Heating technologies for limiting biomass consumption in 100% renewable energy systems

Mathiesen, Brian Vad; Lund, Henrik; Connolly, David

Published in:
CD Proceedings

Publication date:
2011

Document Version
Accepted author manuscript, peer reviewed version

Citation for published version (APA):
Mathiesen, B. V., Lund, H., & Connolly, D. (2011). Heating technologies for limiting biomass consumption in 100% renewable energy systems. In CD Proceedings SDEWES Centre.

Heating technologies for limiting biomass consumption in 100% renewable energy systems

Brian Vad Mathiesen
Department of Development and Planning, Aalborg University, Denmark
e-mail: bvm@plan.aau.dk

Henrik Lund
Department of Development and Planning, Aalborg University, Denmark
e-mail: lund@plan.aau.dk

David Connolly
Department of Development and Planning, Aalborg University, Denmark
e-mail: david@plan.aau.dk

ABSTRACT

The utilisation of biomass poses large challenges in renewable energy systems and buildings account for a substantial part of the energy supply also in 100% renewable energy systems. The analyses of heating technologies show that district heating systems are especially important in limiting the dependence on biomass resources and to create cost effective systems. District heating systems are especially important in renewable energy systems with large amounts of fluctuating renewable energy sources as it enables fuel efficient and lower cost energy systems with thermal heat storages. And also district heating enables the use of combined heat and power production (CPH) and other renewable resources than biomass such as large-scale solar thermal, large-heat pumps, geothermal heat, industrial surplus heat etc. which is important for reducing the biomass consumption. Where the energy density in the building stock is not high enough for districts heating geothermal heat pumps can be recommended for individual heating systems, although the costs and biomass consumption is higher than the district heating solutions.

KEYWORDS

Renewable energy systems, heating technologies, biomass, socio-economy, combined heat and power, solar thermal, geothermal, district heating, heat pumps.

INTRODUCTION

The international focus on renewable energy technologies is as high as ever. The implementation of national targets to increase the amount of renewable energy and reduce greenhouse gas emissions is accelerating the utilisation of resources such as wind, wave, tidal, solar, and biomass. These resources have their own unique advantages and disadvantages. Biomass is a unique renewable resource because it can act as a direct combustible replacement to fossil fuels, which means it can be used in dispatchable centralised power stations. This unique attribute combined with the fact that all other renewable resources are associated with some degree of intermittency makes biomass particularly attractive. In addition, biomass can exist as a solid, liquid, or gaseous fuel which makes it ideal for 100% renewable energy systems, since it can be used in the electricity, heating, and even transport sectors. However, the major drawback with biomass is its availability.

Biomass energy production (such as energy crops) can compete with food production for agricultural land and raw materials. This was brought to light in early 2007 when the demand for maize increased due to ethanol production in the USA. Some commentators believed that this subsequently increased the price of tortillas, a basic food requirement in Mexico, and thus thousands of people protested in Mexico. However, as Fresco *et al.* concluded [1], although the demand for ethanol corresponded with an increase in maize prices, this was most likely a short-term market failure caused by increasing oil prices, an unforeseen demand for maize, and fluctuations in the harvest. Nonetheless, this case study outlines the tentative relationship between biomass and food production, which means 100% renewable energy systems should try to limit its use where possible. Also, even if agricultural land is replaced with biomass resources, it is still unclear how much biomass could be utilised due to the availability of raw materials such as waste, sewage, water, and land. For example, in Ireland it is estimated that miscanthus, a common energy crop, could provide approximately 735 PJ of energy if all the suitable land was utilised [2]. In comparison, the total energy demand in Ireland was 670 PJ. Considering the inefficiencies of converting biomass (from solid to gas or liquid), Ireland's relatively low population density, and Ireland's relatively high agricultural output, this illustrates the importance of reducing biomass utilisation where possible. Similarly, the total estimated residual biomass resource (i.e. resource without affecting food production) in Denmark is approximately 165 PJ [3] compared to an annual energy demand of 809 PJ in 2009 [4]. Once again, this illustrates the importance of minimising the use of biomass in 100% renewable energy systems by incorporating alternatives such as energy savings, intermittent renewable energy, and efficient energy conversion technologies.

In line with this, previous research has examined the efficient utilization of biomass in the transport sector [5], in gasification technologies [6], and in combined heat and power plants [7-9]. Focusing on the heating sector, other studies have also emphasised the advantages of district heating or individual heat pumps for fuel efficiency [10-13]. However, this analysis will investigate biomass required when using various heating technologies in 100% renewable energy systems.

Since 2006 a 100% renewable energy system has been the goal in Denmark. To compliment this, in 2006 [14;15] and in 2009 [9;16] scenarios were developed which outlined how this target could be reached and subsequently for 2050. 2050 was recently set as the official target year by the Danish government. Therefore, a projected energy scenario for Denmark in 2050 will be used as the basis for this investigation, which examines how a large number of heating technologies can decrease the biomass consumption in a 100% renewable energy system.

METHODOLOGY

In order to analyse heating technologies and the use of biomass, it is important to identify a 100% renewable energy system which is a coherent all-round scenario. In the CEESA project a number of studies have been combined in order to create scenarios for 100% renewable energy [17]. Using the CEESA 100% renewable energy scenario (version August 2010), three different 100% renewable energy systems have been created, in order to reflect different penetrations of fluctuating renewable energy and different levels of biomass. These scenarios and the households in these systems are used for the analyses of a large number of both individual and district heating technologies. The analyses are conducted both from a technical fuel efficiency perspective (which includes the hourly balancing of demand and supply) and from a socio-economic perspective. In the constructing of the three 100% renewable energy systems and in the analyses of the heating technologies, the EnergyPLAN energy system analyses tool is used. The energy system analyses are divided into two parts:

1. Is an expansion of district heating feasible in a 100% renewable energy scenario or should we use individual heating technologies based on renewable energy and what are the effects in the three different energy system scenarios?
2. What is the effect of not using the technologies that a district heating system allows to be used, and that cannot be used in an individual household.

The technology prices and characteristics are described in Mathiesen et.al [16]. Please note though that no extra costs have been included for the changes in the waste incineration as these costs are assumed to be connected to waste treatment. Also, for industrial surplus heat no extra cost has been applied as the primary purpose (and fuel costs) is connected to the production of goods.

In relation to fuel prices, 45 DKK/GJ (6,0 €/GJ) biomass has been used for both large and small CHP plants and power plants since it is assumed that woodchip is used. For individual heating technologies though, it is 81 DKK/GJ (10,9 €/GJ) since it is assumed that wood pellets are used. This corresponds to the cost level recommendations from the Danish Energy Authority in May 2009 in long term socio-economic analyses [18]. Please note that these costs include transport and handling costs.

The investigation described in this paper is partly based on the analyses conducted in Heat Plan Denmark 2010 [19], which was a follow-up to the Heat Plan Denmark project from 2008 [12;20]. In these reports various heating technologies were analysed in Denmark for different future years (such as 2020, 2040, and 2060) and an action plan was proposed to implement the most feasible solutions.

