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The many faces of heating transitions. Deeper understandings of future systems in Sweden and beyond

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ABSTRACT

Swedish buildings require additional heating inputs for many months each year, much of which comes from district heating systems fed by fuel combustion, electrical devices and recycled heat sources; localised heating is also generated within individual buildings. Optimised projections using the EnergyPLAN model for a so-called "smart energy" scenario predict dramatic reductions in biomass use accompanied by increases in electricity, recycled heat and biogas. Electricity generation routes are also predicted to change, shifting away from nuclear and biomass sources towards wind, solar and biogas technologies. While such transitions are expected to lower greenhouse gas emissions, current assessment methods rarely examine the breadth of other environmental and material supply aspects at play. Here, a novel new approach provides deeper insights into current and future Swedish heating scenarios for 11 key indicators by considering heat production processes over their full life cycles. Results suggest that favourable reductions are likely in five of these indicators, but these benefits are offset by unfavourable outcomes in others, including all three raw material supply indicators. Ultimately, the study provides a novel example of ways in which additional tools can complement existing modelling techniques and expand the scope of available information used to assist heating transition decisions.

1. Introduction

As with all Nordic countries, Sweden has a cold climate and heating is required for eight to 10 months of the year in most regions [1]. As a consequence, it consumes approximately 50 % more heat energy per person, on average, than the EU as a whole. Not surprisingly, the use of district heating in Sweden is high: in 2014 approximately 93 % of multi-residence buildings were connected to a district heating network [2]. However, this has not always been the case.

Fig. 1 displays the market share percentages of the different heating techniques employed to heat buildings in Sweden between 1960 and 2020. The data indicates that the use of individual oil-based heaters dominated the market during the 1960s, but sharply declined in popularity in the wake of the global oil crisis in the 1970s [3]. District heating subsequently rose in popularity and has continued to steadily increase its market share, mostly under municipal ownership. A national program to develop public housing between 1965 and 1974 assisted in the rise in popularity of district heating as most new buildings were designed specifically to include district heating connectivity [4]. Nevertheless, coal was the dominant fuel in these district heating systems until the end of the 1980s when biomass began to take over the market [5].

Outside of centralised district heating systems, deregulation of the electricity market in 1996 led to an increase in the use of individual heat pumps [4], which have continued to gain acceptance in the last 20 years to become the main competitor to district heating overall [2]. In fact, Sweden is now one of the top countries in the world for heat pump ownership per capita [1] and over half of its residential buildings now have at least one heat pump installed. In this arena, small-sized units tend to be installed in one and two dwelling houses and medium-sized units are used in apartment blocks and commercial buildings; much larger units are used in district heating applications. Lastly, many residents–particularly those in rural and isolated areas of the country where district heating systems are not present–still rely on the traditional

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method of heating their homes via the combustion of oil, biomass and other fuels. Indeed, Fig. 1 suggests that this method of heating still occupies around 9 % of the heating system overall.

District heating is a method for distributing thermal energy–in the form of steam or hot water–throughout a series of insulated pipes to provide heating to multiple buildings within a local network [7]. It is mostly used for space heating applications and to provide hot water to residents and businesses. At present, heat used in district heating systems is predominantly derived from the combustion of fuels [8]. This can be undertaken in heat-only boilers and alongside electricity generation processes in combined heat and power (CHP) plants. Heat can also be obtained from various forms of recycled heat; the use of excess heat from industrial processes and the combustion of fuels condensed from flue gases are common examples of this. Thermal energy is sometimes also transferred directly to district heating networks from geothermal and solar sources. Lastly, electricity can be used to generate system heat using electric boilers and heat pumps of different sizes.

Much like traditional electric boilers and heaters, heat pumps are devices that use electrical energy to produce volumes of warm air or water suitable for heating applications. In a heat pump system, a compressor is used to circulate a refrigerant within a closed loop in order to amplify temperature differentials, much like an air conditioner in reverse [1]. Here, the coefficient of performance (COP) reflects the ratio of heat energy produced to electrical energy used; values of COP depend on the temperature differentials at play but are generally between two and seven for most applications [9,10]. As such, heat pumps offer efficient and attractive pathways for heating spaces using electricity, particularly if renewable forms of electricity can be used. As a result, the use of heat pumps is projected to become an important element of sustainable heating systems and they are widely predicted to achieve wider presence in the district heating systems of the future [4]. More importantly, they are also rapidly gaining popularity as a standalone method for vastly improving the efficiency of heating in buildings [11], particularly in areas where district systems are not available or viable.

Transitioning away from the combustion of fossil fuels in producing heat energy–and, indeed, in producing the electricity used to power heat pumps, boilers and heaters–is widely seen as a way of reducing the environmental burdens associated with heating systems, especially in relation to greenhouse gas (GHG) emissions. Unfortunately, the majority of existing studies that incorporate the environmental impacts associated with heating systems tend to focus solely on GHG emissions. Additionally, within this limited scope, they tend to only consider emissions that occur during the final combustion processes that produce heat energy within these systems. In doing so, these studies neglect the vast number of other emissions–and, indeed, environmental burdens–that occur in other parts of a heating system. Furthermore, they ignore the various material extraction, manufacturing, transportation, maintenance and disposal stages involved in creating and operating heating infrastructure. In an attempt to fill this gap, many are now suggesting that transition pathways should be scrutinised with more rigour so that a deeper and more robust set of environmental and other indicators [12,13] can be identified. Doing so would allow analyses to look beyond simple economic and GHG targets and to consider the impacts relating to all stages and physical aspects of heat production processes [14].

More recently, the incorporation of life cycle assessment (LCA) methodologies into the analysis and modelling of energy systems has been specifically highlighted as a way of integrating these improvements [15–18] and a wide range of studies are now beginning to use LCA concepts for examining transition strategies. The majority of past energy related LCAs have investigated specific technologies or locations [19], although recent efforts have attempted to examine outputs for entire systems, typically by pairing LCA calculations with the outputs of energy models. For example, a significant amount of progress has been made to link global integrated assessment models (IAMs) with LCA calculations [16,20–22] and to smaller national or regional energy models [14,17,23]. It is also worth noting that the usefulness of LCA data in assessing energy systems need not be limited to the direct use of impact indicators. Inventory data from LCA databases can also be used to provide raw material data for processes on a per-unit basis. As such, this data can also be used to derive a variety of material-related indicators using customised methodologies.

