The design of Smart Energy Systems for 100% renewable energy and transport solutions

Mathiesen, Brian Vad; Lund, Henrik; Connolly, David; Østergaard, Poul Alberg; Möller, Bernd

Published in:
Book of Abstracts: 8th CONFERENCE ON SUSTAINABLE DEVELOPMENT OF ENERGY, WATER AND ENVIRONMENT SYSTEMS

Publication date:
2013

Document Version
Accepted author manuscript, peer reviewed version

The design of Smart Energy Systems for 100% renewable energy and transport solutions

B.V. Mathiesen[A*], H. Lund[B], D. Connolly[A], P. A. Østergaard[B] and B. Möller[B]

[A]Department of Development and Planning, Aalborg University, A.C. Meyers Vænge 15, DK-2450 Copenhagen SV, Denmark

[B]Department of Development and Planning, Aalborg University, Vestre Havnepromenade 9, DK-9000 Aalborg, Denmark

ABSTRACT

In this paper we launch the design of Smart Energy Systems through the 100% renewable energy system analyses and research behind the CEESA research project. The transition from fossil fuels towards the integration of more and more renewable energy requires rethinking and redesign of the energy system. Traditionally a lot of focus internationally is put on the electricity sector to solve the integration puzzle focusing on electricity storage technologies e.g. batteries, hydrogen storage and on (electricity) smart grids. In Smart Energy Systems the focus is integration of the electricity, heating and transport sectors, and on using the flexibility in demands and various short term and longer term storage in the different sectors. Such a redesign also entails that the Smart Energy System is comprised of a number of smart grid infrastructures for different sectors in the energy system, i.e. the electricity grids, district heating (cooling) grids, gas grids and fuel infrastructure.

KEYWORDS

Smart energy systems; renewable energy systems; wind power; biomass; smart grids; district heating; combined heat and power; synthetic transport fuels

INTRODUCTION

Currently most energy systems are predominantly based on fossil fuels. More and more focus is being placed on energy savings, renewable energy and handling intermittent resources as the shares of fluctuating resources increase. In the current fossil based system, the flexibility is based on the fuels provided for power plants, boilers and vehicles in liquid, gas, and solid form. Current systems have built up the infrastructure and storage facilities that can provide for the demands by means of transporting fossil fuels over large distances in ships and gas pipelines on the global level and providing national or regional energy infrastructure, gas and oil storage facilities and electricity production. Hence a global system is built up based on the easy storage and density of fossil fuels that can flexibly provide for the demands at the right time and place. While this is the case now, the challenge is how such flexibility and timely energy supply can be provided with more and more renewable energy?

*Corresponding author. Tel.: +45 9940 7218; E-mail addresses: bvm@plan.aau.dk (B.V. Mathiesen), lund@plan.aau.dk (H. Lund), david@plan.aau.dk (D. Connolly), poul@plan.aau.dk (P.A. Østergaard), bernd@plan.aau.dk (B. Möller)

While some integrated studies of the road to 100% renewable energy and transport systems have been already presented [1-5], there is still a predominant sectorial focus; specifically on how to integrate intermittent resources into the electricity sector [6-9]. The purpose of introducing more and more renewable energy into the energy system is to save fuels. In the short term fossil fuels and in the longer term biomass, as biomass is a limited resource that cannot be expected to replace all of the fossil fuels used today. Apart from anthropogenic greenhouse gas emissions from the burning of fossil fuels there are many other reasons why it is important to focus on this transition. Climate change is a recent focus. Security of supply and geopolitical issues, socio-economic consequences of the energy mix, ownership and democracy, business development and job creation are other important parts of the energy system that has been in focus for many decades [10,11]. Fossil fuels have played a major part in these issues.

