An evaluation of the Hotmaps toolbox for national strategic heat planning

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The Hotmaps project

The EU-funded project Hotmaps aims at designing a toolbox to support public authorities, energy agencies and urban planners in strategic heating and cooling planning on local, regional and national levels, and in line with EU policies.

In addition to guidelines and handbooks on how to carry out strategic heating and cooling (H&C) planning, Hotmaps will provide the first H&C planning software that is:

- **User-driven**: developed in close collaboration with 7 European pilot areas
- **Open source**: the developed tool and all related modules will run without requiring any other commercial tool or software. Use of and access to Source Code is subject to Open Source License.
- **EU-28 compatible**: the tool will be applicable for cities in all 28 EU Member States

The consortium behind

Scientific partners

Pilot areas for developing and testing the tool

Executive Summary

This paper assesses the Hotmaps tool design and its properties for application in national strategic heat planning. As part of this evaluation, the tool design is compared with the EnergyPLAN tool which has been applied for the Heat Roadmap Europe studies, among others. The purpose of this comparison is to achieve a better understanding of both tools and achieve a better understanding of the role of Hotmaps tools in national strategic heat planning processes.

Included in the process is two basic functionalities of the toolbox, 1) a functionality that estimates heat demand and heat density at geographical locations and therefore can be used to estimate district heating potentials and 2) a dispatch tool that can be used to model heat supply for certain heat demand of district heating grids.

The first part of the document has the main focus on the Hotmaps dispatch tool. The conclusions highlight that the Hotmaps dispatch tool has important properties for heat planning, emphasising its dependence on inputs from the user and local conditions. The tool is a relatively fast computing optimisation tool. This basic structure helps sustain and stimulate an explorative and iterative approach when searching for the technical solutions that may best fulfill the strategic objectives of the heat planning.

The analysis, however, also point out some limitations and attention points when applied for national strategic heat planning. This includes properties such as exogenously given electricity price based dispatch, lack of representation of other energy sectors and the absence of individual heating areas. The document further describes some possible extensions and adaptations of the Hotmaps tool for future work, beyond the Hotmaps project duration.

In conclusion, the Hotmaps dispatch tool – as a stand-alone tool – is best suited for local optimization rather than national strategic heat planning.

For strategic heat planning at national level, the functionalities for estimating district heating potentials can be combined with a tool like EnergyPLAN. Since EnergyPLAN is not designed to estimate heat demands and heat densities but treat these factors as inputs, the Hotmaps tool supplements well by feeding EnergyPLAN with these inputs.

A comparison is carried out between district heating potentials found in Heat Roadmap Europe and in the Hotmaps tool. The potentials found in Hotmaps (based on the corresponding functionalities in the toolbox, with default values applied) are generally smaller than the potentials identified in Heat Roadmap Europe. The effect of smaller district heating shares is subsequently evaluated at national system level in EnergyPLAN. This exercise is partly carried out to demonstrate how Hotmaps and EnergyPLAN may supplement each other in strategic heat planning analysis. The exercise shows that reduced potentials overall increase total fuel consumption at energy system level. While the district heating potentials must be subject to further research, the exercise demonstrates; 1) how Hotmaps toolbox can be applied in national strategic heat planning processes and 2) how district heating potentials below the Heat Roadmap Europe benchmark will increase fuel consumptions under the given assumptions.

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1 Introduction

This paper assesses the Hotmaps tool design and its properties for application in national strategic heat planning. As part of this evaluation, the tool design is compared with the EnergyPLAN tool which has been applied for the Heat Roadmap Europe studies, among others. The purpose of this comparison is to achieve a better understanding and consistency of both tools and achieve a better understanding of how the tools can contribute to national strategic heat planning processes. The overall aim and purpose is to review the applicability of Hotmaps tools for the national heat planning.

It is of specific interest to compare Hotmaps with EnergyPLAN since EnergyPLAN has been applied for a range of strategic heat planning analyses. The Heat Roadmap Europe studies being the most profiled at a European level. The Heat Roadmap Europe studies can be perceived as feasibility studies where EnergyPLAN has been applied to investigate the technical and economic feasibility of different heat supply scenarios.

The Hotmaps tools are able to provide solutions on a more local level, e.g. for smaller geographical areas, cities, municipalities or utilities. It is therefore relevant to investigate the consistency of these local solutions from the Hotmaps tool with the national level scenarios.

However, the two tools cannot be directly compared without clarifying the methodological context.

Below, the paper will proceed by first clarifying the methodological approach for strategic heat planning as outlined in the Hotmaps Handbooks developed in Task 5.1 and Task 5.2. In continuation of this, a description is provided of the methodological context in which the reference tool EnergyPLAN is developed and applied.

Second, the Hotmaps dispatch and EnergyPLAN tools are directly compared in order to 1) clarify the inputs and output of the model 2) evaluate the overall design of the Hotmaps tools for the purpose of the national heat planning.

Third, different scenarios analysed in the tools are compared to investigate the tools and provide examples of their results.

The analysis is restricted to the parts of the Hotmaps toolbox which are more developed. This includes basic functionalities regarding heat demand mapping and the Hotmaps dispatch tool.

The document was developed as a ‘dynamic document’ along the tool development and the experiences gained by tool application. A first version of the document has been uploaded to the portal by the end of November 2019. A second extended version was finalised during 2020, including further lessons and results gained from scenario development.

2 Methodological considerations for developing national scenarios in strategic heat planning

An overall approach for strategic heat planning is described in the Hotmaps Handbook on strategic heat planning and the Hotmaps Handbook on comprehensive assessment of district heating and cooling [1][2].

