to reduce GHG-emissions by 17% by 2020 from 2005 levels was achieved in 2015 with a reduction in this period of 19.9% [38–41]. The renewable energy targets of 49% by 2020 had been achieved in 2013 [42,43]. One important driver for the Swedish energy transition is the world's highest CO_2-tax of US$126/t$CO_2$eq applicable on non-ETS sectors [28].

4. Energy Supply Potentials in the Northern Counties of Finland, Norway and Sweden

This section provides an account on additional energy supply potential from different resources (hydropower, wind power, biomass, energy peat, solar energy, waste and industrial energy integration, ocean energy) at the national level and then more in detail, as in the intentions of the Authors, in the selected northern counties of Finland, Norway and Sweden. Where it was not possible to find detailed data because of the aggregation levels in the available publications and in the accessible databases, the data are presented only at national level.

The technical and economically feasible potentials for capacity and energy output provided in this paper consider the following categories of constraints restricting the theoretical potentials:

(a) constraints from legislation (e.g., protection of rivers, bird conservation areas, but not policy targets or caps);
(b) constraints from market conditions (with a focus on prices and costs, but not on demand, i.e., the required amount of a resource is not considered, but only the amount that would be economically feasible to exploit under current and near-future market prices and costs);
(c) constraints from technical limitations (such as bottlenecks in transmission infrastructure, which are taken into account where appropriate).

Since potential estimations depend on different sets of constraints, each applicable only to a particular energy resource, further details on these constraints are specified in each of the following subsections.

4.1. Hydropower

Hydropower plays an important role in the Nordic energy system. 24% of electrical energy in Finland, 96% in Norway and 41% in Sweden was generated by hydropower in 2016. In addition to this significant share of electric energy generation, hydropower is crucial for balancing intermittent electricity generation with consumption both within domestic markets and between interconnected partner countries [10]. Since electricity is also key in the heating sectors of Finland, Norway and Sweden, the seasonal storage capability of hydropower in Norway and Sweden is crucial for covering the heating demand during the cold season. These roles of hydropower become increasingly critical, considering the option of a partial nuclear phase out in Sweden by 2020 (with a full phase out by 2045) and a continued high dependency from imported electricity in Finland. The exploitation of some of the remaining hydropower potentials will also be required to enable the integration of a growing share of weather dependent electricity generation in the Nordic electricity system [44,45].

Potential definition in hydropower investigations

Investigations of hydropower potential usually start from the technical feasibility of the locations, which defines the technical or exploitable hydropower potential. These technical potentials are then reduced by environmental restrictions, when the sites are located on rivers or river stretches within national parks or otherwise protected areas (tourism and fishery interests belong to this category as well). Difficult political procedures for the development of proposed sites on border rivers can also exclude otherwise feasible locations. Small-scale hydropower is often included in the technical potential analyses, but the authors mention low financial profitability, which require some form of state aid, and also environmental concerns, which need to be considered. Transmission grid bottlenecks can also exclude potential sites from being considered as technically and economically significant, at least in the shorter term. Finally, differences in the potential analyses can be motivated by the technical focus—mainly on energy generation, like in the Swedish investigations [46], mainly on peak and load balancing capacities as in one of the Norwegian studies [47], or considering all these aspects as in the extensive Finnish study [48].

Finland

A 2008 investigation into the hydropower potential of Finland concluded that a total of about 1.7 GW (6.7 TWh) would be technically relevant for exploitation [48]. Of these, 462 MW are located on river systems that are protected by law and 502 MW are located at border rivers where the construction of hydropower plants has also been concluded to be unrealistic, remaining with a technical and economically significant potential of about 736 MW. A potential of 63 MW results from small-scale hydropower, but low financial profitability and environmental considerations are obstacles to the development of these resources. In Lapland only the river Kemi has a hydropower potential of 594 MW that is considered as technically and economically significant. Other hydropower potentials in Lapland include the Ounas river in northern Lapland with 349 MW, but the river is environmentally protected [48].

Norway

The techno-economic potential for new hydropower in Norway, in addition to the installed capacity of 30.7 GW in 2016, has been considered as good, taking also into account dispatchability, seasonal availability and costs of production [35]. The green electricity certificate system incentivizes investments in new hydropower generation, including smaller run-of-river plants (<10 MW), upgrades of existing dams and large-scale hydro power plants [49]. An investigation into Norwegian hydropower potential with the prerequisite of covering peaks and load balancing needs of the Nordic electricity system provides two main scenarios [47]. The first scenario considers new balancing capacities of 20 GW by 2030 by upgrading existing generation capacities and constructing new hydro-pump storage units at existing reservoirs only. In the second scenario, Norway is envisioned as the green battery of Northern Europe by 2050. This could be achieved with an additional generation capacity of 50 GW, requiring the exploitation of the full hydropower potential in Norway and additional significant investments in domestic transmission infrastructure and increased interconnection capacities to the rest of Europe [47,50]. Such developments would contribute to a faster decline of non-renewable electricity generation in the countries around the North Sea [51–53]. Another study from 2008 estimates the total hydropower potential that is technically and financially feasible to exploit in Norway to 205 TWh, not considering small-scale hydropower. 46 TWh are located on protected river stretches, remaining with a total potential of 159 TWh. Subtracting the current generation of 143 TWh in 2016 results in a hydropower potential still available for exploitation of about 16 TWh [54].

Exploitation of small-scale hydropower (<10 MW) is promoted by the adoption of the Swedish green electricity certificate scheme [50]. A total capacity of 1 285 MW (3.9 TWh) from small-scale hydropower will be available by 2020 in case all 429 of the permitted plants will be commissioned [55]. The potential for small-scale hydropower in Norway has been estimated at 18 TWh with investment costs below 3 NOK/kWh, and additional 7 TWh with investment costs between 3 and 5 NOK/kWh. Finnmark has a small-scale hydropower potential (considering all categories) of 223 MW, Troms 606 MW and Nordland 1297 MW [56]. By the end of 2017 twelve construction permissions for large scale developments (>10 MW) are granted, one in Finnmark, three in Troms and eight in Nordland [49].

Sweden

Hydropower development in Sweden more or less stopped in the 1980s, mainly for environmental protection reasons [42,57]. Most of the technical potential, which is unavailable due to environmental legislation, is located in the two northernmost counties of Sweden—on the three rivers Torne, Kalix and Pite in Norrbotten county and Vindel river in Västerbotten county, which are fully protected [58]. 9 GW of new hydropower capacity could be theoretically added to the existing 16.2 GW installed capacity, with the major share on the four protected rivers in Norrbotten and Västerbotten, generating an estimated 29 TWh additional energy to the current average annual production of 66 TWh. Considering current legal restrictions about 1.9 GW capacity could be installed (on new sites and by upgrading existing hydropower stations) and an additional 6 TWh generated, according estimations presented in [46].