The EnergyPLAN energy system analysis tool

The energy systems analyses are all conducted hour by hour in the energy system analysis tool EnergyPLAN, i.e. for both the technical system analyses as well as estimates of economic consequences [21]. EnergyPLAN is an input/output tool that performs annual analyses in steps of one hour. Inputs are demands, demand distributions, capacities of technologies, fluctuating renewable energy distributions, and a range of costs (such as investments, fuel, and CO_2). A number of technologies can be included enabling the reconstruction of all elements of an energy system, which enables the user to analyse an almost infinite variety of alternatives including wind integration technologies, as well as the interrelation between the electricity and heat supply with high penetrations of CHP. The model makes it possible to use different regulation strategies putting emphasis on heat and power supply, import/export, ancillary services, grid stability and excess electricity production. Outputs are energy balances, resulting annual productions, fuel consumption, and import/exports. The EnergyPLAN tool is particularly suitable for analysing radical changes in energy systems and renewable energy systems with high intermittency. In the analyses here the EnergyPLAN tool is used for technical analyses of the energy system in a closed (and balanced) energy system. The technical optimisation used represents a system in which the electricity and heat demand is met at all times and the tool uses the installed capacities to minimise the fuel consumption, which in this case is the biomass consumption.

The 100% renewable energy systems used in the analyses

In the analyses here a version of the CEESA scenarios from the autumn of 2010 has been used based on further development of scenarios in the IDA Climate Plan 2050 [9;16]. Special emphasis has been placed on the heating sector, using the analyses in Heat Plan Denmark [12]. The energy system represents a coherent strategy and scenario for a 100% renewable energy system in 2050 (including transport), along with two transitional target years: 2015 and 2030.

In the construction of the 100% renewable energy system a number of integration technologies are also necessary. In the short term (5-10 years) with about 30-40% fluctuating renewable energy, it should be ensured that the CHP plants use their thermal storages to produce electricity (and heat) when the electricity is needed, while minimising the use of boilers for district heating. This is also the case for current CHP plants. Also in the short term it is important to install heat pumps, which can enable extra electricity consumption at times with large amounts of wind power and which is fuel efficient. Flexible electricity demand can be implemented but has a limited effect compared to other technologies for integrating renewable energy [10]. In the next steps, beyond 40-45% fluctuating renewable energy, it is important that the transport sector is integrated, i.e. that electric vehicles are charged at times with high fluctuating renewable energy penetration (in 10-20 years). At this point it is also important that other technologies such as small CHP, electric vehicles or large CHP fuel cells can provide ancillary services, in order to have a fuel efficient system compared to the existing system where large conventional power plants are operating at all times to ensure this. With more than 50% wind power, electrolysis becomes important in order to integrate fluctuating renewable electricity production [11].

The energy system reveals that 100% renewable energy systems will be technically possible in the future and that implementing energy savings, renewable energy and more efficient conversion technologies can have positive socioeconomic effects, create employment, potentially lead to large earnings on exports and lower health related emissions.

In CEESA the energy system is highly integrated regarding the electricity, heating and transport sector. From the current energy system in Denmark the district heating system has been expanded from a net coverage of 46% to about 67% in 2030 based on the analyses in Heat Plan Denmark [12]. In these analyses emphasis has also been put on limiting the consumption of biomass. However biomass is still needed in the energy system in order to produce heat and power (and also in industry and transport). This energy system enables the following:

1. The district heating in this renewable energy scenario enables the use of combined heat and power and other renewable resources not applicable in individual solutions such as geothermal, large-scale heat pumps or solar thermal, industrial surplus heat etc. Hence the effects of such technologies can be analysed.
2. On the other hand this energy system enables the analyses of individual heating technologies instead of district heating.

In future energy systems the main challenge is not new buildings, but existing buildings. In the CEESA scenarios, heat savings of 25% are implemented in the period from 2010 to 2020, corresponding to an improvements of 75% in the least insulated houses. Towards 2030, the houses are insulated to 50% of the current heat demand, which is based on reports from the Danish Building Research Institute (SBI) [22-24]. In combination with the heat savings in the district heating areas, there is a synergy of expanding the district heating grids, because the piping network can supply more houses and the costs of marginal expansion are rather low [12;20]. In the 100% renewable energy scenario new buildings use 75 per cent of the demand they use today and have renewable energy installed onsite, enabling them to be energy neutral on an annual basis.

In the 100% renewable energy scenario used in the analyses here, the aim has been to minimise the biomass consumption in order to keep it within the level of the Danish residual biomass resources. In CEESA (august 2010 version) the IDA Climate Plan 2050 scenario has been further developed so that less biomass is now used. This has been achieved by increasing the share of wind power, installing more large heat pumps and electrolysers, by replacing fuel in industry with electricity consumption and by implementing high speed trains to replace some fuel in the aviation sector. This changed the biomass consumption to 260 PJ and the total primary energy consumption to 436 PJ (about 36 PJ less than in the IDA Climate Plan 2050 if gasification losses are taken into account). The total primary energy supply is about 800 PJ today in Denmark. The cost of this CEESA scenario were also analysed and results indicate that it is lower than the business-as-usual reference energy system, however this needs to be analysed further in the future for 100% renewable energy systems [9]. Hence, the 100% renewable energy scenario used here is one of the most coherent and well analysed available for a national energy system.

In the CEESA project the biomass potential has been assessed to be about 250 PJ excluding waste resources (20-40 PJ depending on development). This amount can be found by a number of combinations of conventional agriculture, organic farming, nature reserves and energy crops. In all cases though, the current agricultural landscape has to be changed to other crops and/or another combination of the mentioned elements, in order to have this amount of biomass.

With a larger consumption of biomass in e.g. the heating sector as analysed here a larger restructuring of the agricultural production is required or a larger import of biomass would be required.

As mentioned the 100% renewable energy system used in the analyses here has been constructed with the aim of keeping biomass consumption at a low level and at the same time maintaining a cost-effective system. In order to analyse the effects of different heating technologies on the biomass resource in 100% renewable energy systems, the scenario mentioned above has been used in order to create three 100% renewable energy scenarios.

The first 100% renewable energy scenario is the same as the scenario described above (*100RE High wind*). In this scenario the wind power share is 70% of the electricity consumption, including consumption for transport. In addition to this 9% of the consumption is covered by photo voltaic and 5% by wave power, which can also be characterised as fluctuating production. For more information about the energy system, the technology efficiencies and costs please refer to [9;16;19].

In order to make a broader analyses of heating technologies in a number of different possible future 100% renewable energy scenarios, *100RE High wind* has been used to create two more scenarios with a lower wind power share and hence a higher biomass share, which are:

- In *100RE Low wind* the production from wind turbines has been reduced to half or 35%. The 4,450 MW onshore wind power is kept, however the offshore wind power is reduced from 5,625 to 1,300 MW.
- In *100RE No wind* the remaining wind power is removed.