The Hotmaps Handbooks defines strategic heat planning as *action plans for realising long term visions of radical change in key parameters of the heat supply* [1]. Historically, these key parameters include fuel demand, environmental factors and security of supply. This definition is oriented towards action – action that is based on a long-term perspective and analysis, and is striving for radical change. Radical change is understood as transitions involving changes in both technologies, organizations, regulations, user habits and more, over a relative short time scale, in the current case before 2050. Radical change will not be achieved by existing market and policy frameworks supporting status quo, which is why Strategic Heat Planning is needed. The definition is shaped for the current situation in Europe where radical change away from a fossil fuel-based energy supply is required. It reflects the view that radical changes necessitate a strategic analysis of, and long-term perspectives on, single initiatives [1].

From this departure, the present paper addresses how calculative tools may contribute during the heat planning process.

The procedure for strategic heat planning outlined in the Hotmaps Handbooks is structured in three phases. This approach outlines a procedure which is recommended for strategic heat planning during radical change. It consists of three parts; a technical analysis, an analysis of existing institutional and organisational conditions, and an implementation plan:

- Phase 1: Construct technical scenarios for a strategic heat supply
- Phase 2: Evaluate existing framework conditions and identify key stakeholders
- Phase 3: Make an implementation plan

For Phase 1, the Hotmaps Handbook I further specifies a seven-step approach to the technical analysis which is applied in search technical system designs which fulfill the strategic aims [1].

The approach developed in the Hotmaps Handbooks is developed on basis of a long tradition of theories and practices of strategic energy planning at Aalborg University [3][4][5][6].

Partly, this approach to strategic energy planning is also embedded in the tool which has been applied for the Heat Roadmap Europe studies; EnergyPLAN.

2.1 Heat Roadmap Europe scenarios and the EnergyPLAN Tool

2.1.1 Design of the EnergyPLAN tool and its methodological background

The EnergyPLAN tool is developed in context of the ‘choice awareness theory’ described in “Renewable Energy Systems: A Smart Energy Systems Approach to the Choice and Modeling of 100% Renewable Energy Systems.”[7]. In this context, the tool is designed to simulate technical scenarios developed by the user. The approach has connections to philosophies of how energy system models may support democratic planning processes which is described in e.g. [8] and [7] . As such, the tool is designed to explore the technical feasibility of system scenarios for the purpose of supporting the transition to renewable energy systems. Hence, EnergyPLAN does not generate ‘solutions’ for the user but rather tests the technical feasibility of users’ ideas through simulation. Therefore, energy demands and energy supply technologies are inputs to the model, as the purpose of the model is to test how different ideas of supply technologies and demand initiatives affect aggregate outputs such as fuel consumption, biomass use, CO2 emissions and economic costs. The technical feasibility is tested through a simulation of a whole year with an hourly resolution. The model will evaluate if some demands are not met or if the scenarios will result in excess electricity production in specific hours during the simulation year.

The technical feasibility studies is part of an energy planning approach embedded in the choice awareness theory. The approach can be outlined according to the following 4 steps:

1) Identify and design relevant technical alternatives.

2) Conduct socioeconomic feasibility.

3) Identify institutional barriers.

4) Formulate new policies in terms of aims and regulatory change.

As may be derived by comparison, the Hotmaps Handbooks on strategic heat planning is based on a very familiar methodological approach and logic.

2.1.2 The Heat Roadmap Europe scenarios as feasibility studies

In the Heat Roadmap Europe studies, a GIS model has been developed to identify and estimate heat demands and potential heat sources. In perspective of EnergyPLAN, these results can be applied as inputs to scenario development where the demands and potentials identified by the GIS model may enter the EnergyPLAN model in order to explore the effects on the total energy system at a given geographical level, e.g. a national level. As such, separate studies in GIS and other methodologies are used for the development of scenarios which are then evaluated in EnergyPLAN.

The openness and high degrees of freedom at the input side implies that EnergyPLAN is also used to evaluate the aggregate effect of several local scenarios at, e.g., a national level. This dialogue between local and national scenario development is important. For example, over-utilisation of biomass resources can be a risk in local scenario development.

3 The Hotmaps tools for national strategic heat planning

The Hotmaps tool is a series of tools - a toolbox – being developed for specifically assisting the heat planning processes in Europe. Figure 1illustrates the planned tools under development and their relation in the heat planning process.