A more recent study by SWECO [59] is restricted to the ten largest energy-producing Swedish rivers and as a technical focus it analyzes the technical potential for increasing capacities for load balancing rather than additional energy generation potentials. It considers an extension and adjustment of river flows to optimize for zero spill losses. The capacities on these rivers could be increased by 24% on average, resulting in a total of 3.4 GW additional capacities. Extrapolating this result to other exploited river stretches, a total of 3.9 GW generation capacities could be added. In Norrbotten the currently installed capacity on the Lule river and the stretch of Skellefte river that is located in Norrbotten is 4.5 GW. The SWECO study estimates the additional potential on Lule river at 735 MW and on the entire Skellefte river at 251 MW (the share on the Norrbotten stretch of Skellefte river is 33 MW). About 1900 small-scale plants contribute 4.3 TWh (about 6.5%) to Swedish annual hydropower production. An upgrade of these existing facilities could increase the output to about 10 TWh [60].

Summary—Hydropower

Significant technical potential for additional hydropower exists in Finland, Norway and Sweden and are presented in Table 5.

Table 5. Hydropower—installed capacity and generation in 2016, ranges of potentials (technical; technical and economical), small-scale technical potential.

Country Northern County	Installed by 2016 (GW)/(TWh)	Potential * (GW)	Potential * (TWh)	Small-Scale (Tpot)	Comments
Finland	3.2/15.8	1.7–0.7	6.7–2.7	63 MW	-
Lapland	-	0.9–0.6	3.2–2	-	Only on Kemi river
Norway	30.8/143	50–20 (a)	62–16 (b)	8.3 GW	(a) Peak and load balancing scenarios (GW) (b) energy estimations (TWh)
Finnmark	-	1 **	-	223 MW	Small-scale HP Norway:
Troms	-	3 **	-	606 MW	- 18 TWh with <3 NOK/kWh
Nordland	-	8 **	-	1297 MW	- plus 7 TWh with 3–5 NOK/kWh
Sweden	16.2/61.2	9–1.9 (3.9 ***)	29–6	6 TWh	No specific data on county level. Three
Norrbotten	4.5/15.2	0.8 ***	-	-	of four large protected rivers are located in Norrbotten.

* 1st number = technical potential (Tpot); 2nd nr = technical and economical potential, see also comments. ** No potential for large-scale (>10 MW) available. Numbers are construction permissions by 2017. *** SWECO-report: only added capacities estimated.

Theoretical and technical hydropower potentials are drastically reduced by environmental protection of rivers and river stretches, border issues and also by bottlenecks in the existing transmission infrastructure. 20 GW additional hydro-pump storage capacities can be built in Norway at existing reservoirs only, a full development of hydropower potential could add about 50 GW capacity also requiring significant investments in transmission infrastructure. In Sweden, from a theoretical potential of 9 GW, mainly located in the northern county of Norrbotten—on three protected rivers—and on one river in Västerbotten, about 1.9 GW could be added at new sites and a capacity of 3.9 GW could be added by upgrading existing sites and by optimizing river flows of already exploited rivers. Finland considers 736 MW out of a total potential of 1.7 GW as technically and economically feasible, the river Kemi in Lapland has a total potential of 594 MW considered as feasible.

4.2. Wind Power

Installed wind power capacities are continuously increasing in Finland, Norway and Sweden, very large additional potentials exist both onshore and offshore [53,61–63].

Potential definition for wind deployment estimates

Estimations for wind power potentials need to consider many variables, including climatic conditions from weather prediction models supplying data for monthly, seasonal, yearly variations, minimum and maximum wind speeds on different hub heights, as well as the impact of icing risks amongst others. Technically feasible offshore potentials depend on water depth and distance to the shore in addition to wind speed [64]. Power curves from selected wind turbines matched with wind data then provide potential energy outputs on a specific site. Efforts in providing climate data in form of wind atlases have been made in all countries [65–67], with different spatial resolutions and for different hub heights, but actual estimations on installed capacity and energy output potentials are not the norm due to the many technical variables to consider. In addition to technical and economic potential estimations for onshore and offshore areas more factors (or constraints) need to be taken into account, including distances to existing physical infrastructure, military concerns, environmental concerns and the interests of other economic activities such as shipping, tourism and fisheries. Capacities in the existing transmission infrastructure can also be limiting for wind power deployment.

An investigation on offshore wind potentials for the entire Baltic Sea Region (BASREC [68]) concluded in 2012 that 300 GW are possible with then current technology in attractive locations. The above mentioned constraints reduce this technical potential to 200 GW. The study applies another deduction of 80% from this potential for limitations not yet considered, remaining with a 40 GW offshore deployment potential in the Baltic Sea Region. It is worth noting that the capacity of commercially available wind turbines has increased from 2 MW in the early 2000s to 6–8 MW in 2017, and the development of 12–15 MW turbines seems to be realistic in the near future. Accordingly, wind energy potential estimations from specific years have to be reinterpreted keeping in mind such dynamic technological improvements [69,70].

Finland

In 2016 Finland had 1539 MW wind power capacity installed, 32 MW offshore, generating 4.1 TWh or 4.7% of the electricity generation [13]. A 6 TWh national target exists for 2020 resulting from the maximum wind power capacity eligible for receiving a feed-in-tariff under the current legislation [71–73]. The Finnish WindAtlas provides information on annual average windspeeds for on– and offshore areas, where it points out that especially offshore, along the coastline of the Baltic sea where the shallow waters are advantageous for wind power installations, technical potentials are very large [65]. An estimation of 12.6 GW about onshore wind turbine capacity was derived from proposed regional plans in 2011 [74]. The BASREC report [68] indicates that 66 out of 99 most suitable offshore locations in the Baltic Sea are located in the Finnish area. 31 GW offshore deployment potential is located in the Gulf of Bothnia in Northern Finland, 11 GW in central Finland, 27 GW in southern Finland and 2 GW in south-east Finland, in total 71 GW considering known constraints. Applying an 80% attrition rate for further constraints results in an offshore wind potential of 14 GW and about 60 TWh for Finland.

Norway

Norway had 838 MW wind power capacity installed in 2016, 2.3 MW offshore, generating 2.1 TWh or 1.4% of the 2016 electricity generation [13]. 205 MW were installed since 2012 under the common green electricity certificate system [75]. Technical estimates for the onshore wind power potential range from 419 TWh to 1847 TWh, considering different average wind speeds and percentages of land area used, but environmental considerations put clear limitations to such estimates [35,66,76]. According to a 2008 investigation [64], the Norwegian offshore wind power potential ranges from 6.4 GW to 141 GW, depending on maximum water depth between 20 m and 100 m and minimum distance from the shoreline between 1 km and 20 km. This investigation did not estimate the wind power output. If the same average generation factor applied in BASREC (~4200 MWh/MW) were applied to obtain a very rough estimation, the Norwegian yearly offshore generation would range between 27 TWh and

592 TWh. This estimation should be significantly revised upwards considering that 12–15 MW wind turbines can be expected by 2020 and that floating wind turbine technologies will allow to exploit deeper waters [70,77].