The EnergyPLAN model can analyse the consequences for the operation of power plants as well as CHPs, heat pumps and electrolysers etc. in the energy system. As expected the total biomass consumption increases significantly as well as the total costs of the system. In Figure 2 the biomass consumption in the three scenarios is illustrated. The total costs of the three scenarios are 95.0 billion DDK/Year, 96.9 billion DKK/Year and 99.0 billion DKK/year respectively.

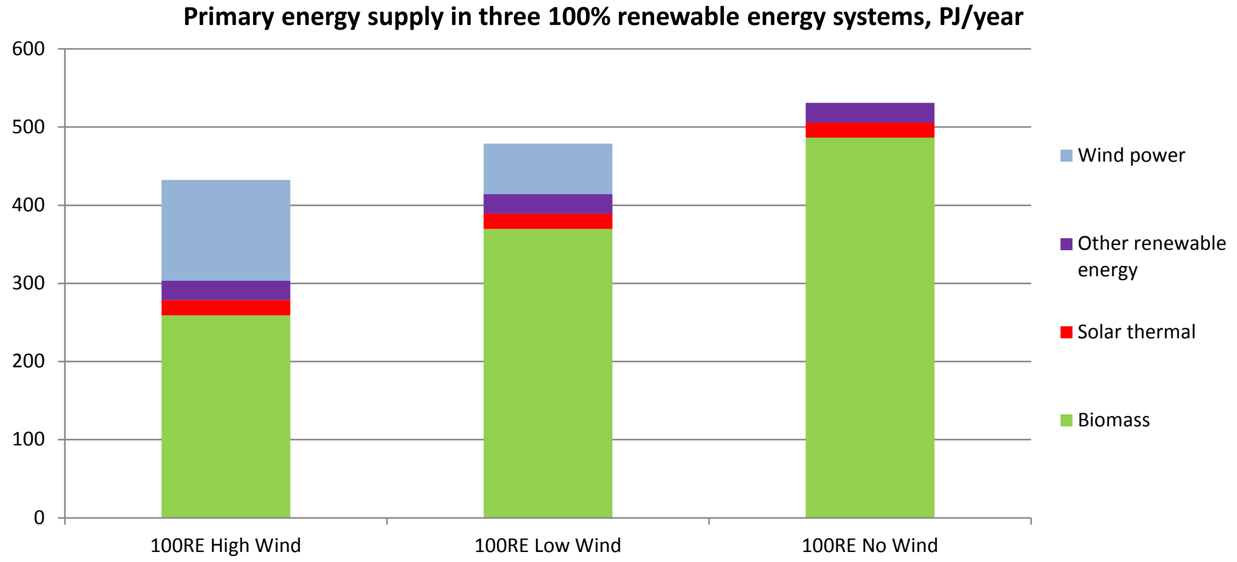

Figure 1, Primary energy supply in the three 100% renewable energy scenarios used in the analyses of heating technologies as well as the scenarios in the IDA Climate Plan 2050.

RESULTS OF THE ANALYSES OF INDIVIDUAL HEATING TECHNOLOGIES

In the first part of the analyses the different heating technologies are analysed by changing 21% (or app. 20 PJ) of all heating and hot water consumption. The remaining part is kept as it is in the renewable energy system: 46% is covered by district heating (the current Danish level of district heating) and 23% as individual heating covered by heat pumps and supplemented by solar thermal and biomass boilers.

The effects of changing technology for 21% of the net end heat demand is analysed with: biomass boilers (Boilers), heat pumps (HP), electric heating (EH) or micro fuel cell CHP (micro-CHP) based on biogas or hydrogen/synthetic gas. These solutions are compared to connecting this part of the demand (up to 67%) to district heating including the grid losses. In the analyses the marginal changes in biomass consumption and costs are shown and all technologies are also analysed with 1 TWh of solar thermal.

In Table 1 the results of the analyses of the heating technologies in the *100RE High Wind* scenario are listed. As illustrated district heating is the most fuel efficient technology and most cost effective technology.

Table 1, Technical and socio-economic results of the analyses of individual heating technologies and district heating for 21% of the heating demand in *100RE High Wind*.

	District heating	Biomass boiler	Biomass boiler & solar	Heat pumps	Heat pumps & solar	Electric heating	Electric heating & solar	Micro-CHP (bio)	Micro-CHP (bio) & solar	Micro-CHP (syn)	Micro-CHP (syn) & solar
Fuel consumption (PJ/year)											
CHP	42.2	31.8	31.8	36.1	35.6	44.8	43.7	24.2	26.0	57.9	54.8
Power plants	6.3	11.1	11.1	12.1	12.1	21.2	17.1	8.6	9.6	42.0	34.9
Boilers	10.5	4.0	4.0	4.0	4.0	4.0	4.0	4.1	4.1	4.3	4.2
Waste CHP	39.9	39.9	39.9	39.9	39.9	39.9	39.9	39.9	39.9	39.9	39.9
Transport	59.8	59.8	59.8	59.8	59.8	59.8	59.8	59.8	59.8	59.8	59.8
Households	3.2	27.9	23.5	3.2	3.2	3.2	3.2	43.4	30.9	3.2	3.2
Industry	68.5	86.5	86.5	86.5	86.5	86.5	86.5	86.5	86.5	86.5	86.5
Gasification	28.8	27.3	27.3	28.7	28.6	33.4	32.1	75.5	60.3	42.5	39.7
Primary Energy Supply (PJ/year)											
Biomass	259.3	288.3	283.9	270.5	269.8	293.0	286.4	342.1	317.1	336.3	323.1
Solar thermal	19.3	18.6	22.2	18.6	22.2	18.6	22.2	18.6	22.2	18.6	22.2
Wind etc.	153.6	153.6	153.6	153.6	153.6	153.6	153.6	153.6	153.6	153.6	153.6
H_2 surplus	0.0	-1.3	-1.3	-1.2	-1.2	-1.1	-1.2	-1.4	-1.4	-0.8	-1.0
Excess elec.	0.0	3.7	3.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total	432.3	463.0	462.2	441.5	444.5	464.1	461.1	512.9	491.6	507.8	497.9
Socio-economic costs (Billion DKK/year)											
Fuel	14.1	17.4	16.9	14.7	14.6	15.9	15.6	21.5	19.2	18.4	17.6
O&M costs	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.1	0.1	0.3	0.3
Fixed costs	15.6	15.0	15.1	15.0	15.0	14.9	14.9	15.6	15.6	16.1	16.2
Investments	65.1	63.9	64.3	65.8	66.2	63.5	63.8	62.6	62.7	68.4	68.7
Total	95.0	96.5	96.3	95.6	96.0	94.5	94.5	99.8	97.7	103.2	102.8

In Figure 3 the marginal changes in the primary energy supply are illustrated for individual heating technologies in the *100RE High Wind* scenario. The marginal changes are compared to the fuel consumption in a situation where approximately 20 PJ heat demand or 21 % (of all heating and hot water consumption) is covered by district heating (column 1 in Table 1).