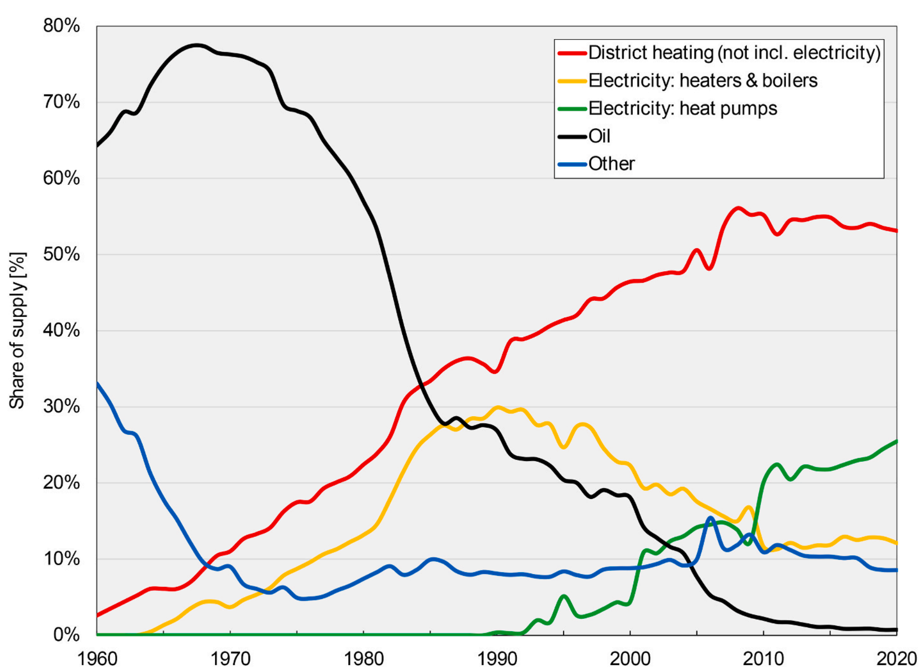

Fig. 1. Generation sources, by percentage of energy share, for heat supply to residential and service sector buildings within the Swedish energy system. Note that all forms of electrical heat generation are grouped together, including those used in district heating networks. As such, district heating totals do not include the electrical component. The “Oil” and “Other” categories incorporate all other sources at the localised building level. This includes, for example, the combustion of oil, logs, wood pellets and natural gas in decentralised boilers, fireplaces and furnaces. Data sources [2,6].

In any case, Bartolozzi et al. [24] report that, historically, very few LCA studies have been conducted that specifically evaluate district heating systems. Furthermore, the identified studies–and, indeed, the few more recent investigations–are almost all centred upon specific technologies or stages of a process, or on systems at the facility or city scale [25–27]; similar conclusions about the scarcity of detailed LCA-based analyses were also drawn by Jeandaux et al. [28].

To fill this gap, a methodology was derived for undertaking more detailed environmental assessments of full district heating configurations. To the best of our knowledge, the study represents the first time that the LCA approach has been applied to a national level system and incorporates all aspects of a heating system, including the electricity inputs to a system and the contributions of both district heating and isolated heat generation. Moreover, it is one of the few studies designed

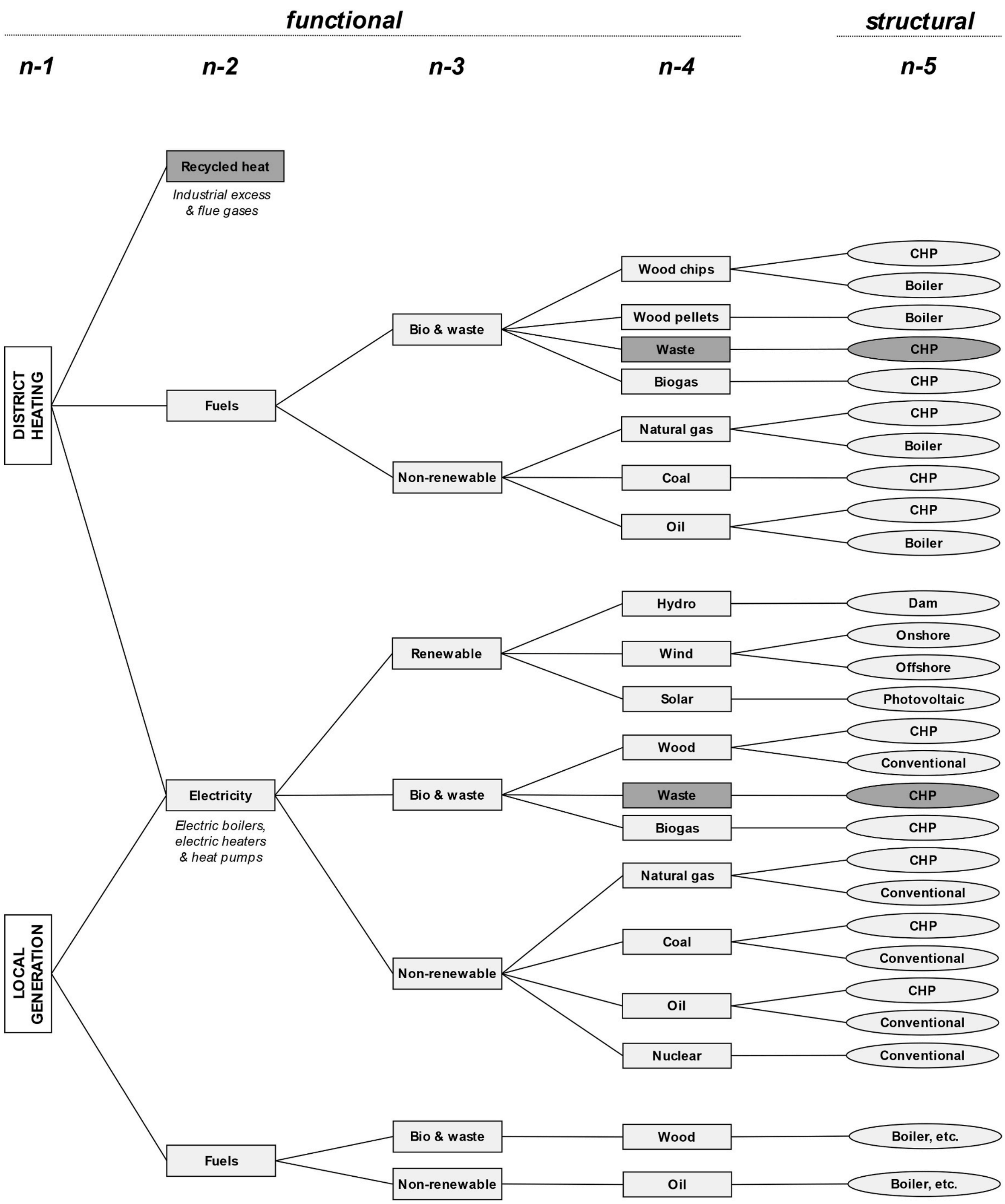

Fig. 2. Representation of Swedish heating system used in the analysis. District heating systems receive inputs from the direct combustion of fuels, heat generated from utility-scale electrical heat pumps and boilers, and from recycled heat sources. Locally generated forms of heat are also included, assumed to be from smaller-scale electrical boilers, heaters and heat pumps, and from combustion boilers, fireplaces and furnaces assumed to predominantly burn wood and oil, all of which occurs at the building level. All electrical inputs to both groups are disaggregated into typical technological categorisations and scaled according to "energy mix" data for electricity within a given scenario. Note that heat and electricity from waste and recycled heat sources–shown shaded in the figure–are not included in the impact analyses as they are assumed to be essentially "neutral" processes. However, in reality, some smaller impacts are still likely to be generated in relation to the infrastructure related to these activities.

to facilitate a thorough analysis and comparison of historical system configurations *and* future configurations defined by optimised modelling outputs.

Here, we apply a newly derived approach [14]–developed within the Sustainable Energy Transitions Laboratory (SENTINEL) project [29]–to enable a wide variety of environmental and material supply indicators to be quantified using historical data for the Swedish heating system. More importantly, we couple the workflow to outputs from the EnergyPLAN model [30,31] to provide a more-detailed overview of a potential future scenario for the system. In doing so, we provide a further demonstration of the broader range of useful indicators that can be produced when linking energy models with methodologies that allow more complete assessments of environmental outcomes to be made using detailed LCA data.