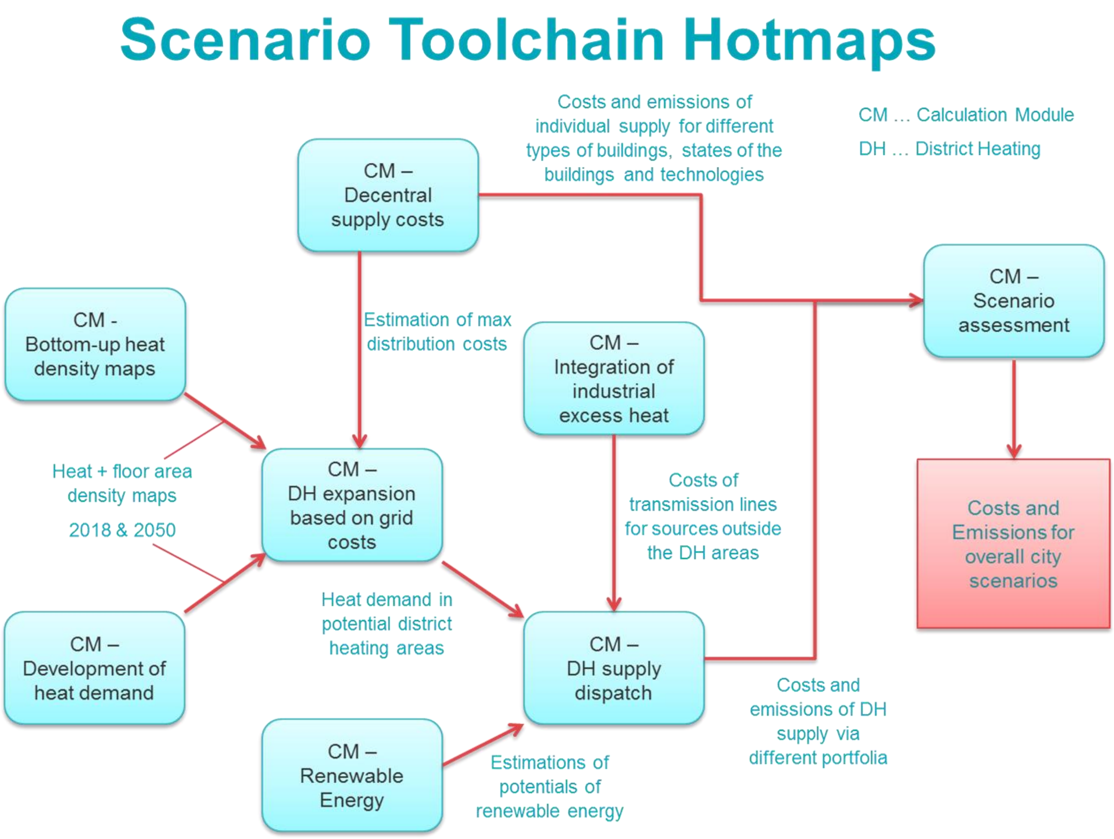

Figure 1. Illustration of the Hotmaps toolbox.[9]

For comparing with EnergyPLAN and Heat Roadmap Europe, the heat demand mapping functionalitiesand dispatch tool is of primary interest. The dispatch tool will have the main focus in the next section as it is the most comparable to EnergyPLAN.

The Hotmaps functionalities regarding estimating heat demand and heat densities are not found the in the EnergyPLAN tool, and therefore these parts of the Hotmaps toolbox cannot replace but rather supplement and inform the modelling in an EnergyPLAN-like tool. This tool combination for national energy analysis is demonstrated in chapter 4.

The Hotmaps dispatch tool is developed for modelling district heating supply systems on the heat production side. The tool is designed so that the user defines and dimensions heat supply technologies as well as choses the distributions of various exogenous variables including heat demand and electricity prices. The tool then simulates the supply system at an hourly basis for a whole year. It dispatches the supply technologies according to minimizing hourly marginal supply costs with reference to the exogenously defined electricity price distribution.

3.1 Tool comparison – applying Hotmaps Dispatch tool for national heat planning

Apendix A provides an overview of all the inputs and outputs from Hotmaps and EnergyPLAN, respectively. In this section, the focus is on a comparison between the Hotmaps district heating supply dispatch tool and EnergyPLAN.

In general, the following points can summarize the differences:

- EnergyPLAN simulates the whole energy system, including the heat sector, the electricity sector, the gas sector and partly the transport sector and industry. Hotmaps focuses on the heating sector.
- The heating sector in EnergyPLAN is structured in three aggregated district heating areas and one aggregated individual heating area. The Hotmaps dispatch tool aggregates the heating sector to one single area with no possibility to differentiate between different district heating areas and no dedicated area for individual heating.
- EnergyPLAN may dispatch according to several different simulation strategies divided into two main categories of technical and economic simulation, respectively. The technical simulation strategies seek to minimize fuel consumption while fulfilling demands. The economic simulation strategies operate according to short term electricity and heating costs, calculated endogenously based on fuel price inputs. In comparison, the Hotmaps dispatch tool simulates according to exogenously given electricity price distribution.
- As output, EnergyPLAN provides data on the hourly simulation and provides some aggregated results such as total fuel consumption, broken down to different categories as well as total costs and CO2 emissions. At the current state, the Hotmaps dispatch tool only provides total costs and CO2 emissions.

The overall picture is that EnergyPLAN as a system simulation tool is designed to be more open on the input side in order to evaluate a wide spectrum of scenarios. Likewise, the tool has a broader focus in the sense that includes sectors not included in Hotmaps. On the other hand, Hotmaps is a more specialised tool. The two tools may supplement each other well as outputs from the Hotmaps model can be used as input in EnergyPLAN in order to evaluate the Hotmaps scenarios in a wider context.

When applying the Hotmaps dispatch tool for national strategic heat planning, it has different strengths and limitations. Referring to the approach to strategic heat planning outlined in the Hotmaps Handbooks, the tool has good features for supporting the process;

1) The tool requires the user to define and dimension the supply technologies to be simulated. Compared to other alternative models which automatically ‘optimizes’ these choices, the former approach stimulates a more conscious learning process in the heat planning.
2) As a simulation tool it calculates the output relatively fast.
3) The two points above combined helps sustain and stimulate an explorative and iterative approach when searching for the technical solutions that may best fulfill the strategic objectives of the heat planning. In this respect, it is to a large extent similar to EnergyPLAN.

Based on the Hotmaps Handbook approach to strategic heat planning, there are also limitations or points of attention for the user to be aware of when applying the tool.