Both of the micro-CHP solutions increase the total biomass consumption by 60 to 80 PJ. The reason for this is a number of issues related to the systems interaction with the energy system. With regard to micro-CHP with biogas the analyses reveal that while the technology can produce heat rather efficiently for the household, three related effects occur 1) the micro-CHP cannot produce as efficiently as other CHP plants in the energy system, and thus pushes out more efficient CHP production, 2) while doing this slightly more electricity has to be produced at condensing power plants (also in a system with 70% wind power) and 3) sometimes the heat demand occurs when the electricity demand is covered by other sources and the flexibility of a single-house thermal storage system is rather low. For micro-CHP on hydrogen (or other synthetic fuels derived from electrolysers) the losses in the electrolysers are supplementary to the effects mentioned above, which more or less outweighs the savings in biomass (and gasification) compared to the biogas alternative. In addition to the low fuel efficiency, this micro-CHP is the most costly alternative, even when optimistic cost assumptions are used, which is the case here.

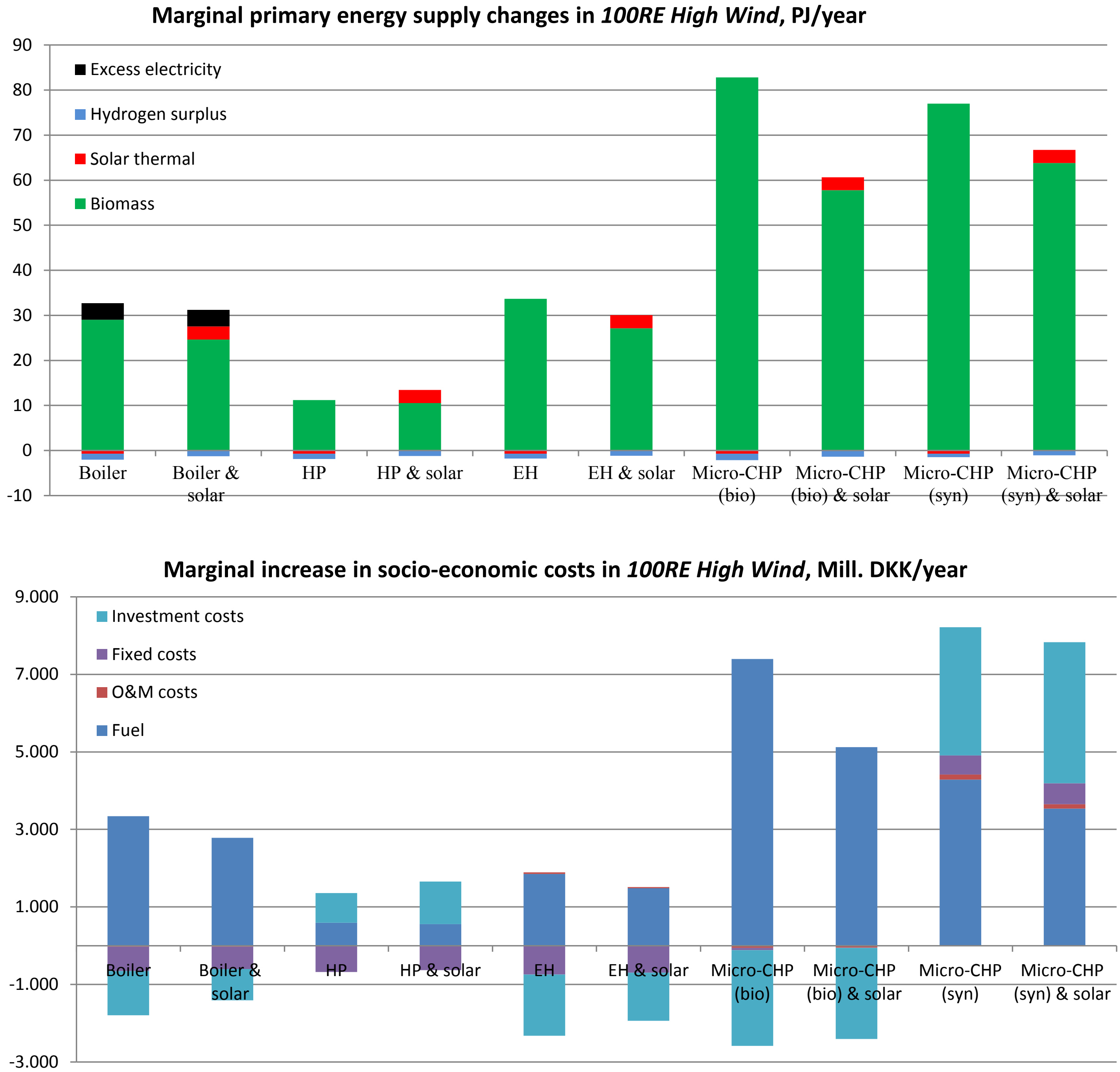

Figure 2, Marginal changes compared to district heating supply in the primary energy supply and in the socio-economic costs of individual heating technologies in the *100RE High Wind* scenario.

The electric heating alternative is rather cost effective and is on the same level as the district heating alternative with the cost assumptions used. This is primarily due to low cost of installing electric heating in the household, since no central heating system is required. In the short term however, this would not be the case for existing houses (with central heating) and in the long term electric heating is a rather fuel inefficient alternative to district heating: It increases the fuel consumption by app. 30 PJ.

The biomass boiler also increases the fuel consumption significantly i.e. by app. 30 PJ. And the costs cannot compete with other individual alternatives or district heating.

Individual (ground source) heat pumps are the most feasible alternative to district heating. They require 10 PJ more biomass than the district heating alternative, and have slightly higher socio-economic costs, however this is highly dependent on the fuel cost assumptions. Although slightly more expensive than electric boilers, they are less sensitive to changes in fuel costs.

The technologies have also been analysed in combination with 1 TWh of solar thermal, corresponding to what is normally regarded as technically feasible representing about 18% of the heat demand. The solar thermal can contribute to lowering the biomass demand in all alternatives, however the district heating alternative is still more fuel efficient and cost effective (except for the electric heating option).

All of these heating technologies have an effect on the system's ability to integrate wind power production. In all scenarios it means that hydrogen is produced now which cannot be directly used where it is produced. This however is of much less significance than the large increases in biomass consumption. The biomass boiler increases the excess electricity production slightly, however this is also of less significance than the increase in biomass consumption.

The results mentioned above are analysed in a high wind penetration scenario. In Figure 4 the same analyses has been performed in systems with less wind power and no wind power.

The conclusions derived above do not change on the basis of these analyses. It can be seen how electric heating gradually requires less biomass consumption as wind power is added, but maintains a rather high consumption in the high wind scenario. Also electrolysers have to use more electricity from biomass plants with less wind, making this alternative use even more fuel. The micro-CHP on biogas however has a slightly lower biomass consumption with less wind energy due to more opportunities to push out less efficient electricity production at central power plants. The micro-CHP alternatives are still the least efficient however.