Sweden

Sweden shows an increasing trend from the 6519 MW installed wind power (202 MW offshore) generating 15.4 TWh or 10.3% of the electricity generation in 2016, with 17.4 TWh estimated for 2017 [13,78]. Detailed municipal general plans allow for 30 TWh wind power, of which 10 TWh offshore, by 2020 [79–81]. The BASREC report [68] estimates the potential for offshore wind capacity in Swedish Baltic Sea waters at 23 GW considering known constraints, further deduction of 80% as proposed by the report results in 4.6 GW or 19 TWh deployment potential.

Summary—Wind Power

Estimated wind power deployment potentials do not provide limitations for the achievement of the currently set political targets for wind power. The three countries of Finland, Norway and Sweden all have very favorable conditions for continued growth of wind power, both onshore, with a large share in the northern counties due to high average wind speeds and low population densities, and offshore, along the coastlines in the Baltic Sea and in the North Sea. National on– and offshore potentials are presented in Table 6.

Table 6. Wind power—installed capacity and generation in 2016, national potential wind power deployment ranges on– and offshore.

Country	Onshore Offshore	Installed by 2016 (MW)/(TWh) (Total)	Potential (GW/TWh)	Comments on Potential
Finland	**onshore**	1507 MW/4.1 TWh	12.6 GW	Estimation based on regional plans, 2011 [74].
	offshore	32 MW	71–14 GW (60 TWh)	From BASREC report. Technical potential (constraints considered)—80% additional attrition.
Norway	**onshore**	836 MW/2.1 TWh	1847 TWh–419 TWh	Different technical criteria, not considering constraints.
	offshore	2.3 MW	141 GW–6.4 GW	No estimation for energy generation available.
Sweden	**onshore**	6317 MW/15.4 TWh	20 TWh (a)	(a) From general master plans—dedicated land and offshore areas for wind power deployment.
	offshore	202 MW	10 TWh (a)	
	offshore (b)	-	23 GW–4.6 GW (19 TWh)	(b) From BASREC report. Technical potential (constraints considered)—80% additional attrition.
Baltic Sea Region (offshore)			300 GW–200 GW–40 GW	From BASREC report. Technical potential—constraints—80% additional attrition.

4.3. Solar Energy

Annual solar irradiation in the southern parts of Finland, Norway and Sweden is comparable to the northern regions of central European countries, resulting in similar annual solar energy generation potentials. The solar energy potential in the northern counties of Finland, Norway and Sweden is about 20% less compared to the southern ones, with approximately 98% of output occurring during March to October, or about 88% between April to September [82–84].

Solar thermal energy in Nordic countries can complement other heating (and cooling) technologies for DH, individual building heating and industrial processes where low-temperature heat demand is required during summer months. In 2015 solar thermal installations (glazed and unglazed water collectors) accumulated 41 MWth in Finland, 30 MWth in Norway and 349 MWth in Sweden, as compared to 13,226 MWth in Germany and 837 MWth in Denmark [85].

Potential definition for solar energy estimates

Technical potentials utilizing land areas are almost limitless and can be estimated within a range between 675 (north) and 850 (south) kWh/kWp solar electricity generation for Finland from optimally—inclined fixed—tilted systems, 550–850 kWh/kWp for Norway and 675–1000 kWh/kWp for Sweden [83]. Kosonen et al. [86] base their estimations, which are labelled as long-term market potential (2050), on a future 100% renewable energy system, with the constraint of a local power supply (the energy demand has to be satisfied locally within an area of 10,000 km^2, as proposed by Pleßmann et al. [87]). Other authors consider available south or near-south facing roof areas for their estimations on solar energy potential (e.g., [82,88]).

Finland

The Government of Finland envisioned an installed solar PV capacity of 10 MW by 2020 in the NREAP from 2010 [30]. By 2015 15 MW had been installed. Finland considers energy generation from solar PV to be between 0.2 and 18 TWh by 2050 in different scenarios of the Energy and Climate Roadmap 2050 [71]. Pasonen et al. [82] calculate a solar PV potential of 3 TWh considering PV installations on 60% of south-facing roof areas. Kosonen et al. [86] assume a long-term solar PV market potential for Finland at 24 GW (18 TWh with average 800 kWh/kWp) installed on 484 km^2 or 0.14% of available land area. Small solar thermal installations were estimated to reach 100 GWh and large installations complementing DH to 300 GWh by 2020 [89].

Norway

An estimation on rooftop and building integrated solar PV potential considering technical and economic factors, provided in the Norwegian white-paper on national energy policy, results in 5.1 GW installed capacity producing 3.8 TWh by 2030 [35]. Utilizing the same area with solar thermal systems instead of solar PV a maximum thermal energy production of about 10 TWh per year could be achieved. Kosonen et al. [86] estimate the Norwegian solar PV market potential by 2050 at 43 GW (30 TWh with average 700 kWh/kWp) installed on 864 km^2 or 0.22% of land area.

Sweden

117 MW solar PV were approved in Sweden by mid-2017 under the green electricity certificate scheme [90], exceeding the expected 8 MW solar PV for 2020 in the NREAP from 2009 [43]. Molin et al. [88] analyze the rooftop solar PV potential in a municipality in southern Sweden and find that 19% of solar supply rate can be achieved by utilizing tilted high-yield roof-tops only, 43% supply rates are achievable utilizing flat roofs, and 88% of the annual building electricity consumption can be supplied by solar PV when the totally identified roof potential is utilized and overproduction is exported to the grid. Household electricity consumption was 35 TWh in 2016 resulting in possible solar electricity generation of 6.7 TWh, 15 TWh and 31 TWh, respectively, considering the different supply rates by Molin et al. (these would need to be adjusted downwards to take into account a national average solar irradiation). Kosonen et al. [86] estimate the Swedish solar PV market potential at 43 GW (37 TWh with average 850 kWh/kWp) by 2050 utilizing 858 km^2 or 0.19% land area.

Summary—Solar Energy

Solar energy yields in the selected northern counties are about 20% lower than those in the southern regions of the respective countries. Estimations for solar potentials have wide ranges depending on considered available areas for installation—roof areas or land areas (Table 7).

Table 7. Solar energy—installed capacity in 2015 (solar PV and solar thermal), solar PV market potential by 2050 [86] (installed capacity and estimated solar energy generated).