1) The dispatch strategy for the simulation is based on minimizing short-term costs based on electricity prices. These electricity prices are based on an exogenously given price distribution. This may work well seen from the point of view of a smaller, local district heating system. However, for a national heat planning, it must be considered to be a potentially severe limitation. For example, if the heating sector is fully electrified at a national scale, it would likely influence electricity price. However, the tool does not capture this interaction between electricity prices and the heating sector, which may be problematic as the tool is designed for optimizing dispatch according to electricity prices.
2) The process outlined in **Error! Reference source not found.** the three phases of strategic heating planning as described in the Hotmaps Handbooks, emphasizes the separation between technical analysis and institutional analysis, where the former is recommended to be performed before the latter. In this context, it is a potential limitation that the Hotmaps dispatch tool simulates according to electricity prices as these are institutional in character.
3) The dispatch tool only quantifies monetary costs and CO2 emissions as outputs. Other factors may also play a role for national heat planning, for example, biomass consumption, imports of natural gas and others.
4) Since the heating sector is aggregated to one single district heating area to be dispatched, this can create some problems if the district heating sectors in a country are more diverse. Furthermore, it is difficult to simulate individual heating areas as part of the same dispatch as district heating areas.
5) In a smart energy system approach, in which Heat Roadmap Europe is conducted, the Hotmaps dispatch tool does not provide sufficient guidance regarding how the choices made in the heating sector interacts with other energy sectors.

4 Analysis of national system effects of the Hotmaps district heating potentials using EnergyPLAN

Chapter 3 assesses the Hotmaps dispatch tool and concludes that it has it main strength in local heat planning processes. However, references are also made to other functionalities of the Hotmaps toolbox which could be very useful in a national strategic heat planning process.

The objective of this chapter is 1) to demonstrate how the Hotmaps mapping tool can be used in national strategic heat planning, 2) to compare to Hotmaps output regarding district heating potentials on the national level for certain threshold settings to Heat Roadmap Europe [10] and 3) evaluate the energy system effects of changed potentials in district heating.

The scenario comparison is made for three countries: Spain, UK and Denmark. For Spain and UK, a comparison is made to the Heat Roadmap Europe scenarios [11][12] while for Denmark the scenario are based on the IDA 2050 vision [13].

4.1 Method

The analysis takes point of departure in Heat Roadmap Europe 2050 scenarios (HRE) for UK and Spain and the IDA 2050 scenario for Denmark.

District heating shares are then changed on basis of input from the Hotmaps toolbox (Work carried out in Hotmaps WP6). Reduced district heating shares are replaced with individual heat pumps – likewise, increased district heating shares replaces individual heat pumps.

The added electricity demand created by increased capacity of individual heat pumps is covered by biomass fired power plants (PP). This choice is not taken as a suggestion for a 'good solution' but rather to obtain a straight forward indicator for decreased/increased system efficiency. Hence, it must be expected that the system fuel consumption could possibly be decreased by deploying added renewable energy capacity, i.e. photovoltaics and wind power. However, such addition would create imbalances which would require changes across all sectors in order to achieve the 'best' solution [14], and thus the end-scenarios will end up deviating a lot from the HRE-reference; changing many variables and making comparison difficult. Thus, to secure comparability with HRE, added PP capacity covers any additional electricity demand beyond the balanced HRE. The electrical efficiency of the biomass fired PP capacity is 29% - determined on basis of the technology catalogue from the Danish Energy Agency. The PP is prioritized as the last option and only dispatched when CHP capacity and VRE capacity is dispatched to the largest extent possible within each hour. The CHP capacity is decided by following the procedure as explained in the method input below.

4.2 Inputs

Based on a Hotmaps toolbox estimation of total heat demand in 2050, the Hotmaps toolbox estimates a district heating 'realisable potential'. The HRE scenarios have deviating – generally larger - estimations of total heat demand in 2050. In order to align the numbers, the Hotmaps numbers for district heating potentials is scaled up with a factor equal to the relation between the total heat demand in the Hotmaps scenarios and the total heat demand in the HRE scenario (as denoted in Equation 1).

$$Input_i = D_{HRE} / D_j ,$$

Equation 1: Method for adjusting inputs into a HRE conform scenarios

where $input_i$ is an input to EnergyPLAN, D_{HRE} is the total heat demand in the HRE scenario for the country and D_j is the total heat demand for the given Hotmaps scenario. The same principle is applied for Denmark where the HRE scenario is replaced by the IDA2050 scenario [13].

Three different Hotmaps scenarios are created on the basis of different inputs to the Hotmaps tool. In the Hotmaps tool, two basic inputs are given for calculating district heating potential. These parameters are 1) the heat density and 2) a minimum total heat demand in a given geographical area. For each country, two of the three Hotmaps scenarios apply a minimum heat density of 250 MWh/(ha*yr) while the minimum heat demand is varied from 30 to 10 GWh/yr. The third scenario applies a heat density of 125 MWh/(ha*yr) and a minimum heat demand of 10 GWh/yr. The three scenarios are labelled accordingly as "250/30", "250/10" and "125/10".

The networks loss in the thermal grids is assumed to be the same percentage as in the HRE and IDA reference scenarios[1].

Table 1: Demands – Spain (TWh/year)

	250/30	250/10	125/10
Hotmaps heat demand	90.883	90.883	90.883
HRE heat demand	99.38	99.38	99.38
DH share	0.4	0.45	0.61
DH scenario demand	39.752	44.721	60.6218
DH EnergyPLAN input	43.2087	48.60978	65.89326
Individual HP demand	59.628	54.659	38.7582

[1] Spain: 8%, UK: 9%, Denmark: 20%.