A lot of focus is placed on the integration of renewable energy into the electricity grid. E.g. the whole smart grid community has a strong focus on the use of smart meters, flexible demand and storage options in the electricity sector. Research shows however that the integration of the heating sector is important to create a fuel efficient energy system and that such integration is economically and environmentally feasible [12-14]. In integration of the heating sector, the electricity sector can be connected to heating by the means of large scale heat pumps using district heating networks and large thermal heat storages. Also lower value renewable energy sources can be utilised in the heating sector if we implement district heating [14]. The great challenge however is the transport sector. Various scenarios have shown how no single technology can solve the transport puzzle [15]. Also the use of current biofuels is heavily debated and the biomass use is controversial even with new bio-refining technologies due to the connection to food production and land-use increase. In other words, in the future it is equally important to save biomass as it is to save fossil fuels.

Our hypothesis is that heavy integration of the different sectors using energy will create the most fuel efficient and low options for 100% renewable energy and transport systems. In this paper we lunch the design of Smart Energy Systems for 100% renewable energy by highlighting the key components in such systems. We use a concrete smart energy system design from the strategic research project CEESA (Coherent energy and environmental system analyses) as the case to illustrate such design. In this project we have conducted analyses of 100% renewable energy and transport system designs. It should be noted that there can be many other scenarios using the Smart Energy System design highlighted in this paper.

METHODOLOGY

There is considerable knowledge about most parts of the energy system. In this paper we combine previous research results in Smart Energy Systems and in this process describe the research behind.

The paper builds on different phases the energy system can evolve though, where more and more sectors of the energy systems can be integrated using research results based on detailed analyses in the Advanced Energy System Analysis Computer tool EnergyPLAN in some cases in combination with GIS (geographical information systems) for mapping and analysing heat demands [16]. This model includes whole national or regional energy system, i.e. heat and electricity supplies as well as the transport and industrial sectors. All thermal, renewable, storage, conversion, and transport technologies can be modelled by EnergyPLAN [17]. The tool is a deterministic input/output tool and, general inputs are demands, renewable energy sources, energy station capacities, costs, and a number of optional regulation strategies for import/export and excess electricity production all on an hourly basis. The tool is now also able to include analyses combining intermittent renewable energy sources with the production of synthetic gasses or liquids in addition to the capability to include different types of biofuels.

The final recommendations regarding the design of Smart Energy Systems builds on a case study from the strategic research project CEESA. The design is put forward using principle diagrams of the energy system with ideal and optimised operation.

After describing the design presented through the research as described above, the overall results in the CEESA project is presented. Transport is one of the key challenges in society and has had special attention in the 100% renewable energy scenarios also developed in CEESA. The CEESA project was interdisciplinary and involved more than 20 researchers from 7 different universities or research institutions in Denmark. The results include further development and integration of existing tools and methodologies into coherent energy and environmental analysis tools as well as analyses of the design and implementation of future renewable energy systems.

FROM ELECTRICITY SYSTEMS TO SMART ENERGY SYSTEMS

Without changing anything in the energy system 20-25% of intermittent renewable energy sources can normally be integrated in most energy systems [8,13]. The electricity based system is illustrated without intermittent renewable energy in Figure 1, (1a) and combined renewable energy in (2a) in Figure 2. As can be seen in such principle diagrams significant losses occur in the conversion in the power plant. By introducing renewable energy, e.g. wind power, a part of the fuel used could be replaced. Here 25% is assumed possible based on the fact that the peaks during the year of the intermittent resources will reach the current electricity peak demands at some point and further integration will increasingly be curtailed. In this section we argue to change from a sectorial approach to an integrated approach – going from the focusing on electricity, heat and transport systems separately to looking at the sectors coherently.

The integration of the electricity and heating sectors

As the debate about the integration of intermittent renewable energy sources increases sectorial backgrounds create sectorial focuses on solving the integration challenge as well. From the viewpoint of the electricity sector this has created a research and business area, often combining the intermittency on sources connected to the electricity grid to the individual consumer under the assumption that demands can integrate renewable energy. Also such focuses lead to the notion of direct storage of electricity in batteries, fly wheels or in fuels used for electricity production again, e.g. hydrogen from electrolysers. Our research claims that:

"…all kinds of electricity storage should be avoided,
if the aim is to put electricity back on the grid!"