In the analyses the different changes in the technologies producing district heating, i.e. the CHP unit which uses gasified biomass and the boilers which uses solid biomass, is the reason for the dip in the *100RE Low wind* with biomass boilers.

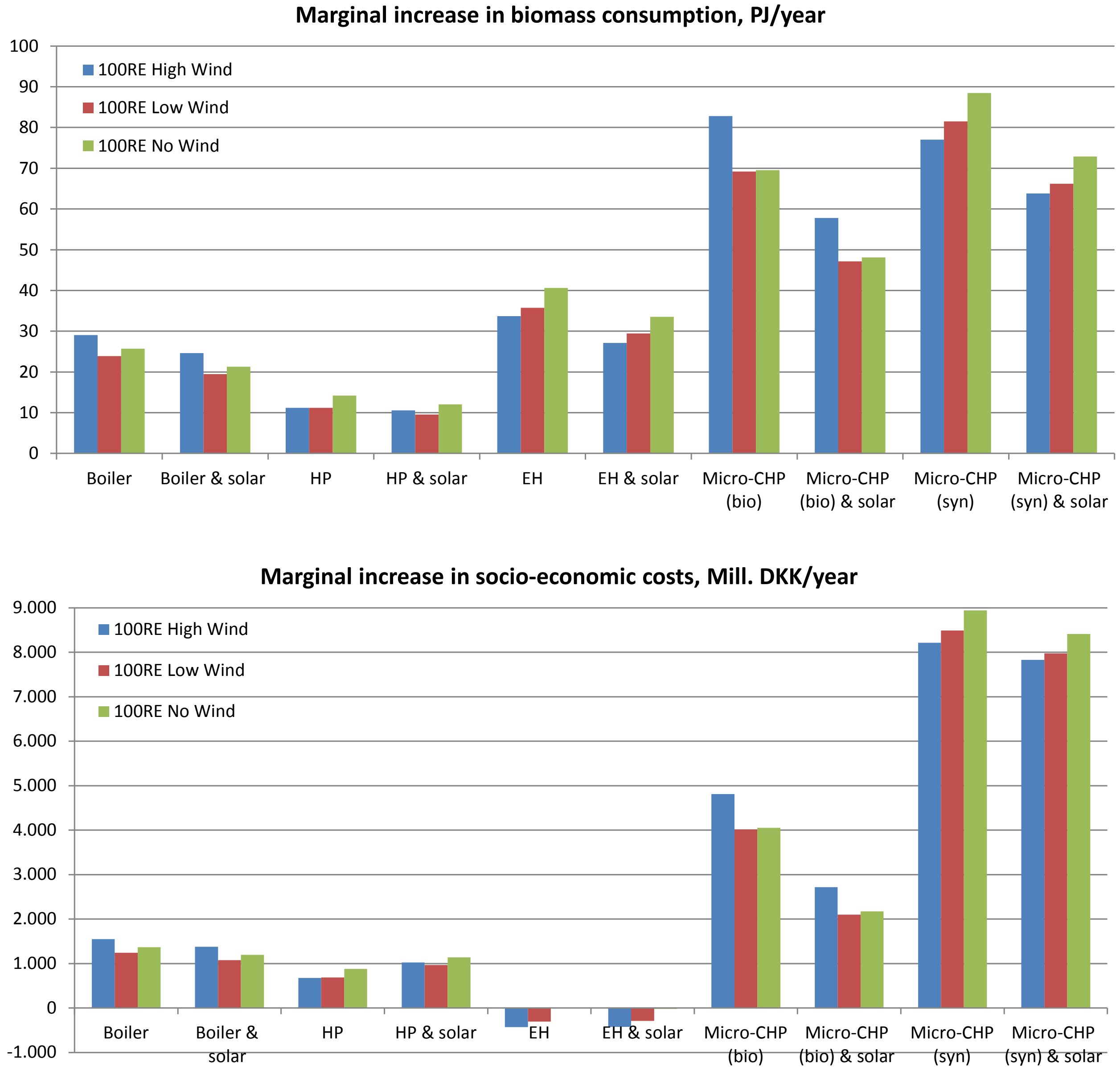

Figure 3, Marginal changes compared to district heating supply (21% decrease in district heating supply) in the primary energy supply and in the socio-economic costs of individual heating technologies in the three 100% renewable energy system with different amount of wind power.

From the first part of the analyses it can be concluded that the district heating option is the most fuel efficient alternative and while the costs of electric heating are comparable, the biomass consumption is significantly higher for electric heating. As an alternative to district heating, heat pumps can be recommended.

RESULTS OF THE ANALYSES OF DISTRICT HEATING PRODUCTION TECHNOLOGIES

In the second part different district heating production technologies have been analysed. The results of the analyses are not directly comparable to the analyses in the first part however, but district heating is analysed as a separate solution in the first part already. In the second part the following technologies are analysed:

- Boilers replace all other district heating production (about 100 PJ), also combined heat and power
- Large-scale solar thermal corresponding to app. 11% of the district heating production. With the existing thermal heat storages 5% of the district heating demand (including net losses) in 50% of district heating areas with large central CHP plants can be produced with solar thermal or 2.5% of 24.34 TWh. With 8 GWh of extra thermal heat storage 50% for the decentralised small CHP plants, 25% solar thermal can be implemented corresponding to 1.39 TWh. Currently about 20 GWh of thermal heat storage is installed in small CHP. In areas that do not currently have CHP but supply heat with boilers, 50% of the district heating demand is covered with solar thermal in 90% of these plants areas, corresponding to 80 GWh as long-term heat storages. Here an hourly loss of 0.01 % is included. Hence 1.25 TWh or 94% of the production can be utilised in these areas.
- Large-scale heat pumps in district heating areas. 400 MWe is placed in decentralised small CHP areas and 800 MWe in district heating areas with large CHP plants. As a precaution, it was assumed that the heat pumps could only cover 50% of the demand at all times, to ensure that the necessary temperature level is always achieved. The COP value used is 3.5.
- Industrial surplus heat of 2.65 TWh.
- Heat from waste incineration in boilers from 11.1 TWh waste.
- Heat from waste CHP incineration from 11.1 TWh waste.
- Waste CHP incineration with geothermal heat production using absorption heat pumps. The geothermal units cover 15% of the district heating demand in district heating areas with large central CHP.

In Table 2 the results of the analyses of different district heating production technologies in *100RE High Wind* are listed.

Table 2, Technical and socio-economic results of the analyses of different district heating production technologies in *100RE High Wind*.