The analysis begins by defining the system in accordance with the available data, including all inputs to district heating networks and locally generated heat sources. Separate analyses are then undertaken for historical configurations from 2015 and 2019 and compared to a projected "smart energy" scenario for the system in 2050 using results from the EnergyPLAN model. The sections that follow provide a thorough description of the input data, presentation of the results obtained for a range of indicators and a final discussion of the key outcomes.

2. Methodology

In order to assess the characteristics of different historical and future configurations of the Swedish heating system, a customised version of the ENBIOS workflow [14] is defined and implemented, as described in the sections that follow.

2.1. System definition

The first stage of the analysis involves the definition of a customised hierarchical structure for the system at hand. The structure is based on the "dendrogram" concept defined within the MuSIASEM accounting method [32] and is governed by the available data and goals of the analysis. In this case, a dendrogram was created to represent the supply of heat energy within the Swedish energy system, as shown in Fig. 2. Here, the hierarchy captured in the dendrogram is defined in accordance with the available categories provided in the historical data [33,34] and projected modelling outputs [35] for Sweden. Firstly, it includes the heat energy distributed within district heating systems. This includes heat derived from the direct combustion of fuels, from utility-scale electrical infrastructure such as heat pumps and boilers, and from so called "recycled" sources like industrial excess heat and flue gas condensation. Secondly, heating generated in individual buildings *outside* of district heating systems are considered. This includes the combustion of oil, biomass and other fuels in local boilers, fireplaces and furnaces and the use of smaller-scale electrical heat pumps, boilers and heaters at the building level.

In the end, 27 structural processors at the "n-5" level are aggregated into 10 source categories at the "n-4" level: hydro, wind, solar, wood/biomass, waste incineration, biogas, natural gas, coal, oil and nuclear. These are further grouped into three renewable energy classes at the "n-3" level: renewable, non-renewable, and bioenergy and waste. The direct use of fuels and the use of electricity are then delineated at the "n-2" level; the utilisation of recycled heat is also included at this level. Ultimately, the heating system is reduced to district heating and local generation processes at the "n-1" level. It should be noted that heat and electricity generated from the incineration of waste and recycled heat sources are included in the system definition but are not considered in the impact analyses beyond the summary of energy sources. This is because such sources are considered to be essentially "neutral" processes based on the use of existing sources of energy that would otherwise go unutilised. Nevertheless, it is recognised that, in reality, some impacts would be generated from the infrastructure related to these processes.

2.2. Additional specifications

With the system specified, a selection of additional specification data is required to define the way in which the analysis is undertaken. First of all, individual life cycle inventory (LCI) data is required for each of the structural processors in Fig. 2; these are taken from v3.8 of the Ecoinvent LCA database [36,37]. Where possible, specific processes for Sweden are chosen. Where this is not possible, nearby countries or regional processes for Europe are used; global or "rest-of-world" values are used only when no other appropriate processes are available. A summary of the processes assigned to each processor in the defined system is given in Table S1 in the supplementary material. Where multiple suitable listings are available, an effort is made to select processes that represent the average or most typical values in that category to avoid biasing issues resulting from processes that reflect outlier values. Again, as no indicators are to be generated for waste incineration, no definitions are supplied for these processes.

Final indicator values are then able to be calculated using the standard workflow [14]. The majority of these indicators use life cycle impact assessment (LCIA) methods to generate a range of environmental impact and resource use indicators. These methods are again taken from v3.8 of the Ecoinvent LCA database; all selections are part of the "ReCiPe Midpoint (H)" group [38]. Values for three additional raw material indicators are also derived using the material requirement values from LCI listings in conjunction with previously defined methodologies [39,40]. A summary of the methods adopted for calculating the final 12 indicators is provided in Table 1.

2.3. Historical data

The Swedish Energy Agency (Energimyndigheten) provides detailed annual data for district heating and electricity supply systems as part of its "Electricity supply, district heating and supply of natural gas" ("El-, gas-och fjärrvärmeförsörjningen") series of reports. For district heating, the reports provide totals for the generation of district heating from fuels, and the breakdown of which fuel inputs provided these outputs for both CHP plants and heat-only boilers. Accordingly, total amounts of energy generated from each fuel and plant type can be calculated. Here, ten of the most common fuel/plant combinations are used; where only one plant type is significant, the combined totals of both are used. Values are also provided for industrial excess heat and flue gas condensation, collectively assigned as "recycled heat" sources. Calculated final totals using the 2015 [41] and 2019 [33] versions of the report are shown in Table 2. Values are also shown for heat created via local generation processes–i.e., those outside of district heating systems–based on data from the Swedish Energy Agency and available elsewhere [2,6]. It is worth noting that values for 2020 are not used in the analysis as they are significantly different than those in preceding years as a result of drastic changes in energy use patterns resulting from the COVID-19 pandemic.

Electricity inputs into the electric boilers and heat pumps used within district heating systems for these years are also listed in the respective reports and are summarised in Table S2 in the supplementary material. No specific historical data is available for the use of electricity in heat pumps, heaters and boilers outside of district heating systems. However, the *total* amounts of electricity used to generate heat in *all* applications are also available elsewhere [2,6]. Subtracting district heating input amounts from these totals, therefore, provides the totals used to generate heat from electricity at local levels. The heat totals created in these processes are then calculated assuming direct 1:1 conversion for boilers and heaters and a COP of 2.0 for heat pumps, as per previous historical estimates for Sweden [6]; it is noted that historical COP values for district heating are reported to be between 3.9 and 4.2.

Thorough breakdowns of electricity generation are also provided by the Swedish Energy Agency for 2015 [41] and 2019 [33]. A summary of the electricity mix, by technology, is shown in Table 3. Note that no distinction between onshore and offshore wind energy is provided in the

Table 1
Listing of methodologies used in deriving final indicators. A full listing is contained in Table S1 in the supplementary material.

Group	Indicator	Method	Units
Total energy	Energy generation	Summing heat output values	TWh
LCIA [37]	GHG emissions	"climate change", GWP100	Tg CO_2-eq
	Land occupation	"agricultural land occupation", ALOP + "urban land occupation", ULOP	x10^3 km^2
	Water depletion	"water depletion", WDP	TL
	Fossil depletion	"fossil depletion", FDP	Tg oil-eq
	Metal depletion	"metal depletion", MDP	Tg Fe-eq
	Freshwater eutrophication	"freshwater eutrophication", FEP	Gg P-eq
	Marine eutrophication	"marine eutrophication", MEP	Gg N-eq
	Human toxicity	"human toxicity", HTPinf	Tg 1-4-DC
Raw materials	Material supply risk	[39,40]	yr
	Env impacts relating to material supply	[39]	yr
	Env justice issues relating to material supply	[39]	yr

Table 2
Summary of historical and projected heat generation in district heating systems and at the local generation level. A single plant type is use in instances where one type dominates the observed data or where only one type is represented in the LCI database. Sources [2,6,33,35,41]:

	Fuel	Plant type	Heat generation		
			2015	2019	2050
			[GWh]	*[GWh]*	*[GWh]*
District heating					
Recycled heat			*8816*	*9377*	*18,190*
Fuels	Wood chips	CHP	12,066	12,188	1,939
		Boiler	5,622	5,671	463
	Wood pellets	Boiler	2,637	2,260	184
	Waste	*CHP*	*12,019*	*13,893*	*5,876*
	Biogas	CHP	30	116	7,754
	Natural gas	CHP	1,221	741	
		Boiler	85	23	
	Coal	CHP	1,938	1,270	
	Oil	CHP	371	348	
		Boiler	397	251	
Electricity			4,503	3,899	14,992
Local generation					
Electricity			24,989	29,329	31,338
Fuels	Wood		8,400	7,210	4,250
	Oil		900	600	