Energy storage is rather different from direct electricity storage. While energy storage is very important, the round trip conversion losses with electricity storage should be avoided. The principal is to charge an energy storage facility when excess electricity production occurs and discharge the facility when a shortfall in electricity supply occurs. This ensures that supply and demand matches on the electricity side. At present however, there are only two large-scale (i.e. >100 MW) energy storage technologies that have been implemented: pumped hydroelectric energy storage (PHES) and compressed air energy storage (CAES). With both of these there is an inherent energy loss, with each having a round-trip efficiency of approximately 85% and 65% respectively. Hence, when assessing energy storage, there is a balancing act between integrating more intermittent renewables and reducing the overall efficiency of the system. Salgi and Lund [18] investigated the feasibility of CAES and compares CEAS to other alternatives. The results indicated that smaller CAES had little impacts, while larger ones could have, but it would require very large storage capacities to eliminate excess production altogether. Overall, the modelling results indicated that due to the widespread use of CHP (combined heat and power) in Denmark used in the case study, at low wind penetrations there was not enough excess production for storage to charge and at high wind penetrations there was not enough power-plant only hours for the storage to discharge. In a subsequent paper Lund and Salgi [19] compared a fixed investment in CAES to the same investment in alternative sources of flexibility such as electric boilers, large-scale heat pumps and electrolysers. The feasibility study results indicated that heat pumps and electric boilers reduce the costs of operating the Danish energy system significantly more than CAES. Therefore, these forms of flexibility should be implemented in Denmark before CAES. However, if CAES plants can save investments in power plant capacities in the system, the CAES technology may become feasible to the system.

Mathiesen 2008 investigates the role of fuel cells and hydrogen in future energy systems [13]. In some studies hydrogen is proposed to be produced and then used in micro-CHPs or other means of electricity production. In the short term, electrolyser hydrogen is not suitable for fuel cell applications; and in the long term, some applications of electrolysers are more suitable than others. Other energy storage technologies, such as large heat pumps in CHP plants and battery electric vehicles, should be implemented first, because these technologies are more fuel and cost-efficient and micro-CHP should be avoided completely [12,13]; both in systems with and without CHP plants. Electrolysers should only be implemented in energy systems with very high shares of intermittent renewable energy (+50%) and that other integration options are significantly more important [13]. In a 100 % renewable energy system however, they constitute a key part, because they displace fuels derived from biomass – but not by using hydrogen for electricity production to the grid.

These case studies about current technologies and potential future technologies highlight the issue of electricity storage as the main mean of integrating intermittent resources. Electricity storage technologies such as batteries or flywheels may have a function as the mean to manage the grid in few extreme situations but should be avoided as the main mean of integration. What are then the options if we want to increase the intermittent renewable energy penetration?

The electricity sector is only a part of the energy sector. The heating (and cooling) sector poses a significant challenge as well. When looking at the energy supply from the view point of the heating sector, a number of options can be applied as mentioned already in the case studies above. In Figure 1 a number of principle diagrams illustrates how the electricity and heat can be supplied assuming that we need 40 units of heat when we need 30 units of electricity and 30 units of fuel for transport before we start introducing intermittent renewable energy sources.