Table 2: Demands – UK (TWh/year)

	250/30	250/10	125/10
Hotmaps heat demand	282.347	282.347	282.347
HRE heat demand	297.36	297.36	297.36
DH share	0.42	0.51	0.81
DH scenario demand	124.8912	151.6536	240.8616
DH EnergyPLAN input	137.2431	166.6523	264.6831
Individual HP demand	172.4688	145.7064	56.4984

Table 3: Demands – Denmark (TWh/year)

	250/30	250/10	125/10
Hotmaps heat demand	33.608	33.608	33.608
IDA heat demand	42.71	42.71	42.71
DH share	0.28	0.31	0.61
DH scenario demand, total	11.9588	13.2401	26.0531
DH scenario demand, G2	4.390691	4.861122	9.565434
DH scenario demand, G3	7.568109	8.378978	16.48767
DH EnergyPLAN input, G2	5.488364	6.076403	11.95679
DH EnergyPLAN input, G3	9.460136	10.47372	20.60958
Individual biomass boiler	1.44	1.44	1.44
Individual HP demand	29.3112	28.0299	15.2169

DH supply input in EnergyPLAN

The difference in DH demand between Hotmaps and HRE is used to scale down district heating inputs proportionally (District heating inputs includes both district heating demands and supply technologies and capacities). Hence, the distribution of heat sources in district heating sector is assumed to remain unchanged. Only the total volume of district heating supply is changed. The capacity of the different technologies are therefore adjusted accordingly, based on the same procedure as described above. The efficiencies of the conversion technologies remains unchanged compared to the reference.

The EnergyPLAN model is a tool for simulating national energy systems, including electricity, heating gas and transport. The tool simulates the system with an hourly temporal resolution. Further descriptions of EnergyPLAN can be found in chapter 3 & 4 and on the EnergyPLAN website [15]. EnergyPLAN groups the district heating sector in three groups. Group 1 (G1) is heat only district heating areas, Group 2 (G2) is reflecting decentralized/smaller district heating areas with CHP capacity and Group 3 (G3) is centralized/larger district heating areas with CHP capacity.

Table 4: EnergyPLAN supply inputs - Spain

EnergyPLAN category	EnergyPLAN subcategory	**Technology**	**Scenario 250/30**	**Scenario 250/10**	**Scenario 125/10**	**HRE**
Supply	***Heat&El***	Boilers (MJ/s)	5511.0	6199.88	8404.28	9539
	CHP, CMO	Electric capacity (MW-e)	77705.17	87418.31	118500.38	134500
	CHP, BPMO	Electric capacity (MW-e)	3947.65	4441.11	6020.17	6833
		Thermal capacity (MJ/s)				
		Industrial CHP (TWh/year)	1.97	2.22	3.00	3.41
	Heat only	Solar thermal, G3 (TWh/year)	0.78	0.88	1.19	1.35
		Solar thermal, Storage G3 (GWh)	77.99	87.74	118.94	135
		HP, electric capacity (MW-e)	1155.47	1299.90	1762.09	2000
		Industry (TWh/year)	4.14	4.66	6.32	7.17
Balancing and storage	***Thermal***	Thermal storage. Group 3. (GWh)	43.21	48.61	65.89	74.79

Table 5: EnergyPLAN supply inputs - UK

EnergyPLAN category	EnergyPLAN subcategory	**Technology**	**Scenario 250/30**	**Scenario 250/10**	**Scenario 125/10**	**HRE**
Supply	***Heat&El***	Boilers (MJ/s)	14795.26	17965.67	28533.72	14392
	CHP, CMO	Electric capacity (MW-e)	203033.92	246541.19	391565.41	197500
	CHP, BPMO	Electric capacity (MW-e)	11751.52	14269.70	22663.64	11431.22
		Thermal capacity (MJ/s)				
		Industrial CHP (TWh/year)	0.00	0.00	0.00	0
	Heat only	Solar thermal, G3 (TWh/year)	2.32	2.82	4.48	2.259266
		Solar thermal, Storage G3 (GWh)	232.26	282.03	447.92	225.9266

		HP, electric capacity (MW-e)	3495.27	4244.25	6740.87	3400
		Geothermal, G3 (GWh)	1.05	1.28	2.03	18.94557
		Industry (TWh/year)	19.48	23.65	37.56	1.022911
Balancing and storage	***Thermal***	Thermal storage. Group 3. (GWh)	137.24	166.65	264.68	133.5024

Table 6: EnergyPLAN supply inputs - Denmark

EnergyPLAN category	EnergyPLAN subcategory	**Techology**	**Scenario 250/30**	**Scenario 250/10**	**Scenario 125/10**	**IDA**
Supply	***Heat&El***	Boilers, G2 (MJ/s)	1866.44	2066.42	4066.18	4400
		Boilers, G3 (MJ/s)	3223.85	3569.27	7023.40	7600
	CHP, CMO	Electric capacity (MW-e)	1908.86	2113.38	4158.59	4500
	CHP, BPMO	Electric capacity, G2 (MW-e)	636.29	704.46	1386.20	1500
		Thermal capacity, G2 (MJ/s)				Auto
		Electric capacity, G3 (MW-e)	1484.67	1643.74	3234.46	3500
		Thermal capacity, G3 (MJ/s)				Auto
		Industrial CHP, G2 (TWh/year)	0.51	0.56	1.11	1.2
			0.00	0.00	0.00	
	Heat only	Solar thermal, G2 (TWh/year)	0.74	0.82	1.62	1.75
		Solar thermal, Storage G2 (GWh)	12.73	14.09	27.72	30
		Solar thermal, G3 (TWh/year)	0.25	0.28	0.55	0.6
		Solar thermal, Storage G3 (GWh)	0.00	0.00	0.00	0
		HP, electric capacity, Gr2 (MW-e)	127.26	140.89	277.24	300
		HP, electric capacity, Gr3 (MW-e)	169.68	187.86	369.65	400
		Geothermal, G2 (TWh/year)	0.55	0.61	1.19	1.29
		Geothermal, G3	1.42	1.57	3.10	3.35

		Industrial Excess Heat, G2 (TWh/year)	0.52	0.58	1.14	1.23
		Industrial Excess Heat, G3 (TWh/year)	1.72	1.90	3.74	4.05
Balancing and storage	***Thermal***	Thermal storage. Group 2. (GWh)	23.75	26.30	51.75	56
		Thermal storage. Group 3. (GWh)	23.75	26.30	51.75	56

4.3 Output and analysis

The output patterns are somewhat similar for all three countries. Therefore, the analysis of each country is not commented separately since it would entail a high degree of repetition. Also, the identical effects identified across country cases is strengthening the generic conclusions on the effect of district heating shares on national energy systems.