Table 3
Summary of historical and projected electricity mix by technology. Sources [33,35,41]:

Technology group	Plant type	Share in electricity mix		
		2015	2019	2050
		[%]	*[%]*	*[%]*
Hydro		46.6	38.8	21.9
Wind	Onshore	10.0	11.8	47.7
	Offshore		0.004	16.5
Solar		0.1	0.4	7.5
Wood	CHP	5.5	6.6	0.6
	Conventional	0.002	0.002	0.8
Waste incineration		*1.7*	*2.1*	*0.9*
Biogas		0.005	0.008	4.1
Natural gas	CHP	0.3	0.2	
	Conventional	0.04		
Coal	CHP	0.6	0.5	
	Conventional	0.2	0.1	
Oil	CHP	0.2	0.2	
	Conventional	0.1	0.04	
Nuclear		34.8	39.3	

data. Despite this, the Global Wind Energy Council (GWEC) provides breakdowns of installed capacity for Sweden for both years [42] and this data was used to further delineate the single wind energy totals. Nevertheless, the totals for offshore wind remain very low.

2.4. Projected data

Predictions for 2050 are provided by modelled outputs from the EnergyPLAN model [30,31], as listed in Table 2. In particular, results were provided for Sweden [35] as a sub-region within a wider model simulation of a "smart energy" scenario [43,44] for the European energy system created as part of the sEEnergies project [45]. This scenario seeks to maximise the use of renewable energy technologies while creating a more flexible energy system where interactions between sectors are optimised. Outputs from the model provide a thorough inventory of district heating outputs from boilers and CHP units for a range of fuels. However, in this scenario it was assumed that all energy produced in boilers and CHP units are fed by wood chips, wood pellets and biogas; natural gas and all other fossil fuels are assumed to have been phased out by 2050. Nonetheless, it is noted that EnergyPLAN provides a single total for biomass use and no distinction is made between raw wood chips and processed pellets. Therefore, to maintain this delineation and allow comparison with the historical scenarios, the biomass total is split according to the observed ratio for 2019 [33]. Values for recycled heat sources are also given, as are the totals from the local combustion of fuels, assumed to be entirely derived from wood products in 2050.

The amounts of heat generated from electricity in the 2050 scenario–in district heating and localised applications–are also shown in Table 2; a full listing of the inputs and outputs for different infrastructure at each of these levels is also provided in Table S2 in the supplementary material. Note that the values for electricity inputs to electrolysers–that generate hydrogen later used in district heating networks–and for heat supplied from solar thermal infrastructure are also supplied in the EnergyPLAN data. Here, these values are arbitrarily bundled into the electricity totals for district heating because no life cycle assessment (LCA) data is available for these processes.

Again, electricity inputs and heat output totals from heat pumps are defined in accordance with a given COP value; a value of 4.0 was assumed in the EnergyPLAN calculations for district heating. However, for localised heat pump use, only the electricity inputs to these devices are included in the EnergyPLAN results. Although a conservative COP value of 2.0 was used for historical heat pump data calculations [6], a COP of 3.4 was assumed when calculating outputs from future local heat pumps, in line with estimates for more advanced household heat pump technologies [46]. This also enables the total heating supply to be approximately in line with historical totals. Meanwhile, all boilers are again assumed to simply convert electricity to heat in a 1:1 ratio.

For the electricity itself, EnergyPLAN provides a detailed breakdown of all contributing technologies, including the split between CHP and boilers, where appropriate. A summary of the projected electricity mix, by technology, is listed in Table 3. The sum of electrical inputs to heat generation can then be proportioned pro-rata to the different electrical generation processes.

A breakdown of the total inputs to the Swedish heating system–as defined in Fig. 2–is provided in Fig. 3. It includes historical data for 2019 [6,33] and projected values for 2050 [35]. The data indicates that the

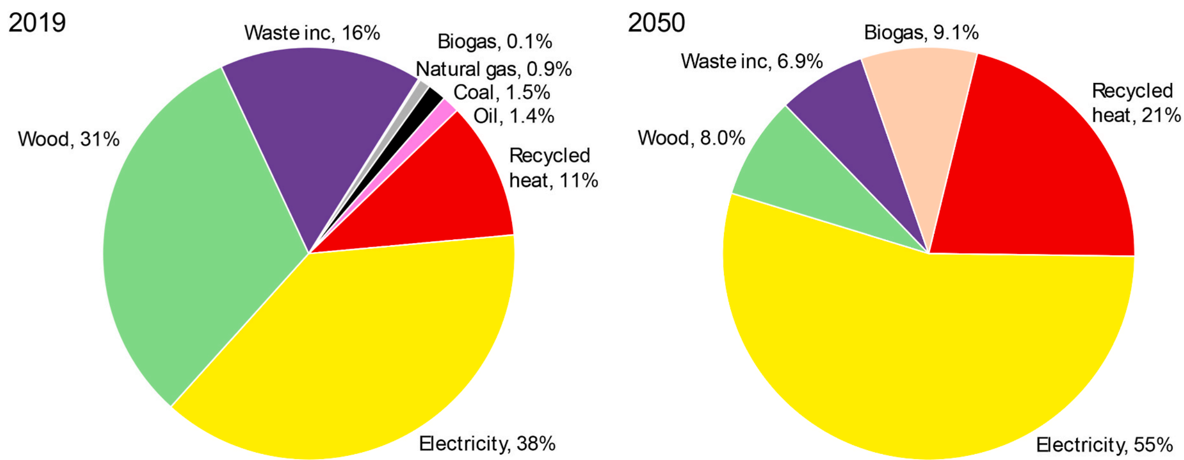

Fig. 3. Historical and projected percentage breakdowns of total heat generation. A further breakdown of the electricity component is given in Fig. 4. Data sources [6,33,35].

share of electricity use is expected to rise from 38 % to 55 %. Most notably, this projection assumes a drop in wood biomass use from 31 % to around 8.0 %. The direct use of waste in incinerators is predicted to decrease from 16 % to 6.9 %, while biogas derived from waste will rise from negligible levels in 2019 to around 9.1 % in 2050. All fossil fuels will be eliminated. The breakdown of electricity generation, as illustrated in Fig. 4, is also expected to change. The biggest change is the complete elimination of nuclear power, which represented 39 % of generation in 2019. Wind energy is the biggest mover in replacing nuclear power, rising from 12 % to 64 %; this move also impacts hydro power, which drops from 39 % to 22 %. Solar power also makes a noticeable impact in the electricity market, rising from negligible levels in 2019 to attain a 7.5 % share by 2050. Fossil fuels are also eliminated in the electricity sector and the use of wood and waste reduces significantly. Biogas is again predicted to achieve a small penetration in the market, achieving a 4.1 % share by 2050.

3. Results of analysis

With the system specified and all historical and projected data in place, results are generated at each processor in the dendrogram for each of the indicators listed in Table 1. Scaling of LCI processes is performed using the final amounts of energy that relate to each processor. For heat, the final generation values shown in Table 2 are used. For electricity, the total amount of energy *input* values–as listed in Table S2 in the supplementary material–are used in conjunction with the technological mix data in Table 3.