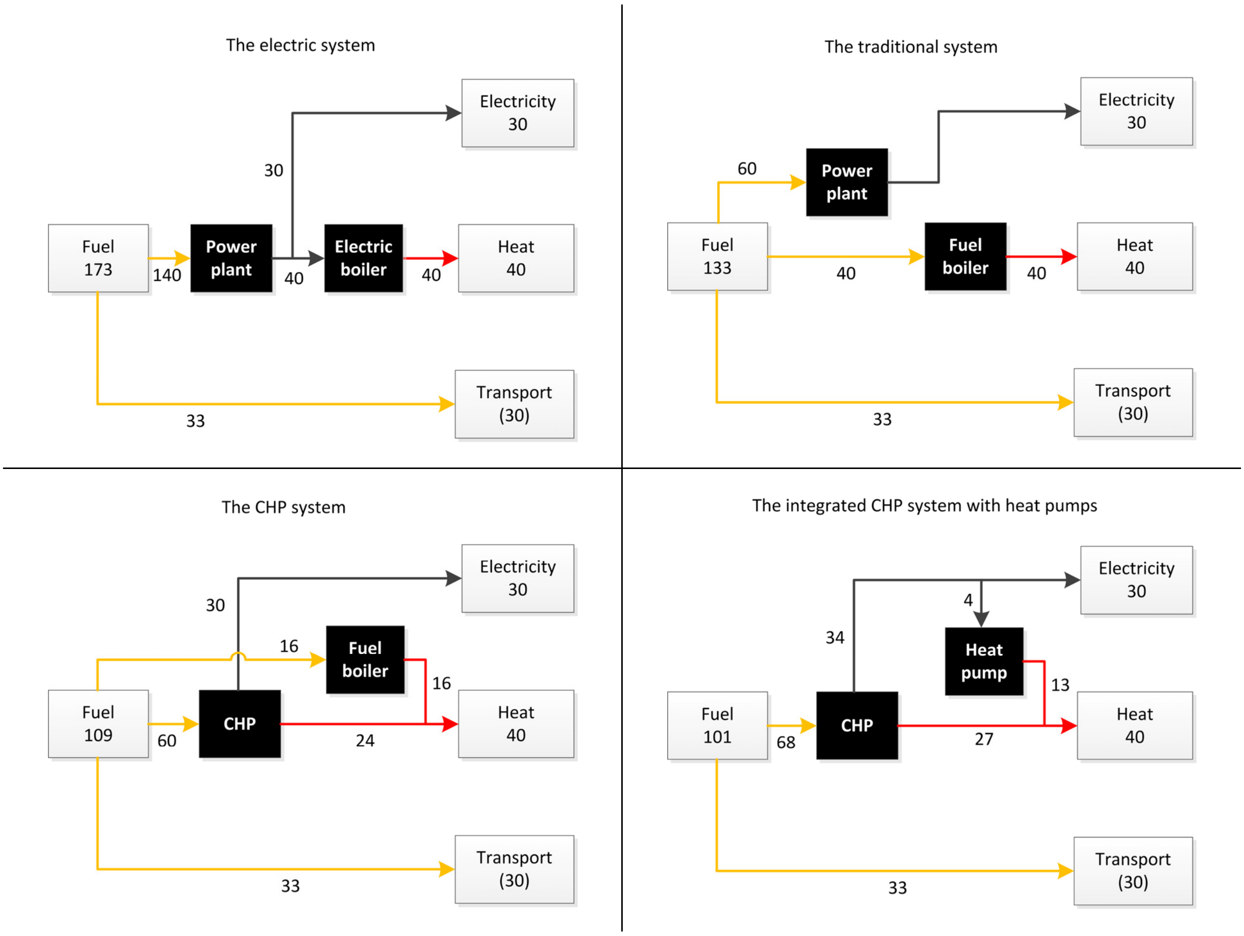


Figure 1, Principle diagram of an electric energy system (1a), a traditional energy system (1b), a CHP system (1c) and an integrated system with heat pump (1d) providing the same energy services.

Going from an electric system (1a) through a traditional system (1b) towards a CHP system (1c) illustrates how the fuel efficiency can be improved significantly – without introducing intermittent resources. The principle diagrams illustrate how redesigning the energy system can significantly improve the fuel efficiency. By 30-40 per cent from the worst case to the best case. The diagrams represent an ideal situation. It does however highlight some of the issues that need to be addressed in the design of energy systems. The fuel inefficiency regarding direct electric heating is reduced significantly going to the CHP energy system. Going from the CHP system to the integrated system with large heat pumps (1d) the issues regarding the balance between the electricity demand and the heat demand becomes apparent as a part of the design of the supply system. As the principle diagram assumes a high electric efficiency in the gas engine or gas turbine CHP plants, a part of supply of heat has to be meet by a boiler in (1c). Heat demands could also be reduced which could reduce the need for boilers in the CHP system. Going towards the integrated system with heat pumps from the CHP system (1c to 1d) does not improve the fuel efficiency significantly.