The main difference between the scenarios for all three countries lies in fuel consumption. Decreased shares of district heating results in an increase of fuel consumption, primarily biomass consumption. The explanation for this increase is that more electricity is supplied from power plants in order to supply the added electricity demand from individual heat pumps. While the individual heat pumps have an efficiency which are comparable to district heating large scale heat pumps, the decreased penetration of district heating grids also decreases the access and utilisation of other heat sources such as waste heat from CHP and industries, solar thermal and geothermal. The decreased utilisation of these heat sources increases the need for fuels to generate heat, primarily through heat pumps via electricity. In addition, it is also plausible that the decrease in storage capacity in the district heating system will reduce the system capacity to integrate and utilise fluctuating renewables.

The CO2 emissions for the different scenarios are shown in Table 7. However, it should be noted that EnergyPLAN accounts biomass as a CO2-neutral fuel. Thus, in order to reflect the more qualitative differences between the scenarios, the underlying biomass and fuel consumptions for all scenarios are presented in Table 9-11 which provide an expression of the fuel efficiencies of the scenarios. The results are also illustrated in Figure 2

*Table 7. EnergyPLAN calculations of annual CO2 emissions, Mt/year. *For Spain and UK. **For Denmark.*

	250/30	**250/10**	**125/10**	**HRE*/IDA****
Spain	26.102	26.102	26.102	26.102
UK	33.261	38.657	35.148	33.087
Denmark	-0.845	-0.043	7.998	9.343

The reasons behind the variations in the CO2 accounts has not been assessed at a deeper level. While increased biomass use would be accounted as CO2 free, this might not be the case for increased use of all synthetic fuels insofar they are utilised and accounted for in the model as gas and liquids and thereby ascribed a positive emission factor. In that case, increased use of syngas and decreased use of biomass might results in increased accounted CO2 emissions. However, it would require a deeper analysis to trace the origins of all fuels and their associated CO2 impact and this investigation was not carried out the in present analysis. However, it should also be noted that the variations in the CO2 accounts are relatively small.

For these reasons, it is recommended to use the fuel efficiency as the main indicator of the overall efficiency when reading the results and comparing the scenarios.

Table 8. Result for Spain.

Scenario	DH share, pct	System Fuel Consumption, TWh/year	System Biomass consumption, TWh/year
250/30	40	1665.32	961.28
250/10	45	1646.37	942.23
125/10	61	1621.33	916.94
HRE	69	1615.86	911.33

Table 9. Results for United Kingdom.

Scenario	DH share, pct	System Fuel Consumption, TWh/year	System Biomass consumption, TWh/year
HRE	41	2049.04	1050.45
250/30	42	2046.55	1047.05
250/10	51	2025.06	998.77
125/10	81	1952.65	941.98

Table 10. Results for Denmark.

Scenario	DH share, pct	System Fuel Consumption, TWh/year	System Biomass consumption, TWh/year
250/30	28	1377.33	1516.67
250/10	31	1372.64	1507.95
125/10	61	1325.53	1420.51
IDA	66	1317.68	1405.92