3.1. Summary of overall changes

A summary of the percentage changes forecast to occur between 2019 and 2050 is given in Table 4. Firstly, as a sanity check, the total amount of heat energy generated in the system under each scenario was assessed and was only observed to vary by 2.5 %; this is well within the range of typical annual variations. Of the 11 proper indicators, adverse changes–where increases are observed–are predicted to occur in six indicators. All of these changes are notably high, from a 98.7 % increase in freshwater eutrophication to a rise of 329.6 % in relation to the environmental impacts generated from raw material extraction. Beneficial changes between 2019 and 2050 are observed in the remaining five indicators, all of which reduce by at least 38 %. The phasing out of fossil fuels, wood biomass and nuclear power by 2050 has resulted in many reductions in key indicators. However, replacing these sources with other renewable energy and bioenergy technologies is also shown to have detrimental effects on future outcomes, especially with respect to wind, solar and biogas sources.

3.2. Findings for key indicators

Results for six key indicators–total heat generation, GHG emissions,

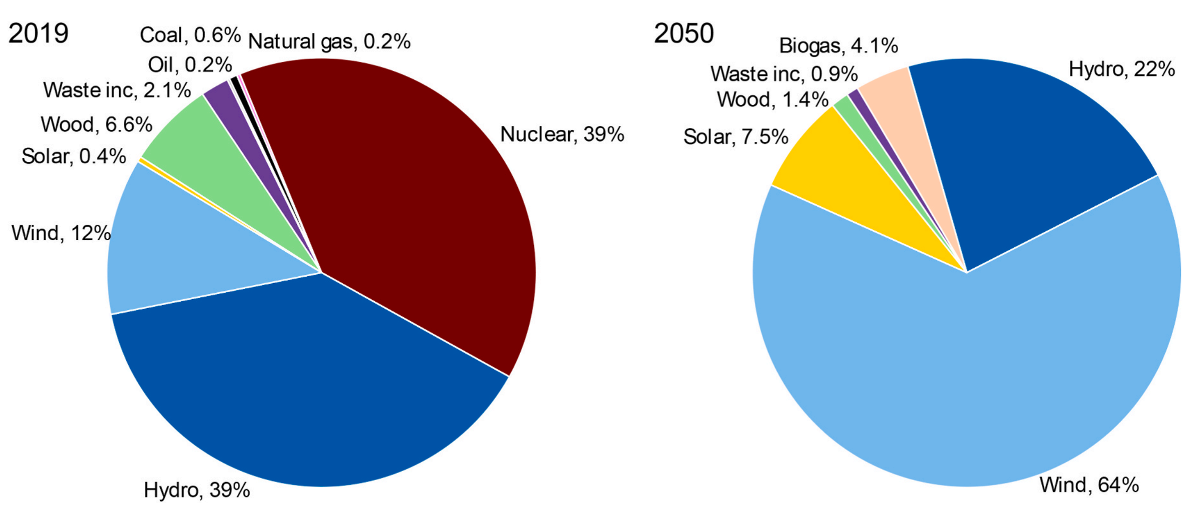

Fig. 4. Historical and projected percentage breakdowns of electricity generation. Data sources [33,35].

Table 4
Summary of percentage changes observed for 12 indicators between 2019 and 2050. Potentially adverse results are displayed in shaded cells. A summary of the key determinants of the predicted changes is also provided.

Group	Indicator	Observed change (2019–2050)	Key determinants of changes
Total energy	Total heat generation	−2.5 %	Annual variations
LCIA	GHG emissions	−38.0 %	Phasing out of coal, oil & wood
	Land occupation	−64.9 %	Phasing out of wood
	Water depletion	+251.7 %	Phasing out of nuclear Replaced by biogas
	Fossil depletion	−49.6 %	Phasing out of coal, oil, natural gas & wood
	Metal depletion	+110.8 %	Wind, solar & biogas
	Freshwater eutrophication	+98.7 %	Phasing out of coal & wood Replaced by biogas & wind
	Marine eutrophication	−45.3 %	Phasing out of wood
	Human toxicity	−47.5 %	Phasing out of wood
Raw materials	Material supply risk	+107.2 %	Wind, solar & biogas
	Env impacts relating to material supply	+329.6 %	Wind, solar & biogas
	Env justice issues relating to material supply	+139.3 %	Wind, solar & biogas

land occupation, water depletion, material supply risk and environmental impacts relating to material supply–are displayed in individual figures in the sections that follow. Results for the remaining six indicators are provided in **section S3** in the supplementary material. Each row of figures illustrates the totals for a given indicator for the two historical system configurations–2015 and 2019–alongside the projected system for 2050. Representations are shown for three hierarchical levels: "n-2" for fuel combustion and electricity, "n-3" for renewability category, and "n-4" for individual technology categories. Brief discussions are also provided for each indicator.

3.2.1. *Total heat generation*

Overall heat energy generation totals–which include all heat production processes and recycled sources–are predicted to remain relatively constant across the three years presented, as shown in Fig. 5. Indeed, the total in the modelled system for 2050 is within 2.5 % of the total recorded in 2019. Observing the historical values of this indicator between 2015 and 2019 reveals that changes of between 1 % and 8 % are commonplace from year to year [33,41,47–49]. This is hardly surprising considering that milder or colder winters can easily affect overall heating requirements. As such, the similarities in total between 2019 and 2050 confirm that the system data has been suitably aligned and prepared, and that direct comparisons can be made between the recorded and modelled systems for the remaining indicators.

The data presented in Fig. 5 also provides a useful overview of the fundamental changes that occur in the system between the recent historical configurations and the future configuration forecast by the model. At the "n-2" level, both fuel-based approaches are observed to lose ground to electrical approaches, particularly in district heating systems. Likewise, the use of inputs from recycled heat sources is seen to almost double between 2019 and 2050. The data at the "n-3" and "n-4" levels–which do not show recycled heat–confirm the projected move away from fossil fuel and nuclear technologies towards cleaner options. In fact, the generation of electricity and heat from wood and waste combustion are also seen to drop away notably. In their place, the use of biogas in CHP plants is predicted to rise significantly. And, while solar energy is expected to make inroads into the electricity market, by far the biggest shift at the "n-4" technological level is in the increased use of wind energy.

3.2.2. *GHG emissions*

Perhaps the most policy-relevant indicator presented here is that of total GHG emissions. Here, following a dramatic decrease of 17.0 % between 2015 and 2019, GHG emissions drop a further 38.0 % by 2050, as shown in Fig. 6. Results at the "n-3" level reveal that these reductions are largely linked to the non-renewable forms of heat. Further analysis at the "n-4" level reveals the direct connection to coal and oil between 2015 and 2019. The complete removal of these technologies, alongside natural gas and nuclear, is a predictably dominant factor in the observed changes by 2050; large reductions in wood use are also a factor. Despite the large rises in wind and solar use predicted by 2050, these processes do not contribute significant amounts of GHG emissions. However, some of these reductions are offset by the emissions created via the increasing use of derived biogas.