Country	Installed by 2015 (MWp)/(MWth)	Potential by Kosonen et al. [86] Solar PV (GWp)/(TWh)	Comments on Potential
Finland	15/41	24/18	TWh with average 800 kWh/kWp
Norway	1.1/30	43/30	TWh with average 700 kWh/kWp
Sweden	104/349	43/37	TWh with average 850 kWh/kWp

4.4. Biomass from Forestry for Energy Use

Bioenergy has the potential for playing a critical role in addressing climate change mitigation, if issues such as sustainability of practices and efficiency of bioenergy systems are adequately considered [91,92].

Potential definitions for biomass from forestry for energy use

Assessments of biomass resources generally apply one of these three approaches: the resource focused approach, the demand driven approach or the integrated approach. Resource focused assessments investigate the bioenergy resource base and can include competition among different uses, environmental and economic criteria. Demand driven approaches typically study economic and implementation potentials and evaluate the feasibility of the projected use of biomass. Integrated approaches combine economic, energy, land use and climate criteria and are mainly applied to address policy questions [93,94].

Estimations on biomass potential depend on a large number of factors and can show very large ranges. Depending on the assessment approaches, the studied type of potential (theoretical, technical, economic, implementation or sustainable implementation potential), the considered constraints and limitations, the absence of a commonly accepted biomass systematization and the use of different quantitative units influence the study results and complicate the comparability [93,95–98].

Following Rettenmair and Berndes, these four potentials are usually represented in studies of biomass resource potentials [93,94]:

- The theoretical potential of biomass for energy use considers fundamental bio-physical limits, such as land availability and achievable yield levels, representing the maximum theoretical productivity under optimal and sustainable management. In case of potential from forestry harvest residues, the theoretical potential is typically based on biomass residues from the existing forestry industry.
- The technical potential further considers current technological possibilities including harvesting, infrastructure and processing. Other land uses (e.g., nature reserves) are taken into account.
- The economic or techno-economic potential reduces the technical potential by applying economic constraints and criteria such as economic profitability under current and expected future market conditions, prices for alternatives, taking also into account subsidies and taxes.
- The implementation or sustainable implementation potential is the share of economic potential where additional environmental, economic, social and policy criteria may be included.

Egnell [95] points out that limiting factors to theoretical potentials also depend on the types of biomass resource and the specific circumstances in the production area, and Ferranti [97] mentions that factors applied on biomass potential for energy use vary according to the types of assessments carried out. Egnell uses the terms theoretical available biomass, which largely corresponds to the theoretical potential as described by Rettenmair and Berndes, and market available biomass, which corresponds to the sustainable implementation potential since it also considers social and additional environmental criteria.

This section aims at presenting technically and economically feasible potentials for the resource (biomass from forestry for energy use) as it is done in the rest of the paper. It is important to keep in mind that the variety of definitions of potentials and the large number of factors influencing the estimations makes it difficult to present robust estimates of how much biomass is actually available. Moreover, time horizons for estimations go to 2050 and beyond, following the nature of the sector and existing policy perspectives.

The ENERWOODS project, which assessed wood based energy systems in the Nordic and Baltic region concluded in 2015 that Nordic forests could increase their productivity by 50–100%. The authors considered this result as a conservative estimate [99].

Finland

The Finnish bioenergy production was 91 TWh in 2015, 80% of the annual renewable energy production [16]. The volume of growing stock in Finland from a productive forest area of 19.5 Mha was 2294 Mm^3 (1441 Mm^3 in the 1970s) with an annual increment of 103 Mm^3 in 2013. The volume of growing stock in Lapland was 350 Mm^3 and the annual increment was 13.3 Mm^3 in 2013 from a productive forest area of 4.07 Mha [100,101]. The Forest Policy 2050, the National Forest Strategy 2025 and the Finnish Bioeconomic Strategy envision and support a continued growth of all bio-based sectors moving Finland towards a sustainable bio-economy [6,102,103].

Finnish potential for recoveries of woody biomass from forestry and forestry residues were estimated between 132 TWh and 186 TWh annually for the period 2003–2013, and between 138 TWh and 154 TWh for the period 2043–2053, in the sustainable and the maximum cutting scenarios, respectively. Differences between southern and northern Finland, including forest structure, age of stands, timber production, affect future bioenergy production potentials [99,104].

Norway

The bioenergy share of renewable energy production in Norway was about 10% in 2014. Bioenergy production reached 18 TWh in 2012, including 10.3 TWh solid biomass [105], largely a result of the 2008 strategy for an increased use of bioenergy. The current additional demand potential for solid biomass was estimated between 3 TWh and 5 TWh [106].

Norway had a growing stock of 849 Mm^3 (578 Mm^3 in 1990) from a productive forest area of 8.2 Mha in 2016. The annual increment increased was at an average of about 24 Mm^3 in the last decade. The northern counties of Nordland and Troms have together productive forest areas of 1.18 Mha, 18% of the land area, whereas Finnmark has negligible forest areas. The growing stock in Nordland and Troms was 61 Mm^3 in 2016. The average annual increment in Nordland and Troms was 1.6 Mm^3 [107]. The Forestry Act promotes sustainable management of forest resources with a view to promotion of local and national economic development [108,109].

Current annual harvest potentials of forestry residues from thinning and final felling in Norway are between 20 TWh and 27 TWh. For the northern counties of Nordland and Troms, these potentials were estimated between 1.7 TWh and 2.3 TWh [99,110,111].

Sweden

The bioenergy share of renewable energy production in Sweden was 60% in 2015 [42]. In 2016 the Swedish National Forest Inventory (the Swedish NFI) estimated the total volume of growing stock in Sweden at 3490 Mm^3 from a productive forest area of 22.8 Mha. The annual increment increased from about 80 Mm^3 in the 1960s to over 129 Mm^3 between 2012 and 2016. The county of Norrbotten has 3.6 Mha productive forest area [112].

In Sweden biomass was repeatedly the object for investigations on its potential for energy use, triggered by the oil crisis in the 1970s and later by increasing oil prices in the 2000s, but also to find solutions for mitigating GHG emissions from fossil fuels by utilizing local biomass resources. Lönner et al. investigated in costs and biomass availability in the midterm in 1998 [113], Hagström analyzed the biomass potential for heat, electricity and vehicle fuel in Sweden in 2006 [114], the Government of Sweden commissioned the oil-committee in 2005 with the objective to reduce the national dependency from oil by 2020 [115], the investigation of the Government of Sweden on bioenergy from agriculture [116] and the FFF-study [117] followed en suite with the aim to achieve a fossil—independent vehicle fleet by 2030. Börjesson published a new study in 2016 on the potential for increased supply of domestic biomass in a growing Swedish bioeconomy [118].