When introducing renewable energy sources however this redesign becomes rather important. In Figure 2 25% wind power is introduced in the four energy systems presented above. Again this represents ideal situations as e.g. the heat pumps would not cover all demands in (2d) but would be supplemented by some boiler operation.

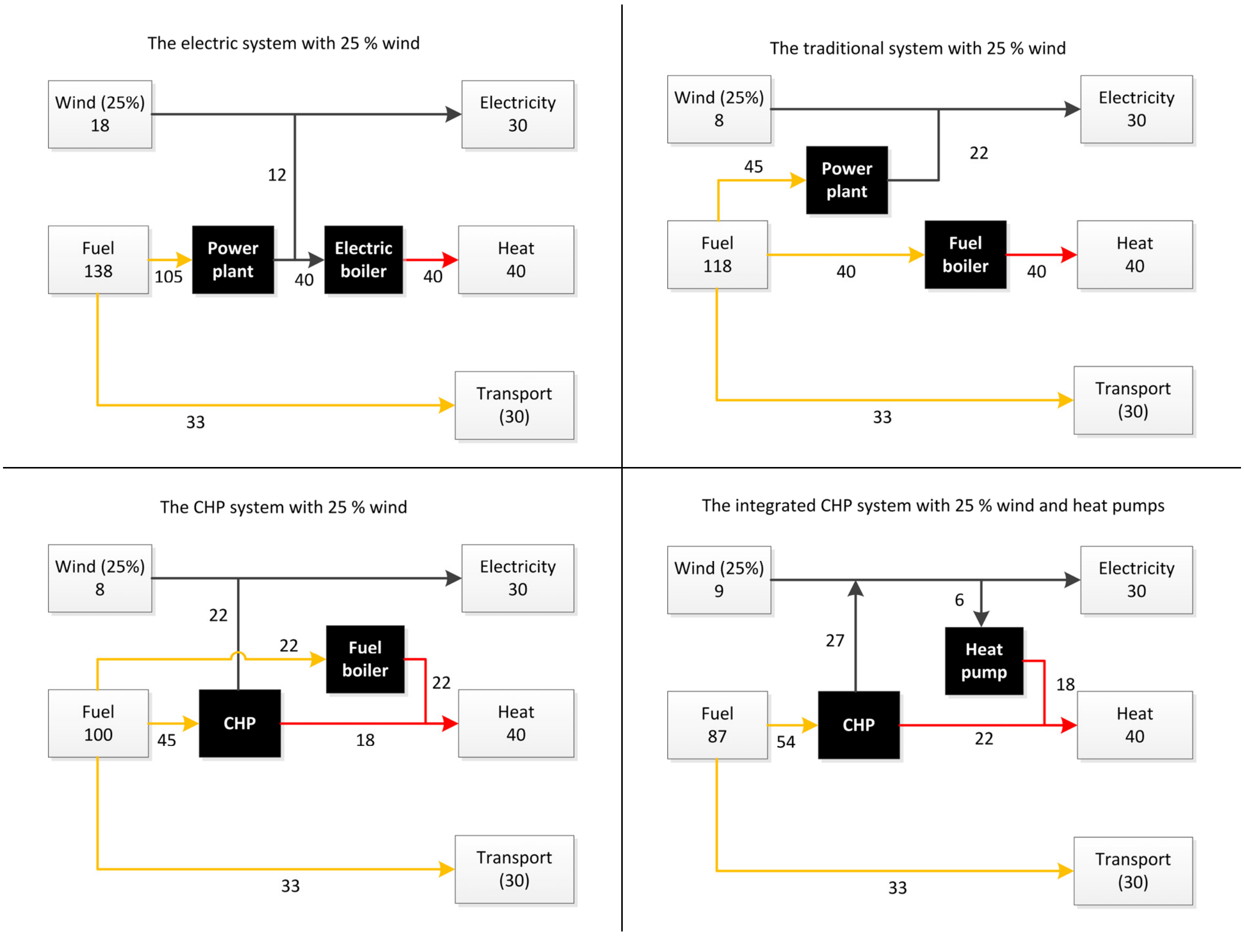


Figure 2, Principle diagram of 25% wind power of the electricity consumption in an electric energy system (2a), a traditional energy system (2b), a CHP system (2c) and an integrated system with heat pump (2d) providing the same energy services.