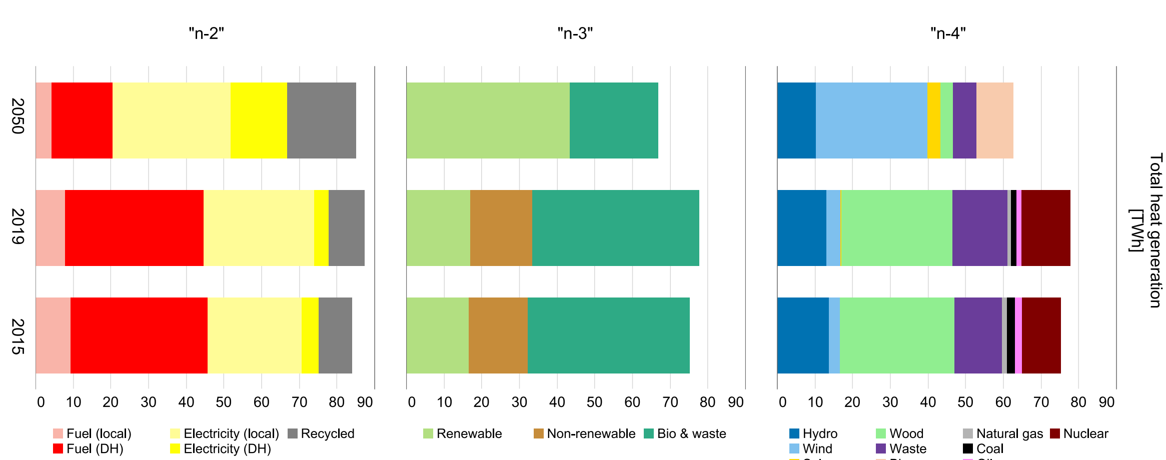

Fig. 5. Comparison of historical and predicted values for total energy generation. Results are shown across three separate hierarchical levels. Note that recycled heat is not shown in the data at the "n-3" and "n-4" levels as it is fundamentally outside of the scope of these classifications.

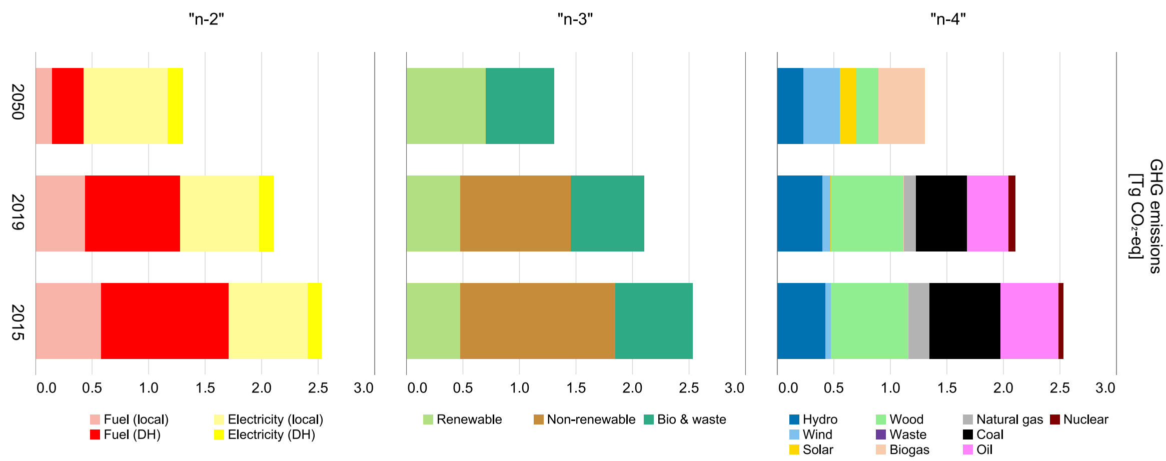

Fig. 6. Comparison of historical and predicted values for GHG emissions. Results are shown across three separate hierarchical levels.

Nevertheless, although no specific GHG emissions targets have been stated for heating by the Swedish government, the country's national energy and climate plan [50] states that net GHG emissions must be reduced to zero and all electricity must be from renewable sources by 2040. As a result, the projected scenario from EnergyPLAN certainly does not come close to satisfying current policy targets using the assumptions used in this assessment. This, again, highlights the differences between the assumptions made in LCA processes against those made in other policy-based quantifications. It also highlights the importance of changing "background" systems when making assessments for future energy systems [17,51].

3.2.3. *Land occupation*

The total areas of land required to maintain the heating system are predicted to fall dramatically under the examined scenario, as shown in Fig. 7. Indeed, the area required in 2050 is close to one third of the amount required in 2019, falling by some 64.9 %. Analysis at the three levels clearly demonstrates that these reductions are almost exclusively linked to the use of wood, which contributes a mere 5.1 % of total heat by 2050, down from 37.9 % in 2019. It is also notable that the majority of the land requirements in 2019 and 2050–totalling 85.5 % and 86.5 %, respectively–are linked to direct heat production from fuels, predominantly from wood. Indeed, wood production is clearly the overwhelming factor regarding land occupation metrics in general. Meanwhile, renewable energy sources contribute less than 1 % of the total requirement, highlighting the dangers posed by bioenergy technologies in this regard.

3.2.4. *Water depletion*

Conversely, the required amounts of water are predicted to more than triple between 2019 and 2050, rising by around 251.7 %, as shown in Fig. 8. Simple visual inspection at the "n-3" and "n-4" levels immediately reveals that this rise is strongly linked to biogas production, replacing the previous dominance of nuclear power which–according to the values presented in Table S3 in the supplementary material–itself requires particularly large amounts of water inputs per unit of energy to generate electricity in steam turbines [52]. According to the applied data [37], the use of biogas to generate heat and electricity in CHP plants requires between 16 and 3300 *times* as much water per unit of heat than all other processes being considered. As such, even though the use of biogas is only predicted to rise from 0.2 % to 15.4 % of total heat energy, its impact on water requirements here is substantial, suggesting the potential risks associated with increasing biogas use. That being said, it must be stated that the LCI data used to define biogas here is the only available listing in Ecoinvent and represents biogas from manure. It is not known if biogas from other sources–e.g., from municipal or agricultural waste or sewage sludge–would return substantially different results.

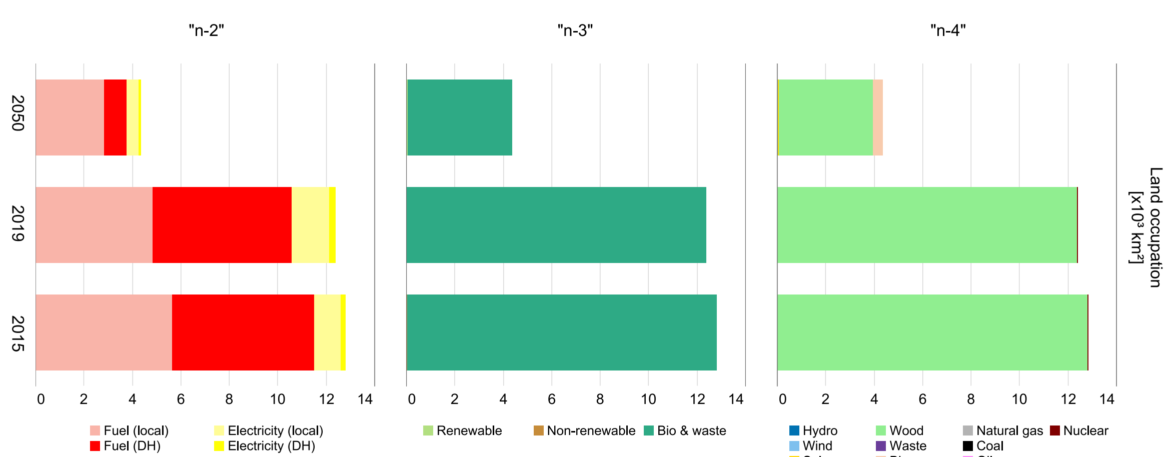

Fig. 7. Comparison of historical and predicted values for land occupation. Results are shown across three separate hierarchical levels.