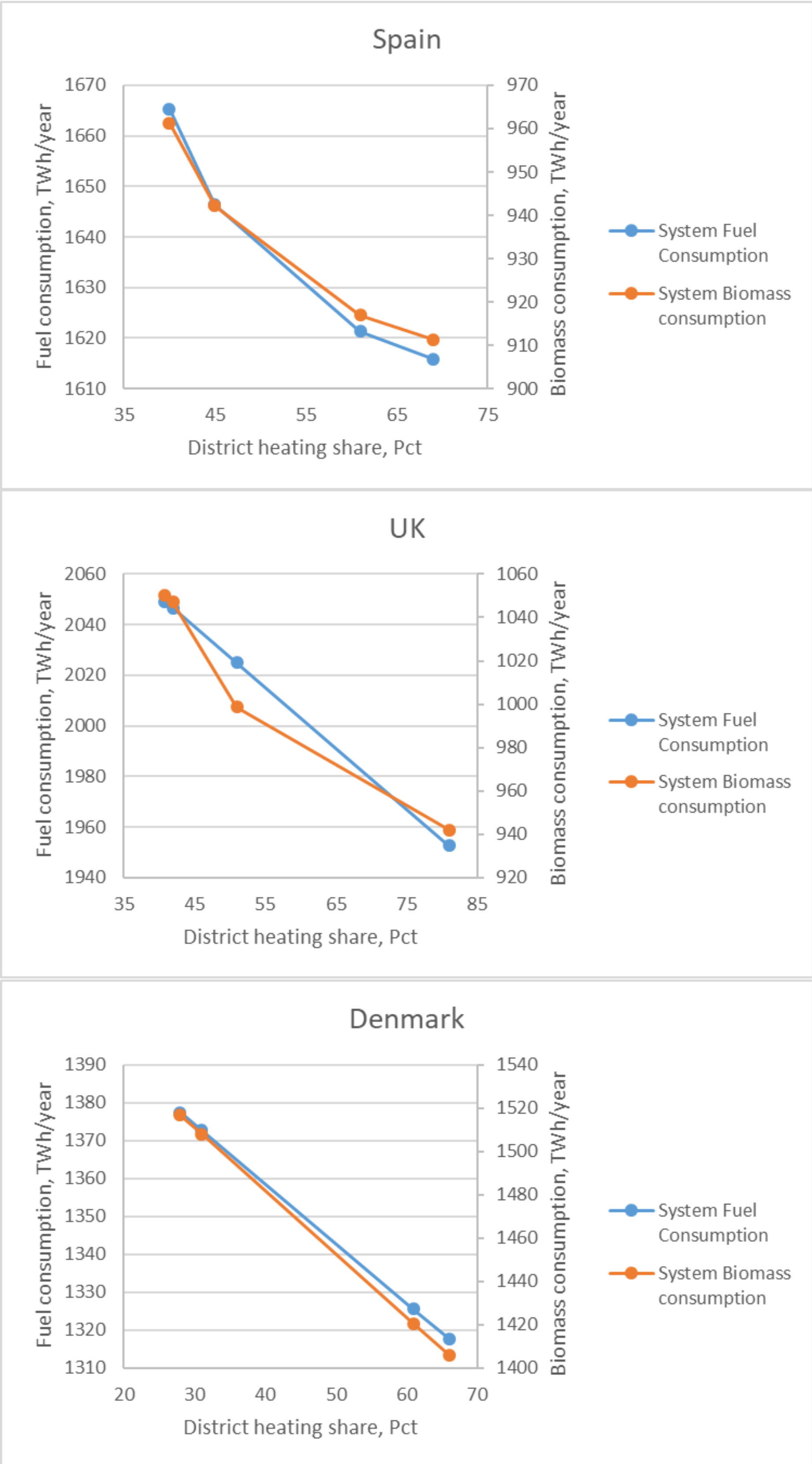

Figure 2. Results for Spain, UK and Denmark.

4.4 Conclusions on national system effects

The overall conclusion from the analysis is that a decreased potential of district heating decreases the overall efficiency of the total energy system. The same tendency is found in all three country analyses.

The district heating potentials identified in the Hotmaps scenarios are generally lower than the district heating potentials used in HRE/IDA scenarios. Which of these potentials are the most feasible has not been assessed in this report since it is beyond its scope. However, this should be the subject of future research since the analysis show that the level of district heating potential has a significant effect on system fuel consumption in all three case countries.

In addition to evaluating the total system efficiency with different district heating shares, the exercise also demonstrates how the heating sector results from Hotmaps can be assessed in an energy sector perspective via EnergyPLAN. Thus, for a national strategic heat planning process, it is recommended to combine a Hotmaps-like tool that estimates district heating potential with an EnergyPLAN-like tool in order to identify the most efficient heating sector solutions. While the scope of the Hotmaps tool is to estimate heat demands and heat densities, the derived district heating potentials can used as inputs to EnergyPLAN. EnergyPLAN is then able to assess the consequences of local heat plans on national system efficiency parameters, such as fuel consumption, emissions, and costs. When applying a dialogue between the two types of tools, consistency and efficiency at the national level can thereby be achieved. Thus, the two types of tools supplement each other well in a national strategic heat planning process.

5 References

[1] Djørup S, Bertelsen N, Mathiesen BV, Schneider NCA. Definition & Experiences of Strategic Heat Planning 2019. https://vbn.aau.dk/da/publications/definition-amp-experiences-of-strategic-heat-planning.

[2] Djørup S, Bertelsen N, Mathiesen BV, Schneider NCA. Guidance for the comprehensive assessment of efficient heating and cooling 2019.

[3] Hvelplund F. Electricity reforms,Democracy and Technological Change. Department of Development and Planning,Aalborg University; 2001.

[4] Hvelplund F, Djørup S. Multilevel policies for radical transition: Governance for a 100% renewable energy system. Environ Plan C Polit Sp 2017;35. doi:10.1177/2399654417710024.

[5] Lund H, Mathiesen BV, Connolly D, Østergaard PA. Renewable Energy Systems - A Smart Energy Systems Approach to the Choice and Modelling of 100 % Renewable Solutions. Chem Eng Trans 2014;39:1–6. doi:10.3303/CET1439001.

[6] Djørup S. Fjernvarme i forandring. Ph.d.-seri. Aalborg Universitetsforlag; 2016. doi:10.5278/vbn.phd.engsci.00137.

[7] Lund H. Renewable Energy Systems: A Smart Energy Systems Approach to the Choice and Modeling of 100% Renewable Energy Systems. Second Edi. Academic Press (Elsevier); 2014.

[8] Lund H, Arler F, Østergaard PA, Hvelplund F, Connolly D, Mathiesen BV, et al. Simulation versus Optimisation : Theoretical Positions in Energy System Modelling 2017:1–17. doi:10.3390/en10070840.

[9] Hotmaps. Hotmaps Wiki 2020. https://wiki.hotmapsdev.hevs.ch/en/Welcome (accessed September 24, 2020).

[10] Paardekooper S, Lund RS, Mathiesen BV, Chang M, Reinert U, Grundahl L, et al. Heat Roadmap Europe 4. Quantifying the Impact of Low-Carbon Heating and Cooling Roadmaps 2018. https://vbn.aau.dk/da/publications/heat-roadmap-europe-4-quantifying-the-impact-of-low-carbon-heatin.

[11] Paardekooper S, Lund RS, Mathiesen BV, Chang M, Petersen UR, Grundahl L, et al. Heat Roadmap Spain. Quantifying the Impact of Low-Carbon Heating and Cooling Roadmaps. 2018.