The energetic value of the annual increment of biomass in forests was estimated at 430 TWh and the annual harvest volumes in the recent years were 190 TWh in a five-year average, where about 110 TWh were energetically used in 2013 [118]. Börjesson largely reconfirmed earlier studies, including the SKA-08 report [119] as presented in ENERWOODS 2015 [99]. An additional 20–40 TWh could be used today for energy purposes, while the additional technical potential for biomass for energy use from forestry was estimated to be between 30 TWh and 70 TWh by 2050, with the highest shares (50%) in the region of Norrland (which includes the county of Norrbotten) and roughly 25% each in the regions of Svealand and Götaland. These ranges consider the techno-economic potential for the higher value and additional ecologic constraints for the lower value [42,118,120].

Summary—Biomass from Forestry

Table 8 presents a summary of current use, current and future potentials for recovery of woody biomass from forestry and forestry residues in Finland, Sweden and Norway and in the northern counties of Lapland, Nordland and Troms (combined) and Norrbotten.

The northern counties of Finland and Sweden have noteworthy resource potentials for increasing biomass use from forestry residues, where much of this potential is underutilized. Considering the already high shares of bioenergy in the heating sector in northern Sweden, an increase of biomass use would be possible by producing biofuels through thermal gasification. Use of energy peat in Lapland is declining and further substitution with biomass is possible. Most DH systems use fossil oil for peak demand (1–2%), which could be replaced by biofuels, produced through thermal gasification of biomass. The situation in northern Norway is different, with only a small forestry industry and very small municipalities, where DH is not feasible in most cases, also due to the lack of water-based heating systems in about 90% of all buildings.

Table 8. Current and future ranges for woody biomass from forestry and forestry residues for energy use in Finland, Sweden and Norway and in the selected northern counties.

Country	**Finland**	**Norway**	**Sweden**
Northern County	**Lapland**	**Nordland and Troms**	**Norrbotten**
Productive forest area	19.5 Mha (64% *) 4.07 Mha (44%)	8.23 Mha (23%) 1.18 Mha (18%)	22.8 Mha (56%) 3.6 Mha (37%)
Volume of growing stock	2249 Mm^3 350 Mm^3	849 Mm^3 61 Mm^3	3490 Mm^3 320 Mm^3
Annual increment	103 Mm^3 13 Mm^3	24 Mm^3 1.6 Mm^3	129 Mm^3 12 Mm^3
Forest bioenergy use	91 TWh N/A **	10.3 TWh N/A	110 TWh 1 TWh
Energy potential (current)	132–186 TWh 17–23 TWh	20–27 TWh 1.7–2.3 TWh	130–150 TWh 4–6 TWh
Energy potential (2050)	138–154 TWh N/A	N/A N/A	140–180 TWh 5–10 TWh

* % of land area; in Sweden excluding national parks and otherwise protected areas. ** N/A = not available.

4.5. Energy Peat

The energy potential from peat is calculated from the technically exploitable amount of peat from peatland and the specific energy content. Other factors concur in determining which peatland can be regarded as energy peatland. Finland and Sweden have mapped such peatland in detail through their national Geological Survey institutions, GTK in Finland and SGU in Sweden, and their national forestry inventories.

Due to the inclusion of peat in the EU-ETS following the classification in the 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Finland and Sweden have notably reduced the consumption of energy peat in the recent years.

Studies suggest that harvesting of energy peat from drained peatland as compared to undrained peatland has high benefits for carbon emissions reductions. Drained peatlands emit CO_2 and nitrous oxide and about 11.4 $MtCO_2eq$ are emitted annually from such areas in Sweden alone, which amounts to about 22% of the annually reported GHG emissions of 52.9 $MtCO_2eq$ excluding LULUCF and foreign transport [121]. Rewetting these areas is one option to reduce CO_2 and nitrous oxide emissions, but would increase emissions of methane. Utilization as energy peat to substitute other fossil fuels would eliminate emissions from the peatlands (and from the fossil fuel combustion) and, when combined with successive reforestation of the harvested areas, these drained peatlands can be converted into carbon sinks [122,123].

Finland has 23.7 billion m^3 energy peat reserves with an energy content of 12,800 TWh available from 1.2 Mha peatland technically suitable for exploitation, 5.2% were actively producing in 2016. The technically suitable energy peat reserves in Lapland amount to 8567 Mm^3. From the national energy peat consumption of 16 TWh in 2016 (declined from around 31 TWh a decade ago), about 3.5 TWh was consumed in Lapland in 2016 [124–127].

Swedish energy peat reserves amount to 6 billion m^3 from a total of 0.35 Mha energy peatland with an estimated energy content of about 6000 TWh. 3.3 TWh energy peat were consumed in 2010, which was also the average in the 2000s, this dropped to 1.4 TWh in 2016. Norrbotten county has about 90,000 ha or 26% of Swedish total energy peatland. Only 1463 ha have been actively producing in 2016 and about 180 GWh were harvested in Norrbotten, 9% of the total harvesting volume in Sweden for that year [112,128–131].

Norwegian peatland of about 2.4 Mha is essentially undisturbed [132].

Summary—Energy Peat

Energy utilities are aiming to reduce energy peat to a share of 5–30% in co-firing with biomass, which still provides improved combustion conditions (increased efficiency, low ash-content, reduces sintering, slag-formation and corrosion) but minimizes carbon emissions. Electricity generated from energy peat is eligible for green electricity certificates in Sweden [133].

In summary, Finland and Sweden have huge domestic resources of energy peat. About 12,800 TWh in Finland and 6000 TWh in Sweden are the national reserves from exploitable energy peatland. Shares in Lapland are 36% from Finnish national reserves, and 26% from Swedish national reserves are located in Norrbotten.

4.6. Energy Recovery from Mixed Municipal Waste (MMW); Biogas

EU Member States are required by Article 28 of the Waste Framework Directive (WFD) to draw up waste management plans (national, regional and local plans) covering the entire geographical territory of a Member State [134]. The WFD establishes a legal framework for the treatment of waste in the EU and sets the basic concepts including "polluter pays principle" and the EU "waste hierarchy".

4.6.1. Incineration with Energy Recovery from MMW

MMW includes waste from households as well as commercial, industrial and institutional waste, which is similar in its nature and composition to waste from households [135].

The EU had a total incineration capacity of 81.3 Mt installed in 464 dedicated MMW incineration plants in 2014. In some countries, including Sweden, also non-hazardous industrial waste is treated in these plants. In 2015 Finland, Norway and Sweden generated 500, 421 and 447 kg of municipal waste per person, respectively (EU28 average: 477 kg/person), of which 48%, 51% and 53% were incinerated with energy recovery [136]. Waste incineration capacities in 2015 in relation to municipal solid waste generation were 48% in Finland, 69% in Norway and 113% in Sweden [137].