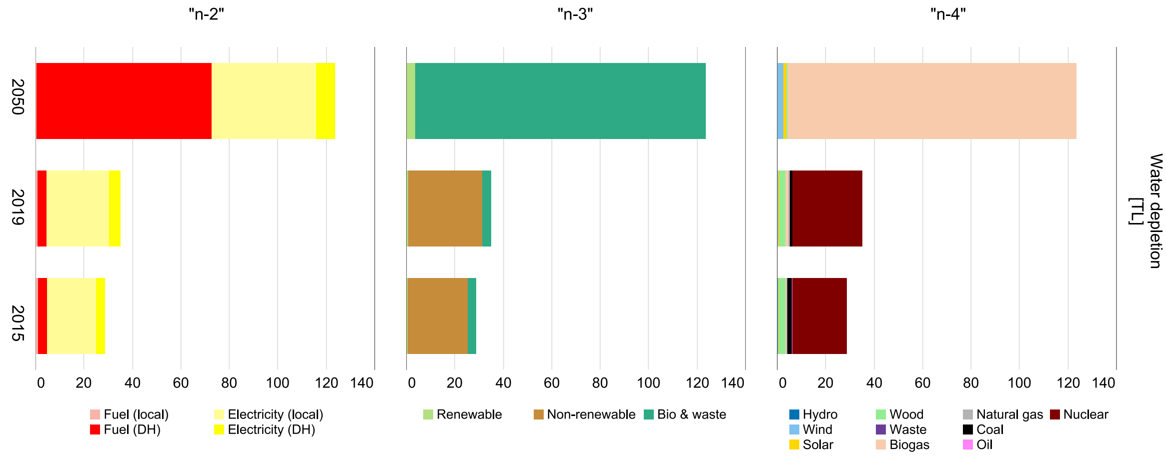

Fig. 8. Comparison of historical and predicted values for water depletion. Results are shown across three separate hierarchical levels.

3.2.5. *Material supply risk*

The overall level of raw material supply risk is forecast to more than double between 2019 and 2050, rising by 107.2 % under this scenario, as shown in Fig. 9. Inspecting the results obtained at the "n-2" and "n-3" levels indicates that this growth is strongly linked to electricity generated from renewable energy technologies, although bioenergy continues to be a factor. Closer inspection at the "n-4" level confirms that wind, solar and biogas are the key contributors to the increase, representing 58.9 %, 12.9 % and 19.5 % of the total in 2050, respectively. As with most processes, neodymium, praseodymium and samarium significantly influence the three key technological groups. Gadolinium and lanthanum are also notable contributors to most SR scores, gallium has a considerable influence on the score for solar power, while phosphorus requirements elevate the overall score for biogas.

3.2.6. *Environmental impacts relating to material supply*

An especially sharp rise is observed in the environmental impacts derived from raw material extraction and processing in the case study, as shown in Fig. 10. In fact, overall values are predicted to quadruple between 2019 and 2050, rising by over 329 %. As with the water depletion indicator, this increase is connected to both direct fuel combustion and electricity generation and is strongly linked to renewable energy and biogas use. Indeed, biogas provides around 49.6 % of the total score in 2050 and its per-unit value for electricity is around 2.42 *times* higher than all other technologies analysed at the "n-4" level (see Table S3 in the supplementary material); this is strongly linked to a higher requirement for platinum group metals (PGMs)–particularly rhodium and platinum–and to gold in some cases. Wind and solar power are again seen to be important contributors here, occupying 32.5 % and 15.0 % of the remaining share, respectively.

4. Discussion

4.1. *Results and implications*

The investigation revealed a balanced spread in results in that reductions were predicted in five of the indicators examined, while the remaining six indicators were predicted to increase. The complete phasing out of fossil fuels and nuclear power and drastic reductions in wood biomass use assumed in the EnergyPLAN scenario for 2050 resulted in beneficial reductions in the GHG emissions and fossil depletion indicators, which drop by 38.0 % and 49.6 %, respectively. At the same time, lower use levels of wood biomass are largely responsible for beneficial reductions in the land occupation, marine eutrophication

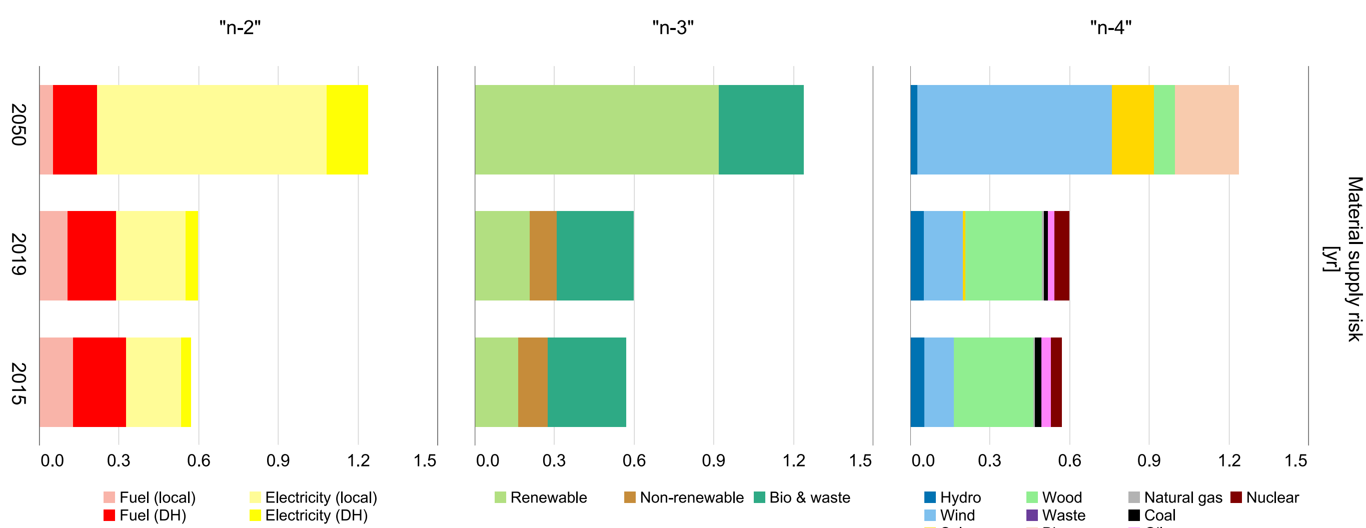

Fig. 9. Comparison of historical and predicted values for material supply risk. Results are shown across three separate hierarchical levels.