	100RE High Wind	100% Biomass boiler	No large-scale solar thermal	No large heat pumps	No electro-lysor heat	No indu-strial sur-plus heat	Waste boiler (no waste CHP)	No waste CHP and geothermal	No geo-thermal
Fuel consumption (PJ/year)									
CHP	42.2	0.0	45.5	38.4	42.3	45.9	44.4	59.4	43.9
Power plants	6.3	45.0	4.6	2.2	6.3	4.1	7.1	10.7	4.5
Boilers	10.5	148.4	16.5	69.8	10.7	13.2	10.4	26.3	12.2
Waste CHP	39.9	0.0	39.9	39.9	39.9	39.9	39.9	0.0	39.9
Transport	59.8	59.8	59.8	59.8	59.8	59.8	59.8	59.8	59.8
Households	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2
Industry	68.5	68.5	68.5	68.5	68.5	68.5	68.5	68.5	68.5
Gasification	28.8	27.9	29.2	26.7	28.8	29.2	29.6	34.5	28.8
Primary Energy Supply (PJ/Year)									
Biomass	259.3	352.8	267.2	308.6	259.5	263.9	263.0	262.5	260.8
Solar thermal	19.3	7.6	7.6	19.3	19.3	19.3	19.3	19.3	19.3
Wind etc.	153.6	153.6	153.6	153.6	153.6	153.6	153.6	153.6	153.6
H_2 surplus	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Excess elec.	0.0	6.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total	432.3	520.0	428.5	481.6	432.5	436.9	435.9	435.5	433.8
Socio-economic costs (Billion DKK/year)									
Fuel	14.1	19.8	14.5	16.8	14.1	14.4	14.3	14.7	14.2
O&M costs	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.3	0.2
Fixed costs	15.6	14.4	15.6	15.6	15.6	15.6	15.6	15.6	15.5
Investments	65.1	62.0	64.5	63.4	65.1	65.1	65.1	65.1	64.9
Total	95.0	96.4	94.8	96.0	95.0	95.2	95.2	95.7	94.8

Figure 5 displays the results of the energy system analyses for different district heating production technologies. The technologies are compared using the *100RE High Wind* scenario. The analyses reveal that that the biomass consumption would increase significantly (up to 100 PJ) if biomass boilers replace all other district heating production. This is especially due to replacing CHP production with heat production in boilers and electricity production in power plants. For the other technologies analysed, large-scale heat pumps have the largest effect on the fuel efficiency, with the biomass consumption increasing by 50 PJ. Solar thermal enables a replacement of 10 PJ of biomass and industrial surplus heat with about 5 PJ of biomass. For waste incineration the picture is more complex. If the waste CHP incineration is replaced by waste incineration boilers the biomass consumption increases by 4 PJ. Geothermal combined with waste CHP incineration can reduce the biomass consumption by 3 PJ, while installing geothermal in combination with waste incineration in the first place decreases the biomass consumption by 2 PJ. In the 100% renewable energy scenarios here, most technologies are used to their full potential. Geothermal however could be slightly increased or used other places than in combination with waste incineration.

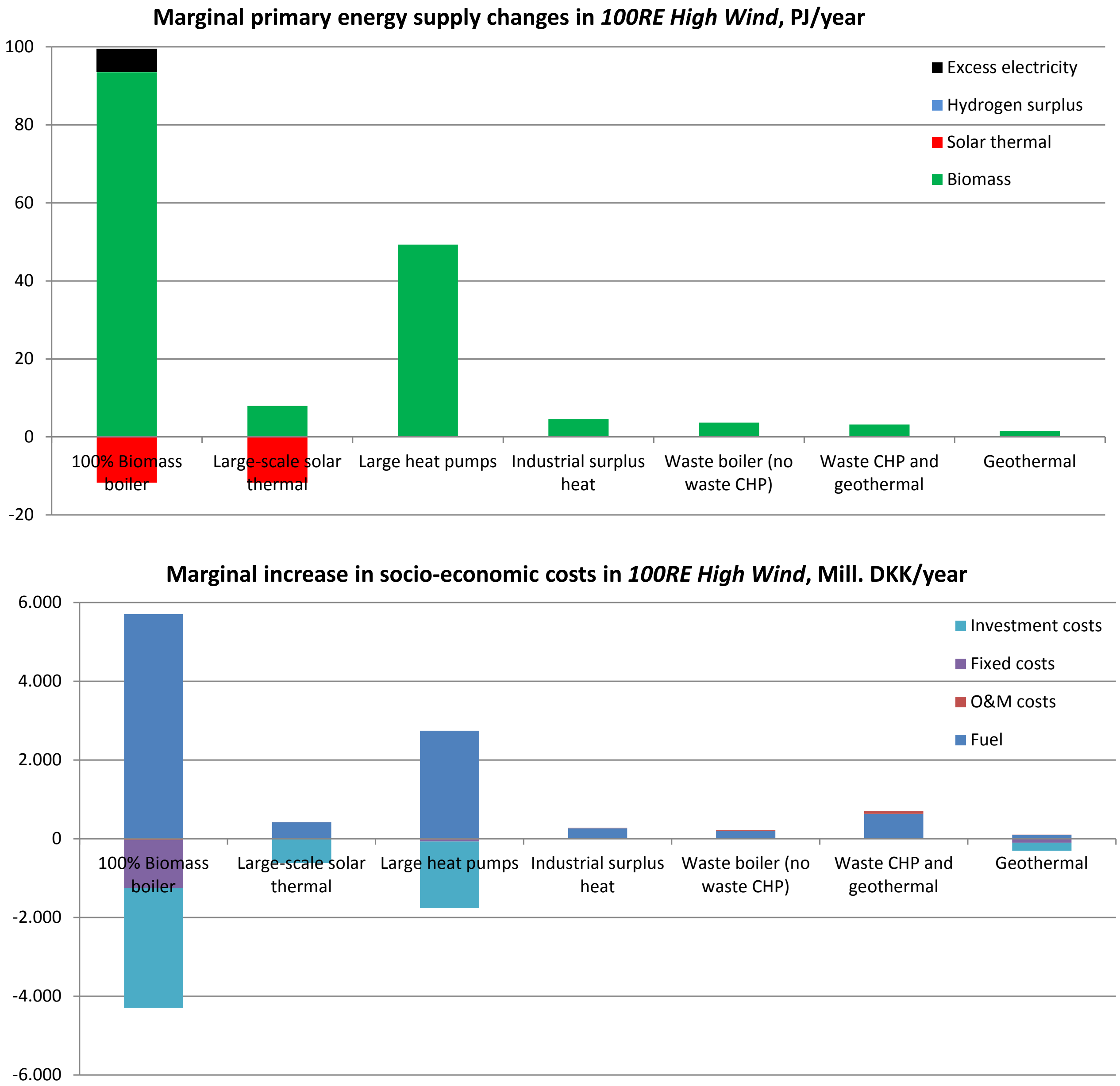

Figure 4, Marginal changes in the primary energy supply and in the socio-economic costs for different district heating production technologies in *100RE High Wind*.

The reason waste incineration does not allow for more biomass savings than illustrated is that the system is rather efficient and hence can produce the missing heat or electricity rather efficiently. Regarding excess electricity, the use of biomass boilers instead of CHP and heat pumps would create a wind power integration problem because heat pumps cannot use the thermal storages and produce district heating in that case. With regard to large-scale heat pumps, the lower electricity consumption would give way to more electrolyser production of fuel for CHP plants, because there are no other technological alternatives to use the excess electricity production in the energy system. None of the alternatives create a surplus hydrogen production as it can all be used in the system when it is produced.