As highlighted the integration of the heating sector with the electricity sector becomes increasingly important in order to increase the fuel efficiency of the energy system. Again if the purpose of increasing intermittent resources into the energy system is to reduce the use of fossil fuels, it is important to redesign the energy system to facilitate this. The role of heat pumps in such energy systems reduces the use of boilers while at the same time using wind power and enabling fuel efficient integration of the renewable energy. Introducing heat pumps can decrease the fuel consumption in energy systems with 25% wind power, but even more wind power can be integrated, up to 40% without reducing the fuel efficiency of the system as mentioned above. Our research claims that for large-scale integration of intermittent resources:

"…the integration of the electricity sector and the heating sector
should be done with CHP plants and large heat pumps
with heat storages in district heating systems where possible"

In several case studies, the use of district heating, heat storages and heat pumps has been highlighted as the more feasible and fuel efficient option compared to individual solutions and Where district heating is not possible individual heat pumps should be used [13,14,20,21]. In Dyrelund et.al [20] and Lund et.al [14] various heating technologies under three distinct scenarios for the Danish energy system were analysed in a feasibility study and a study about what heating systems are suitable in energy systems with large amounts of renewable energy.

Almost 50% of the Danish net heat demand is currently supplied by district heating. The studies investigated whether the current level should be kept combined with individual solutions or whether the district heating systems should be expanded. For the first scenario, all buildings with individual boilers in areas which have or plan to have district heating networks were converted to district heating. In the second scenario, all buildings with gas boilers which were adjacent to district heating networks were converted and finally, in the third scenario, all buildings with gas boilers within 1 km of the district heating were converted. To provide a complete picture, five alternatives to district heating were considered for each scenario: ground-source heat pumps, air-source heat pumps, electric heating, gas micro CHP, and hydrogen micro CHP. For each scenario, the fuel demand, CO_2 emissions, and socio-economic costs were calculated and compared to three reference scenarios (2006, 2020, and 2060) using a technical optimisation. The results indicated that as Denmark progressed towards a 100% renewable energy system by 2060, the electricity consuming options (heat pumps and electric heating) and district heating became the most environmentally and economically attractive alternatives. In contrast, the electricity producing alternatives (micro CHP) became less attractive, which was primarily due to the additional excess electricity production on the system from intermittent renewable energy sources. Other studies confirm such results. Recently similar studies have been conducted on the European scale [22,23] confirming that district heating and heat storages can increase the fuel efficiency significantly and decrease the costs of the energy system while also reducing the greenhouse gas emissions. Individual buildings are not able to provide the same flexibility as in district heating systems by simply applying heat storages or batteries in the houses [12,24,25].

The integration of the electricity and heating sector using CHP plants, heat storages and heat pumps enables fuel efficient integration of more intermittent renewable energy. In Figure 3 such a system is combined with 50% wind power (3a) enabling the fuel consumption to be reduced further compared to the 25% wind power penetration alternative.