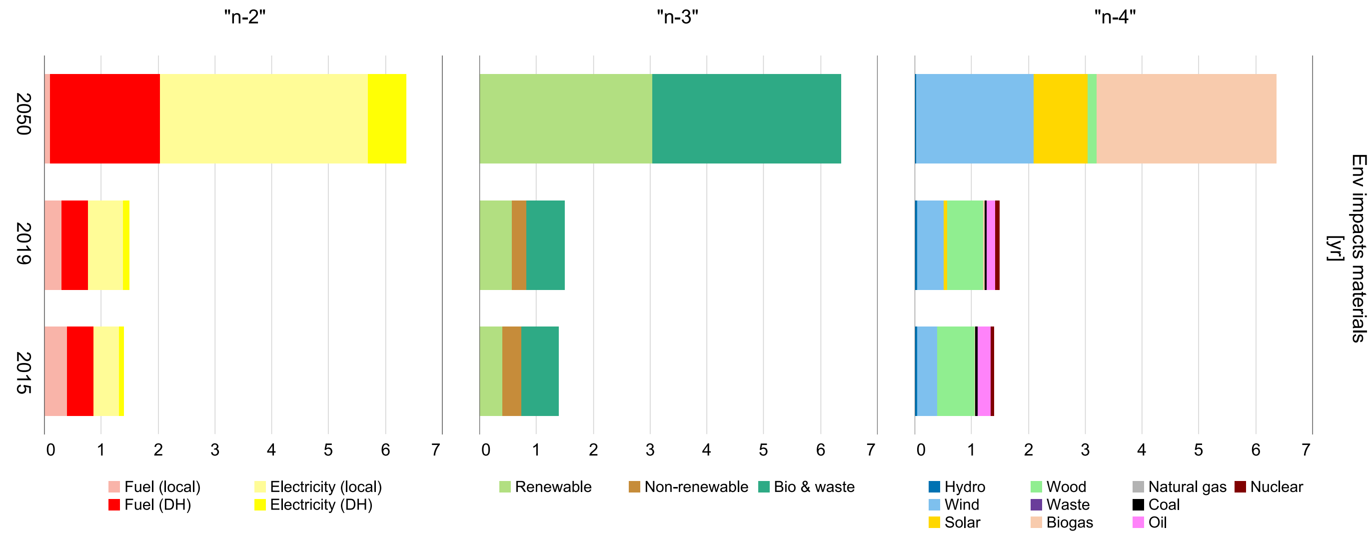

Fig. 10. Comparison of historical and predicted values for environmental impacts relating to material supply. Results are shown across three separate hierarchical levels.

and human toxicity indicators, which fell by 64.9 %, 45.3 % and 47.5 %, respectively. This again confirms the importance of reducing the use of fossil fuels as quickly as possible in order to meet Sweden's future emissions targets and the impacts of climate change both locally and globally. It also provides further evidence of the benefits of curtailing biomass use in future scenarios.

Meanwhile, large overall reductions in water depletion amounts caused by the assumed phasing out of nuclear power were overshadowed by even greater requirements coming from the use of biogas, resulting in a dramatic overall increase of 251.7 % in this category. Similarly, reductions in freshwater eutrophication potential relating to coal and biomass use were more than nullified by the influence of emerging technologies, particularly of biogas, once again, which also dominated the projected values in this category; the value for this indicator is expected to rise by 98.7 % between 2019 and 2050. Both of these findings suggest that the increased use of biogas production in heating and other energy systems should be approached with some caution.

For the remaining four indicators–supply risk, environmental impacts and environmental justice threats from raw material supply, and metal depletion–any reductions relating to the phasing out of fossil fuels, wood biomass and nuclear power are predicted to be strongly offset by the detrimental characteristics of the technologies predicted to replace them. In fact, for all four of these indicators, the dominant contributions in 2050 are clearly produced by three particular technologies: solar PV, wind and biogas. The use of wind turbines represents over half of the overall contributions to the fossil depletion, supply risk and environmental justice indicators in 2050, resulting in large overall increases of 110.8 %, 107.2 % and 139.3 %, respectively. Elsewhere, biogas is found to be the overwhelming individual contributor to the environmental impacts from material supply indicator, contributing almost 50 % of the total 2050 value to result in an overall quadrupling of the 2019 value. Collectively, the results clearly highlight a number of situations in which the adoption of wind, solar and biogas technologies could very easily exacerbate environmental and material supply pressures if they are to be adopted at much wider scales in future systems. They also highlight, once again, the potential issues resulting from greater biogas implementation. Furthermore, if Sweden is to significantly increase the amount of electricity use in its heating system, and if much of this is to come from wind turbines, policymakers also need to be mindful of the potential issues that wind technologies can introduce.

4.2. Limitations and uncertainties

While the results of the analysis provide a series of useful observations, several minor limitations are also identified. Firstly, an issue of uncertainty is acknowledged in relation to the ratio of electricity inputs to heat outputs–the coefficient of performance (COP)–assumed in the heat pumps considered in the study. In the data for historical systems [6], a COP of 2.0 was assumed when calculating the heat outputs derived from electricity use *outside* of district heating systems; empirical data is used for heat from electricity *within* district heating systems, where COP values between 3.9 and 4.2 were observed. Alternatively, electricity requirements in EnergyPLAN are calculated using a "blanket" COP value of 4.0 for district heating; an assumed value of 3.4 is used to calculate heat outputs from electrical inputs in local devices, but these values are not used in the final indicator calculations. In reality, if any of the COP values used to calculate electricity inputs are inaccurate, the total electricity requirement values would change, thus affecting indicator calculations relating to electricity.

Furthermore, it is noted that the indicator values for producing heat and electricity from biogas are calculated using the only available LCI listings, both of which assume that biogas derived from manure waste is used to co-generate the two final energy carriers. At present, no data is available for the use of other sources of biogas and it is unclear if other production techniques would yield observably different results. As such, the results included here do not represent a definitive account of the threats introduced by all biogas-related technologies; additional calculations could be used to provide further insights if and when newer data becomes available.

Lastly, it is recognised that the calculations performed here for electrically generated heat do not include the life cycle impacts relating to the infrastructure items required to transform electricity into heat at both the district heating and local levels. Likewise, the infrastructure required to facilitate the transfer of recycled heat into district heating networks has not been included. Although much of this infrastructure is common to the different scenarios being considered, it is acknowledged that more specialised infrastructure is likely to be required to implement the electrification of future systems, particularly with regards to increased heat pump capacities.

5. Conclusions

Buildings in Sweden require heating for at least eight months in every year. The last 50 years has seen a dramatic shift away from obtaining this heat from oil heaters at the individual building level towards centralised district heating approaches and, more recently, towards the use of electric heat pumps. To investigate the ongoing transition in the Swedish heating system, a newly derived workflow that assesses all sources of district heating and local heat generation throughout their entire life cycles was used to identify and analyse projected changes for a group of 11 key indicators. The analysis used system configuration data for 2015 and 2019 as historical baselines, and a predicted configuration for 2050 derived from the EnergyPLAN model.

Ultimately, the investigation provides a selection of novel and potentially concerning insights into some of the lesser-known consequences of heat generation practices. In particular, the benefits of reducing the use of wood biomass–and, hence, the benefits of avoiding policies that promote wood-based technologies–could potentially be offset by limitations imposed by certain wind, solar and biogas technologies. Above all, it is recognised that, although a wider range of modelling options is becoming available [53], policymakers must continue to juggle a variety of complex issues when planning the energy systems of the future. And, as the pathways of the energy transition continue to be defined, finding compromises between the pros and cons offered by different policy options will not always be easy [54]. This will certainly be the case in colder climates where implementing and maintaining reliable and efficient heating systems will continue to be vital despite the fact that GHG emissions targets and a range of other factors need to be satisfied. In this sense, it is hoped that deeper analyses of this kind can be used to complement existing modelling techniques and expand the scope of available tools for assisting heating policy decisions as we strive to achieve more sustainable energy systems.

CRediT authorship contribution statement

Nick Martin: Writing - review & editing, Writing - original draft, Visualization, Methodology, Formal analysis, Data curation, Conceptualization. **Jakob Zinck Thellufsen:** Writing - review & editing, Formal analysis, Data curation. **Miguel Chang:** Writing - review & editing, Data curation. **Laura Talens-Peiró:** Writing - review & editing, Project administration, Methodology, Funding acquisition, Data curation. **Cristina Madrid-López:** Writing - review & editing, Project administration, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.energy.2024.130264.

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