Finland operated seven incineration plants with a capacity of 1.5 Mt in 2015. In Lapland one waste-to-energy plant is located in the city of Oulu with a capacity of 140,000 t/year [138].

By 2017 Norway operated about 20 waste incineration plants, of which seven are major waste-to-energy plants with a total capacity of 4.2 Mt. Two of the smaller plants are located in the northern county of Troms (in the municipalities of Finnsnes, 11,000 t/year, and Tromsö, 35,000 t/year) and supply heat to the local DH systems [139].

Sweden operated 35 waste-to-energy plants with a total annual capacity of 6.65 Mt in 2016. Two waste-to-energy plants are located in the county of Norrbotten, one in Boden with a capacity of 100,000 t/year and the second one in Kiruna with 70,000 t/year, which receive municipal waste from many municipalities in Norrbotten and from the northern counties in Norway [140].

All three countries have set national targets in their national waste management plans to increase material recycling rates and launched initiatives to climb up on the waste hierarchy ladder towards the prevention of waste implementing circular economy policies. Further potentials for economically feasible energy recovery through waste incineration in these northern counties could therefore be considered as low, if increased waste imports from other countries are not taken into account [141].

4.6.2. Biogas

Biodegradable wastes from households, agriculture and industries were banned from landfills in these three Nordic countries and are either incinerated, composted or converted into biogas in anaerobic digestion facilities. In smaller digestion facilities the produced biogas is flared or utilized for own consumption of heat and electricity. Larger facilities deliver heat and electricity generated from biogas to DH and the grid. Substituting vehicle fuels with biogas achieves high grades of GHG emission reductions (GHG emission savings compared with fossil petrol or diesel are 73% for biogas from municipal organic waste, 81% from wet manure and 82% from dry manure [142–144]).

In 2014 Finland produced 613 GWh biogas. Estimations for biogas potential from waste and manure are in the range of 4–6 TWh per year, about the same amount could be produced from grass silage. 62% of the biogas was used for heating, 22% for electricity generation, 14% was flared and 2% was upgraded to vehicle fuels [145].

Norway produced 672 GWh biogas in 2014 from biogas-plants and from landfills. 6% was converted to electricity, 26% into heat, 29% into vehicle fuels, the rest was flared [145–147]. A biogas potential for 2020 from manure, sewage sludge and foodwaste was estimated at 2.3 TWh in a 2013 report by the Norwegian Environment Agency [148]. Another report estimated the biomass to biogas potential at 4.0–4.4 TWh, which also recognizes the potential for biogas in the northern counties of Norway as limited due to low population and absence of agriculture [149]. A national cross-sectoral biogas-strategy with the objective to stimulate biogas production was presented by the Government in 2014 [150].

In 2016 Sweden has produced 2 TWh biogas, a continued increase from 1.3 TWh in 2007. A high share of biogas (64%) was upgraded to transport fuels, 20% was used for heating, 9% was flared, 3% was used for electricity generation and 3% for industrial use [151]. A 2008 study estimates the Swedish biogas potential from domestic residues (excluding thermal gasification) between 10.6 TWh and 15.2 TWh per year [152], which was largely confirmed in later studies [153]. Norrbotten produced about 33 GWh biogas in 2011. The total biogas potential in Norrbotten (excluding gasification of forestry residues) has been estimated to about 240 GWh [154].

Additional biogas potential exists in all three countries and their northern counties. Depending on national policies and incentives, biogas is currently utilized differently in these countries, with a focus either on upgrading to vehicle fuels or for injection into the natural gas grid, or on utilizing biogas for heating purposes.

4.7. Energy Integration with Industries

Energy intensive industries based in the northern counties of Finland, Sweden and Norway include mining and mineral processing, forestry, pulp and paper and chemical industries, steel and manufacturing. They all have potentials for integrating their energy systems with DH systems of municipalities and with other industries.

4.7.1. Forestry Industries

Forestry industries use the forest as raw material and include sawmills, board, pulp, paper, cardboard, packaging and biofuel industries. Primary and secondary forestry residues are utilized in the wood processing industries as energy resources for the generation of process heat, electricity and biofuels. Overcapacities of heat are ideally exported to DH systems or to nearby industries, and the electricity generated in industrial CHPs is consumed on-site while overcapacities are exported to the national grid. Remaining woody residues are used locally in DH and residential heating and are also processed to wood-fuels with higher energy density, such as pellets, to allow longer transport distances.

Finland

In Finland, wood fuels contributed with 26% to the final energy consumption in Finland, 16% of electricity production and 37% of the heating demand were covered from wood fuels in 2015. The forestry industry consumed about 19 TWh of electricity in 2015, where 10 TWh were produced on site in industrial co-fired CHP plants (mainly biomass and energy peat). The annual increment in forest growth is with 103 Mm^3 exceeding current consumption of 85 Mm^3 [16,101,155], allowing for substitution of energy peat. Seven of the more than 100 large-scale forestry industry facilities are located in Lapland and all have energy collaborations with DH utilities. 166 towns have DH in Finland, supplied from over 1000 heat production units, and about 40 are located in Lapland [156,157].

Norway

Norway has its forestry and pulp and paper industry concentrated in the southern parts of the country, with the exception of a few smaller sawmills and board producers in Nordland [158]. A 2015 strategic report (SKOG22) concludes that forestry industry could quadruple its turnover from 2012 levels, with the largest share in the building sector, and significant potential for biomass use for energy (heat and electricity) and for biofuels (transport) from forestry products [159]. An investigation on the possibilities of establishing new forestry industries in the northern coastal areas concludes that profitability is difficult to be achieved, mainly due to bottlenecks in the transport infrastructure [160].

Sweden

The demand of process heat and steam in Swedish forestry industry is supplied by 96% with biomass. An average of 22 TWh electricity is consumed by these industries, where 5.6 TWh was generated by industrial CHPs in the pulp and paper industry [42,161]. In the county of Norrbotten two major pulp and paper facilities are based in Piteå (SCA and Smurfit Kappa) and operate biomass-fueled industrial CHPs that deliver surplus heat to the Piteå DH system [162]; another one is located in Karlsborg/Kalix (BillerudKorsnäs). About ten larger and three smaller sawmills are based in Norrbotten and at least four wood-pellet producers utilize sawmill residues [163–166]. Two larger sawmills in Piteå and one in Luleå supply heat to the DH system, while in other municipalities sawmills typically provide biomass residues to the municipal DH systems. In some cases, overcapacities of heat from timber drying chambers could be supplied into smaller DH systems, but this is often not economically feasible or has not been considered for other reasons.