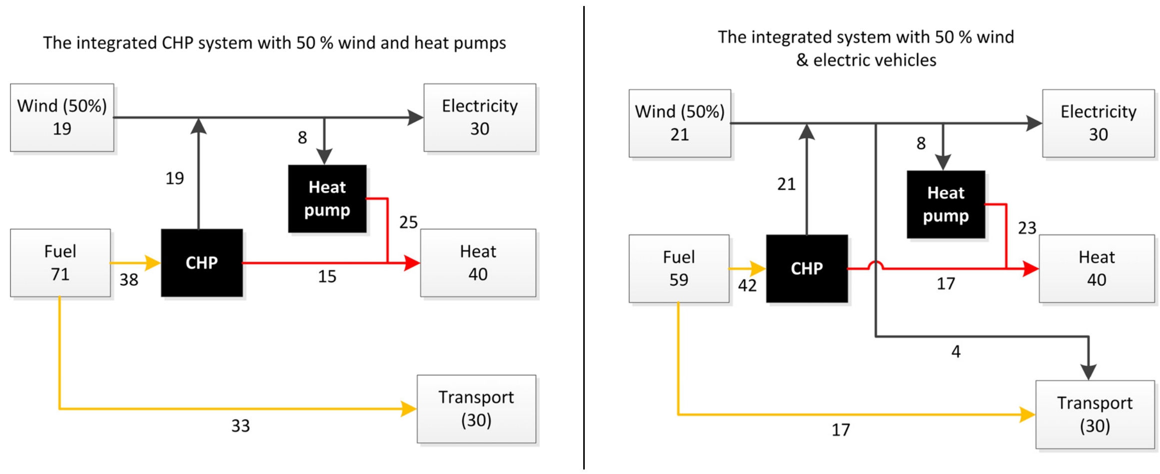


Figure 3, Principle diagram of the integrated CHP system with 50% wind power and heat pumps (3a) and the same systems combined with electric vehicles (3b) covering 50% of the transport demand.

The integration of the electricity, heating and transport sectors

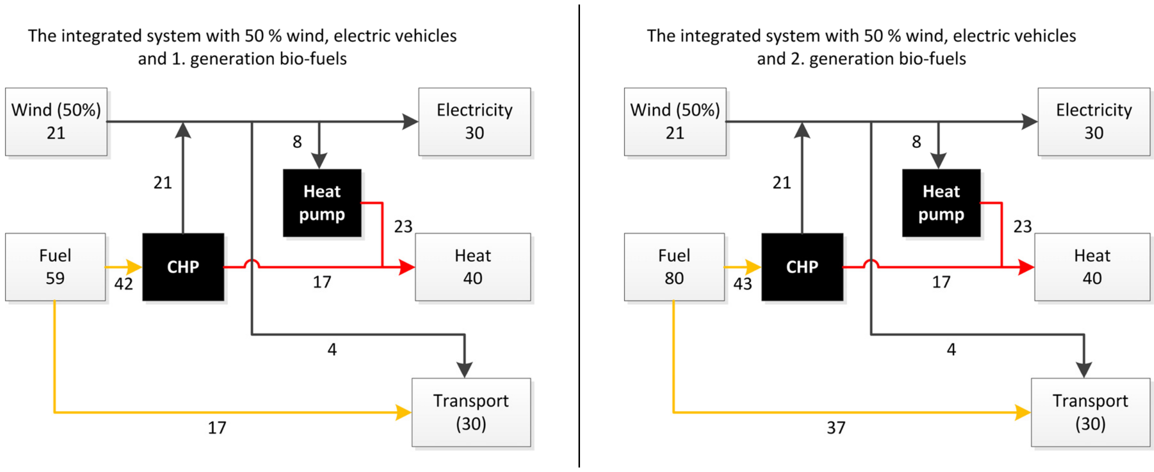
For 50% renewable electricity penetration, flexible electricity demands from the current type of demands and intelligent operation of individual heat pumps have some role in the integration as well, although it is rather small compared to large-scale heat pumps [12]. The next major step is the integration of the transport sector. In Figure 3 a principle diagram of how the transport sector could be partly transformed is illustrated (3b). 50% of the end demand is assumed covered by electric vehicles. Electric vehicles can significantly improve the fuel efficiency and increase the penetration of intermittent renewable energy. As can be seen, the inefficiency of current vehicles and the rather efficient electric vehicles can reduce the fuel consumption in the integrated energy and transport system significantly. The question is what kind of solutions can facilitate that we move the transport sector towards renewable energy? Our research shows that:

"…the integration of the transport sector can increase the renewable energy penetration and transport should be covered by electricity to the largest extent possible".