When analysing the socio-economic costs the district heating production becomes significantly more expensive if it has to be produced with boilers only. Please note that these technologies (CHP plants, solar thermal, heat pumps etc.) have high investments but can save cost on using much less biomass. The heat pumps have significant socio-economic advantages. For the industrial surplus heat and waste alternatives the overall economy is also positive. It should be noted however that no investment costs have been included for these technologies, because the costs are related to waste handling and the surplus heat is assumed available for negligible costs. Regarding geothermal heat, there is a small socio-economic loss. This is due to the fact that the geothermal plant is connected to the waste CHP incineration and decreases the electricity production from this plant, but the other technologies in the system can produce this electricity rather efficiently [25]. The same reasoning can be made for solar thermal. For geothermal, solar thermal and long term thermal storage the investment costs have decreased since the analyses was conducted however.

In Figure 6 the results of the analyses of these systems in the other two 100% renewable energy scenarios are illustrated. The results do not change the conclusions described above. It can be noted however that the need for large-scale heat pumps increases with more and more wind power to ensure that wind power is integrated in the system fuel efficiently. Although, when the system has electricity production from CHP the heat pumps can also decrease the fuel consumption without wind power. It could also be noted that the ability of waste CHP incineration and geothermal to replace biomass is lower in systems with low amounts of wind power, because there are many more opportunities in the system to replace this production with CHP (which is operating to reduce inefficient condensing power production).

Socio-economically it is not feasible to invest in heat pumps without wind power. For the other technologies the changes are insignificant regarding costs compared to the results described above.

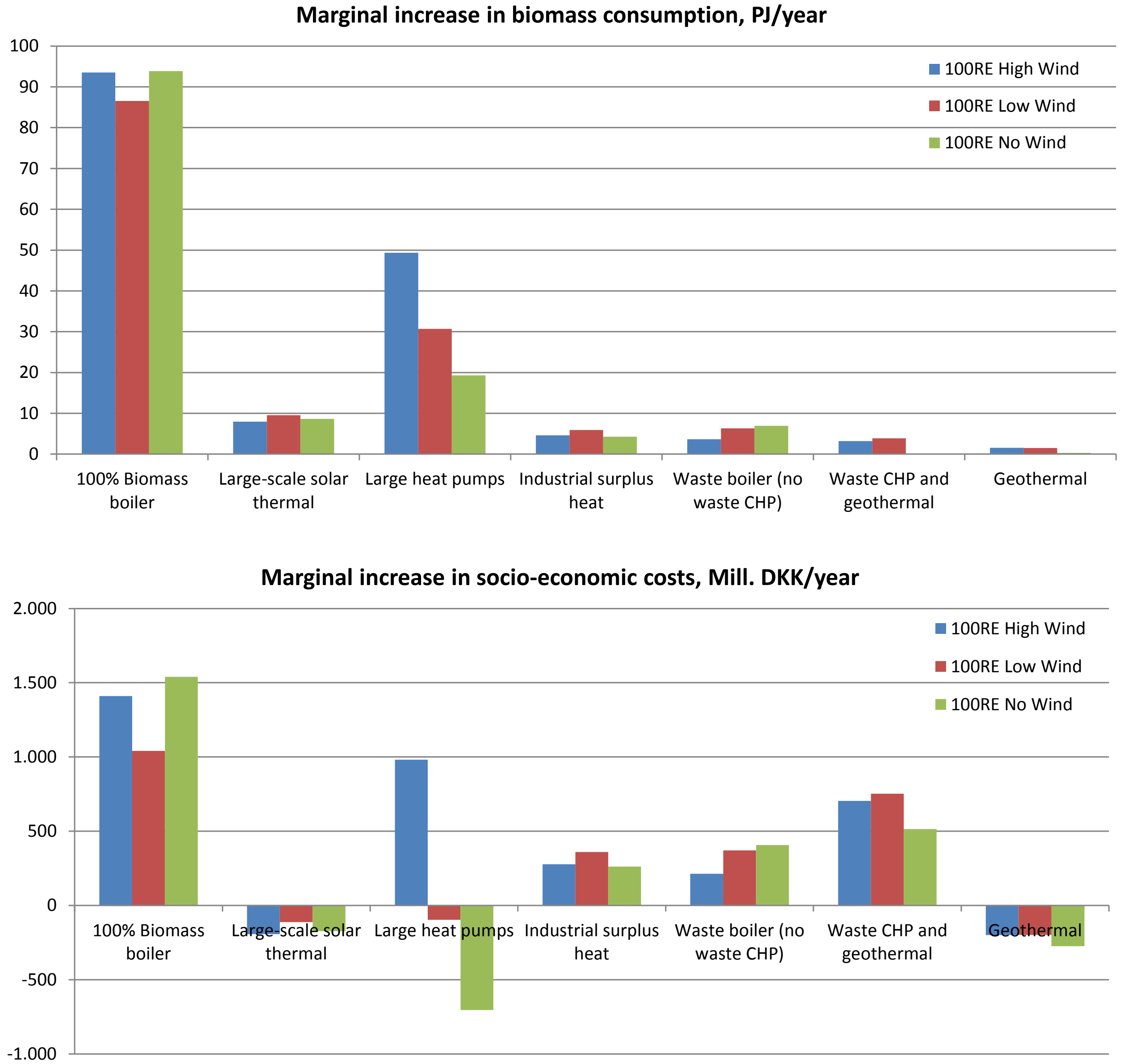

Figure 5 Marginal changes in the primary energy supply and in the socio-economic costs for different district heating production technologies in the three 100% renewable energy system with different amount of wind power.

If we compare the district heating options with the individual technologies investigated earlier, it can also be derived that the difference from the highest to the lowest cost alternatives is much lower for district heating than for the individual technologies, especially micro-CHP. Hence with district heating the risk of having more expensive technologies installed is lower.

Conclusion

In this paper household heating technologies have been analysed in a number of 100 per cent renewable energy systems with varying amounts of wind power. The analyses are conducted in order to assess heating technologies for district heating and individual houses in the context of a future with limited biomass resources, while also taking into account that some solutions are more cost-effective than others. The conclusions of the analyses of household heating in 100% renewable energy systems can be divided into five main parts. The analyses show:

1. That an expansion of district heating can reduce the pressure on the biomass resource in 100% renewable energy systems and is cost-effective compared to individual heating technologies.
2. That an expansion of district heating is more important in renewable energy systems with large amounts of fluctuating renewable energy (such as wind turbines) as it enables a fuel efficient and cost-effective integration of fluctuating renewable energy in the electricity grid.
3. That district heating is important in 100% renewable energy systems as it can allow the exploitation of large-scale solar thermal, large-scale heat pumps, industrial surplus heat, geothermal heat and waste incineration.
4. That CHP is very important in 100% renewable energy systems and that the most efficient CHP technologies require district heating in combination with using thermal storages.
5. That if individual heating technologies are chosen instead of district heating the pressure on the biomass resource will increase 4 to 31 % for the energy system (including all biomass consumption).