DH systems in Norrbotten operate with biofuels (wood-chips, pellets), waste (Boden, Kiruna), waste gas (Luleå), waste heat (Luleå, Piteå) and peat (Gällivare, Haparanda) as fuels. Backup and peak boilers can be fossil fuel operated, but are utilized only 1–2% per year [167,168].

Significant additional resource potentials for biomass use for energy exist, the northern counties only utilize 15% of primary forestry residues, while in southern parts of Sweden about 55% are used [118].

Summary—Forestry Industries

The northern counties in Finland and Sweden have widely utilized the potentials for integration of energy systems between forestry industry and DH. More energy peat in Finland can be replaced by biomass from forestry. Further integration potentials may exist but need to be examined case by case. Norway has no significant forestry industry in the northern parts of the country, hence no potential for integration.

4.7.2. Mining and Minerals Processing

Mining and processing of mineral ores is energy intensive, with major consumptions of electricity, metallurgic coal, natural gas and vehicle fuels. The Nordic region of Finland, Norway and Sweden is the heart of European mining, but is considered as underexplored compared to other regions in the world [3]. Mining activity is increasing in all three countries following national efforts to grow these sectors and also to implement the EU Raw Materials Initiative from 2008 and 2011, aiming to reduce the dependence of EU on imported metals and other critical raw materials [169,170]. While exploitation and processing poses challenges to reliable, affordable and sustainable energy supply, as well as to the sensitive sub-arctic environment, it can also provide opportunities to the energy utility of municipalities, when, e.g., waste heat can be utilized in DH systems or when steam and heat can be delivered from DH to the industrial facilities.

Finland

The exploitation of mineral deposits has provided the raw material base for the Finnish metal industry. Finland operates 46 mines and quarries, and four out of 11 metal concentration mills are based in Lapland (Kittilä, Sodankylä, Kemi) as well as one raw steel producer (Tornio). The Government of Finland promotes new developments and private investments in the mining industry, especially in the northern and eastern regions that have significant development potentials [171,172].

Examples from Lapland include the gold concentration mill in Kittilä, not integrated with the DH system of Kittilä, which is operated with energy peat (98%) and light fuel oil (2%). Sodankylä DH, which is operated similarly with energy peat, wood-chips and oil as reserve fuel, supplies heat to nearby mining facilities. The DH utility in Tornio supplies heat to the steel and chrome works facilities produced with peat and wood-chips, firing oil and coke-gas during peak demand periods [157].

Norway

The mining and quarrying sectors in Norway are relatively small as compared to Finland and Sweden. The northern counties Finnmark, Troms and Nordland have minor mining activities. A special mapping program for these counties, the Mineral Resources in Northern Norway (MINN) program, has shown that further mineral deposits exist, which could provide the basis for new industries [173]. Only about 3% or 181 GWh of heating supply in Norwegian DH systems was sourced from industrial waste heat in 2015 [17]. A potential-study on industrial waste heat from 2009 estimates that waste heat with temperature levels above 60 °C in the range of 10 TWh is available in Norway, 4.5 TWh in the northern counties of Nordland, Troms and Finnmark [174]. One example of a successful integration of metal ore processing facilities with DH is the city of Mo (Nordland), where 99% of the produced heat originates from the industry [175].

Sweden

Sweden has 16 mines in operation, which produced 91% of iron ore, 39% of lead, 37% of zinc, 24% of gold and 9% of copper mined in the EU in 2014. In 2017 178 new exploration permits and 6 exploitation concessions have been approved [176,177]. Mining and steel industry used about

32 TWh energy, of which 19 TWh were fossil fuels and 11.9 TWh electricity in 2015, compared to a total electricity demand from the Swedish industry of about 50 TWh [5,42]. Six mines are located in Norrbotten county: five are iron ore mines, located in the municipalities of Kiruna and Gällivare, and one mine produces gold, copper and silver in Gällivare [178]. The iron ore mine and ore processing facilities in Kiruna complement the municipal DH system, which is largely based on waste incineration, with the provision of waste heat [179]. Gällivare expanded its DH system in the last decade following the growing demand caused by the opening of new mines and processing facilities and resulting in a growing population. In this case the DH system is designed to deliver heat to the industry, which is another model for integration, where the industrial year around demand contributes to a more profitable business case for DH systems in the scarcely populated northern counties [179].

Summary—Mining and Minerals Processing

Finland and Sweden have significant mining and processing facilities in the northern counties. Waste heat resources from industries are well utilized, where locations of industries and DH units are close to each other. One case of mineral processing industry integration with DH exists in Mo, Nordland, Norway.

4.7.3. Iron and Steel Industry

Iron and steel production sites are major consumers of energy (electricity, coal, gas) and also have the potential to deliver waste heat and process gases from their coking plants, blast furnaces and steel plants to existing DH systems and to other industries nearby.

Finnish iron, steel, metal processing and manufacturing industry is well developed and is a major contributor to value creation and export in Finland [180]. Most iron and steel-works in Finland are integrated with municipal DH systems.

In Norway two smelter facilities are located in Troms and Nordland which fall into this category. The Finnfjord AS ferrosilicon (FeSi) smelter is located in Finnfjordbotn in Lenvik, five kilometers from the town of Finnsnes and is not integrated with the DH system [181]. The Elkem Rana AS smelter is located in the industry park in Mo (Nordland) and supplies waste heat to the local DH system [182].

One of the 13 Swedish iron and steel works (SSAB) is located in the municipality of Luleå, Norrbotten. It delivers process gases to the Luleå DH–CHP plant. Electricity and steam is supplied back to SSAB and heat is delivered into the DH system [183,184].

Summary—Iron and Steel Industry

Sweden and Finland are among the top 50 steelmakers in the world and have significant iron and steel facilities in the northern counties, which are integrated with municipal DH systems (Luleå, Norrbotten and Tornio, Lapland). Norway produces a relatively small amount of iron ore and has no crude steel production [185], one ferrosilicon smelter in Mo (Nordland) delivers waste heat to the local DH system.

4.8. Wave and Tidal Power

In addition to the above mentioned electricity generation options, ocean power technologies (such as wave and tidal energy, ocean stream, ocean thermal and osmotic power) have to be considered for their significant potentials to contribute to the future electricity supply system in the northern regions of Europe. Referring to a length of 500 km along the North Sea coast of Norway, the estimated theoretical yearly generation potential from wave power is 10.5 TWh at a distance of 21 km from the shore and 14.7 TWh at a 70 km distance. The total 25.2 TWh would represent a 17% share of Norwegian annual power generation in 2017. The total North Sea wave potential was estimated at 76.8 TWh [186]. The theoretical potential from tidal current energy resources in Norway has been estimated at 17 TWh [187].