[12] Paardekooper S, Lund RS, Mathiesen BV, Chang M, Petersen UR, Grundahl L, et al. Heat Roadmap United Kingdom. Quantifying the Impact of Low-Carbon Heating and Cooling Roadmaps. 2018.

[13] Mathiesen BV, Lund H, Hansen K, Ridjan I, Djørup SR, Nielsen S, et al. IDA's Energy Vision 2050: A Smart Energy System strategy for 100% renewable Denmark. 2015.

[14] Lund H. Renewable Energy Systems: The Choice and Modeling of 100% Renewable Solutions. Elsevier; 2010.

[15] Energyplan.eu. Introduction 2016. http://www.energyplan.eu/ (accessed January 1, 2016).

Appendix A

Data category	Description		
		EnergyPLAN	Hotmaps
Electricity consumption	Industry	Input	Not included
	Individual electric heating and Heat pumps	Input/output	Output
	Electric cooling	Input/output	??
	Centralised heat pump and electric boiler	Output	Output
	Transport	Input/Output	Not included
	PHES pump	Input	Not included
	Losses (including own use)	Input	Not included
Electricity generation potentials	Offshore wind	Input	Not included
	Onshore wind	Input	Not included
	Solar PV	Input	Not included
	CSP	Input	Not included
	Hydro Total	Input	Not included
	Hydro dam	Input	Not included
	Hydro run-of-river	Input	Not included
	Hydro Pumped	Input	Not included
	Hydro storage	Input	Not included
	Geothermal	Input	Not included

	Marine	Input	Not included
	Nuclear	Input	Not included
	Biomass	Input	Not included
Electricity generation potentials - capacities	Offshore wind	Input	Not included
	Onshore wind	Input	Not included
	Solar PV	Input	Not included
	CSP	Input	Not included
	Hydro Total	Input	Not included
	hydro dam	Input	Not included
	Hydro run-of-river	Input	Not included
	Hydro Pumped	Input	Not included
	Hydro storage	Input	Not included
	Geothermal	Input	Not included
	Marine	Input	Not included
	Nuclear	Input	Not included
	Biomass	Input	Not included
Heating demand	Total	Input	Output
	Individual	Input	Output
	District heating	Input	Output
Heat generation (potentials)	Individual gas	Input	Output
	Individual biomass	Input	Output
	Individual electric heating	Input	Output
	Individual heat pumps	Input	Output
	Individual solar thermal	Input	Output
	DH CHP Biomass	Input	Output
	DH CHP Gas	Input	Output
	DH heat pump	Input	Output
	DH industrial excess heat	Input	Output
	DH industrial excess heat heat pump	Input	Output

	DH electric boilers	Input	Output
	Waste	Input	Output
	DH Geothermal	Input	Output
	DH solar thermal	Input	Output
	District heating losses	Input	Input
Heat generation (potentials) - capacities	Individual gas	Input	Input
	Individual biomass	Input	Input
	Individual electric heating	Input	Input
	Individual heat pumps	Input	Input
	Individual solar thermal	Input	Input
	DH CHP Biomass	Input	Input
	DH CHP Gas	Input	Input
	DH heat pump	Input	Input
	DH industrial excess heat	Input	Input
	DH industrial excess heat heat pump	Input	Input
	DH electric boilers	Input	Input
	Waste	Input	Input
	DH Geothermal	Input	Input
	DH solar thermal	Input	Input
Thermal production efficiencies	Centralised boilers	Input	Input
	CHP - thermal	Input	Input
	CHP - electric	Input	Input
	Individual heat pumps	Input	Input
	individual boilers	Input	Input
Cooling demand & production	individual cooling demand	Input	??
	District cooling	Input	??
	Cooling COP	Input	??
Industry energy demand	Total	Input	Not included
	Fuels	Input	Not included
	Various	Input	Not included
Transport	Total	Input	Not included
	Petrol	Input	Not included
	Diesel	Input	Not included
	Aviation fuel	Input	Not included
	Navigation (sea) fuel	Input	Not included

	Electricity	Input	Not included
	EV characteristics (battery and grid capacity)	Input	Not included
Fuel losses	Coal, oil, gas, biomass losses	Input	Not included
CO2	CO2 content for different fuels	Input	Input
Storage	Thermal storage	Input	Input
	Solar thermal storage	Input	Input
	Oil storage	Input	Not included
	Gas storage	Input	Not included
	Hydro pumped storage	Input	Not included
	Dam hydro storage	Input	Not included
regulations	min CHP, grid stabilisation	Input	???
Distributions (hourly profiles)	Electricity demand	Input	Not included
	Individual Heat demand	Input	Input
	District heating	Input	Input
	Cooling demand	Input	??
	Natural cooling	Input	??
	Solar thermal	Input	Input
	Onshore wind	Input	Not included
	Offshore wind	Input	Not included
	PV	Input	Not included

	Hydro water inflow	Input	Not included
	Hydro production	Input	Not included
	Nuclear production	Input	Not included
	Transport	Input	Not included
	Electricity price distributions	Input	Input
	Geothermal power	Input	Not included
Prices (on yearly basis)	Natural gas wholesale	Input	Input
	Natural gas - retail	Input	Input
	Biomass - wholesale	Input	Input
	Biomass - retail	Input	Input
Costs	Investments, O&M, lifetime	Output	Input
	Ind. Boilers	Output	Not included
	Interconnections	Output	Not included
	Electricity grid	Output	Not included
	Transport vehicles	Output	Not included
	EV charging stations	Output	Not included
	District heating pipes	Output	Input
	Large power plants and centralised boilers	Output	Input