Choosing individual heating technologies instead of district heating in the Danish 100% renewable energy system would increase the biomass consumption by between 10 and 80 PJ for the most efficient and least efficient technology respectively, i.e. ground source heat pumps or micro fuel cell CHP. Choosing individual heating technologies would also mean that wind power integration is less effective as large heat pumps in district heating grids would have to be replaced by much less efficient electrolysers or other less efficient technologies to ensure a balanced system. District heating enables the use of heat pumps without which the biomass consumption would increase by 50 PJ. Also it enables the use of large-scale solar thermal to replace about 10 PJ of biomass. If the waste CHP incineration is replaced by waste incineration boilers, then the biomass consumption increases by 4 PJ. Geothermal combined with waste CHP incineration can reduce the biomass consumption by 3 PJ while installing geothermal in combination with waste incineration in the first place decreases the biomass consumption by 2 PJ.

REFERENCES

[1] L. Fresco, D. Dijk, and W. de Ridder, "Biomass, food & sustainability: Is there a dilemma?," University of Amsterdam,2007.

[2] S. Corcoran, J. Murphy, and E. McKeogh, "The potential for biomass energy in Ireland," Berlin, Germany: 2007.

[3] Danish Energy Authority, "Biomasseressourcer, Ressourcer til energiformål i Danmark," Energistyrelsen (Danish Energy Authority), Copenhagen,2006.

[4] Danish Energy Authority, "Energistatistik 2009 (Energy statistics 2009)," Energistyrelsen (Danish Energy Authority), Copenhagen,2010.

[5] B. V. Mathiesen, H. Lund, and P. Norgaard, "Integrated transport and renewable energy systems," *Utilities Policy*, vol. 16, no. 2, pp. 107-116, June2008.

[6] M. Münster and P. Meibom, "Long-term affected energy production of waste to energy technologies identified by use of energy system analysis," *Waste Management*, vol. 30, no. 12, pp. 2510-2519, Dec.2010.

[7] H. Lund, "Renewable energy strategies for sustainable development," *Energy*, vol. 32, no. 6, pp. 912-919, June2007.

[8] P. A. Østergaard, B. V. Mathiesen, B. Möller, and H. Lund, "A renewable energy scenario for Aalborg Municipality based on low-temperature geothermal heat, wind power and biomass," *Energy*, vol. 35, no. 12, pp. 4892-4901, Dec.2010.

[9] B. V. Mathiesen, H. Lund, and K. Karlsson, "100% Renewable energy systems, climate mitigation and economic growth," *Applied Energy*, 2011.

[10] B. V. Mathiesen and H. Lund, "Comparative analyses of seven technologies to facilitate the integration of fluctuating renewable energy sources," *IET Renew. Power Gener.*, vol. 3, no. 2, pp. 190-204, June2009.

[11] B. V. Mathiesen, "Fuel cells and electrolysers in future energy systems - PhD Dissertation." Department of Development and Planning, Aalborg University, 2008.

[12] H. Lund, B. Möller, B. V. Mathiesen, and A. Dyrelund, "The Role of District Heating in Future Renewable Energy Systems," *Energy*, vol. 35, no. 3, pp. 1381-1390, Mar.2010.

[13] M. B. Blarke and H. Lund, "The effectiveness of storage and relocation options in renewable energy systems," *Renewable Energy*, vol. 33, no. 7, pp. 1499-1507, July2008.

[14] H. Lund and B. V. Mathiesen, "Ingeniørforeningens Energiplan 2030 - Tekniske energisystemanalyser, samfundsøkonomisk konsekvensvurdering og kvantificering af erhvervspotentialer. Baggrundsrapport (Danish Society of Engineers' Energy Plan 2030)," Danish Society of Engineers (Ingeniørforeningen Danmark), Copenhagen,Dec.2006.

[15] H. Lund and B. V. Mathiesen, "Energy system analysis of 100% renewable energy systems - The case of Denmark in years 2030 and 2050," *Energy*, vol. 34, no. 5, pp. 524-531, May2009.

[16] B. V. Mathiesen, H. Lund, and K. Karlsson, "IDAs Klimaplan 2050, baggrundsrapport - Tekniske systemanalyser, brændselsforbrug, drivhusgasser, samfundsøkonomiske konsekvenser, erhvervspotentialer, beskæftigelseseffekter samt helbredsomkostninger (IDAs Climate Plan 2050, background report in Danish and English)," Danish Society of Engineers (IDA, Ingeniørforeningen Danmark), Copenhagen, Denmark,Aug.2009.

[17] CEESA, "Coherent Energy and Environmental System Analysis," 2011.

[18] Danish Energy Authority, "Forudsætninger for samfundsøkonomiske analyser på energiområdet (Premises for socio-economic analyses within energy)," Danish Energy Authority (Energistyrelsen), Copenhagen,May2009.

[19] A. Dyrelund, H. Lund, B. V. Mathiesen, F. Hvelplund, C. Bojesen, A. Odgaard, R. M. Sørensen, K. Fafner, S. Knudsen, and F. Ulbjerg, "Varmeplan Danmark 2010 (Heat plan for Denmark 2010)," Ramboll Denmark, Copenhagen, Denmark,Project no. 2010 - 02, Sept.2010.

[20] A. Dyrelund, H. Lund, B. Möller, B. V. Mathiesen, K. Fafner, S. Knudsen, B. Lykkemark, F. Ulbjerg, T. H. Laustsen, J. M. Larsen, and P. Holm, "Varmeplan Danmark (Heat plan for Denmark)," Ramboll Denmark, Virum, Denmark,Project no. 2008 - 01, Oct.2008.

[21] H. Lund, "EnergyPLAN - Advanced Energy Systems Analysis Computer Model - Documentation Version 7.0 - http://www.energyPLAN.eu," Aalborg University, Aalborg, Denmark,Mar.2007.

[22] H. Tommerup and S. Svendsen, "Energy savings in Danish residential building stock," *Energy and Buildings*, vol. 38, no. 6, pp. 618-626, June2006.

[23] K. B. Wittchen, "Potentielle energibesparelser i det eksisterende byggeri Skærpede krav til nybyggeriet 2010 og fremover - Økonomisk analyse (Increased demands for buildings standards from 2010)," Statens Byggeforskningsinstitut (Danish Building Research Institute), Hørsholm, Denmark,Feb.2009.

[24] S. Aggerholm, "Skærpede krav til nybyggeriet 2010 og fremover - Økonomisk analyse (Increased demands for buildings standards from 2010)," Statens Byggeforskningsinstitut (Danish Building Research Institute), Hørsholm, Denmark,Feb.2009.

[25] P. A. Østergaard and H. Lund, "A renewable energy system in Frederikshavn using low-temperature geothermal energy for district heating," *Applied Energy*, vol. 88, no. 2, pp. 479-487, Feb.2011.