5. Energy Situation in Nordic Municipalities

Municipalities located in Lapland, Nordland, Troms, Finnmark and Norrbotten are small in terms of population but large in terms of geographical area (Table 9) [16–18]. Other common challenges are the decline of the population in the rural areas and the ageing of the population, which results in declining supply of a skilled and experienced work force to the industries. Bigger cities, which offer functioning public services and employment opportunities, can withstand this trend and experience population increase to some extent. A growing mining industry, the political will to develop a bioeconomy based on the existing forestry, paper and pulp industry and also the establishment of new industries, such as data centers, have the potential to provide new opportunities for economic development in this region and to increase energy demand.

Table 9. Northern counties, population, area, nr of municipalities.

Northern County	Population	Area (km^2)	Population Density (pple/km^2)	Nr. of Municipalities	Nr. of Munic. Population >50,000	Nr. of Munic. Population 20,000–50,000	Nr. of Munic. Population 10,000–20,000
Lapland	180,207	100,367	1.80	21	1	2	-
Finnmark	76,149	76,149	1.00	19	-	1	2
Troms	161,771	25,877	6.25	25	1	1	1
Nordland	241,906	38,456	6.29	44	1	1	4
Norrbotten	251,080	98,911	2.54	14	1	3	2

The high numbers of energy intensive base industries contribute to a much higher than national average electricity demand per capita. The almost double heating demand per m^2 as compared to southern regions of these countries results from prevailing arctic climate conditions.

The electricity supply of the cities and industries of these northern counties is secured through national electricity systems, interconnected with each other and integrated in the Northern region of the European grid. Larger cities typically own and operate electricity distribution and DH systems. Some own or part-own hydropower stations, wind parks or supply electricity from DH–CHP facilities. All these northern counties contribute significantly to secure the electricity supply in the respective countries with their exploited natural resources—hydro, biomass, energy peat and wind. As it was shown in Section 4 further significant technical and economic feasible potentials exist from all local natural resources.

The heating sectors in these counties show some significant differences. Larger cities in Lapland and Norrbotten operate DH systems, supplied by either CHP or heating plants or by industries that can provide waste heat or waste gases and that are integrated with the DH systems (Table 10). Finland also manages to economically operate DH in smaller cities or settlements of about 1000 citizens and above due to higher electricity prices (this would be more difficult to achieve in Sweden). While Lapland still co-fires large shares of local energy peat, classified as fossil fuel, with biomass, Norrbotten DH systems are to a very large extent fired with biomass only, peak load being in most cases covered by fossil fuel and also electricity. Buildings not connected to DH are heated by electric heating systems, direct or water-based, heat-pump solutions, biomass and to a small and decreasing extent by fossil fuels (or by a combination of the above) [16–18].

Table 10. Counties, municipalities, nr of DH systems, nr of CHP plants in DH, nr of integrated DH systems with industry.

Northern County	Nr. of Municipalities	Nr. of DH *	Nr. of CHP	Integrated with Industry	Comments
Lapland	21	17+	4	3	Energy peat still plays an important role
Finnmark	19	4	-	-	2 DH are probably out of operation
Troms	25	5	-	2	1 is out of operation
Nordland	44	9	-	1	2 DH are probably out of operation
Norrbotten	14	14+	5	3	Integration with industries in 3 cities and with waste incineration in 2 cities.

* The number presented was retrieved from several public sources, mostly municipal websites, for smaller cities the situation is unknown, they not always have websites or otherwise publicly available information.

Norway has no long tradition with DH. A reliable, cheap and abundant electricity supply since many decades created a lock-in effect in the heating and building sector, and also the lack of a larger forest industry and long transport distances for forestry residues, especially in the northern counties, have contributed to this reliance on electricity for heating. About 90% of buildings have direct electric heating, which has effectively inhibited a switch to water-based heating systems due to high investment costs. The Government of Norway has supported the development of DH to reduce increasing electricity consumption from heating demand by utilizing other local resources, such as biomass, waste, waste heat and sea water in combination with heat pumps [106]. Since then, many, (also smaller) municipalities have invested in DH, supplying public buildings and industrial facilities and encouraging developers of new buildings to invest in water-based heating systems and to connect to the DH-grid. However, some of the new smaller DH-systems were forced to stop operations due to economic difficulties [188–190].

While in Sweden it is mandatory for a municipality to develop and maintain an energy plan and to actively improve energy efficiency within its administrative area [191–194], municipalities in Norway and Finland lack these legal obligations, but most are committed to contribute to national targets through voluntary agreements, as published in municipal energy and climate strategies and plans. Many support programs exist, implemented by national and local energy agencies, which include capacity building activities and financial incentives, to enable municipalities to achieve their own commitments for emissions reductions and increased shares of renewable energy production and consumption. Nordic municipalities also actively participate in national and international networks such as the Covenant of Mayors for Climate and Energy [195].

6. Conclusions and Outlook

The rich natural resources in the counties of Lapland (Finland), Finnmark, Troms, Nordland (Norway) and Norrbotten (Sweden) have attracted energy intensive industries in the past decades, and new investments in mining and industries are in progress to further utilize these resources and to counteract population decline by creating employment opportunities. These counties already provide significant shares of national electricity generation by exploiting hydropower, biomass from forestry, energy peat and increasingly wind power. In most of the larger urban settlements in Lapland and Norrbotten heating is typically dominated by biomass-fired DH and integration with industries, while Finnmark, Troms and Nordland largely rely on electric heating.

Relevant additional technical potentials do exist from renewable energy resources, including hydropower, on– and offshore wind power, solar, biomass from forestry, energy peat, waste and biogas, oceanic waves and tides, and integration with industries. Such technical potentials are reduced by many factors, but the remaining sustainable techno-economic potentials are still significant for most of the alternatives. The utilization of these potentials will require investments in transmission infrastructure.

This study makes it apparent that further research is needed into regional energy systems analysis, scenario development and system optimization in order to address the increase in electricity demand from new industrialization, the loss in generation capacity due to nuclear and fossil fuel phase out, and the challenges related to the growing shares of intermittent power supply. New industries located close to municipalities will result in a better integration of energy systems. Forestry residues are widely underutilized in Norrbotten, so the research and development for their conversion into biofuels should be intensified. Lapland needs to reduce the consumption of energy peat and substitute it with other types of biomass. This requires a further detailed analysis of biomass supply potentials, also considering the increasing demand of biomass for biofuels. Small scale DH is often not profitable, but research in improving the technology and the integration with electricity supply, heat pumps, storage tanks and solar thermal solutions could make such systems more economically feasible. Advancing battery and thermal storage technologies, but also power-to-gas-to-power concepts, can complement the hydro-pump storage and hydropower balancing capacities, which will be essential to maximize utilization and integration of intermittent renewable energy resources.

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