In constructing 100% renewable energy and transport systems, a key challenge is to identify means of introducing renewable energy in a manor where most fossil fuels are replaced. By increasing the amount of battery electric vehicles previous analyses have shown that this is possible in hour-by-hour energy system analyses [12,26,27]. In Mathiesen et.al 2009 [12] an analysis of seven different technologies is presented. Here battery electric vehicles constitute the most promising transport integration technology when compared with hydrogen fuel cell vehicles. The problem regarding hydrogen vehicles is that it introduces losses into the system, and that apart from using intermittent resources, that electrolysers will increase the use of power plants as well [27]. Also the use of electric trains can increase the fuel efficiency compared to individual vehicles [1,2,15].

Towards Smart Energy Systems

There are limitations to the parts of the transport demands that can be covered by direct electricity consumption in trains or similar and in battery electric vehicle. The remaining part of the transport demands needs to be covered by fuels that can be transported on board. There are different kinds of biofuels available. In Figure 4 different options for integrating the transport sector is illustrated in principle diagrams in systems with large penetrations of renewable energy.



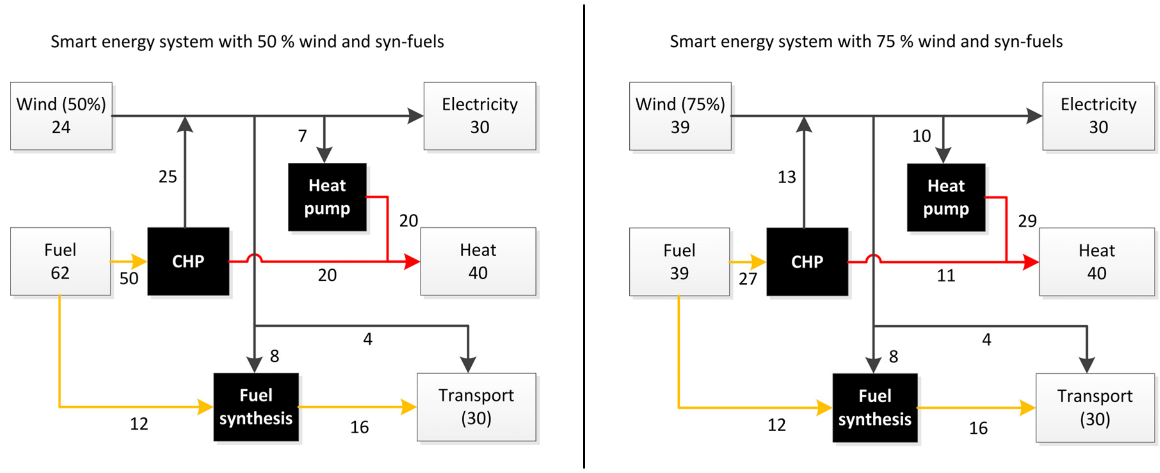


Figure 4, Principle diagrams of integrated energy and transport systems with 1. and 2. generation biofuels (4a) and (4b) and if the Smart Energy System (4c) and its storage options (4d).

Assuming that half of the transport demand can be covered by electricity increases the efficiency and the penetration of renewable energy in combination with large reductions in the fuel consumption. If first generation biofuels are used the conversion losses are rather small as illustrated in 4a in Figure 4. 1. generation biofuel are connected to a number of problems however, as it is based on resources also used for food production and as the land-use can create problems if larger penetrations of such biofuels were to be used. This is why 2. generation biofuels are proposed and why research is increasing in this area. In 4b in Figure 4 the conversion to transport fuels is included in an example of a 2. generation biofuel (with 40% biomass to fuel effiency). As illustrated 2. generation biofuels introduce large conversion losses. If the waste products from such conversions can be used in other sectors for higher value applications or used for the other parts of the energy sector, such conversion losses become less important. In principle – if all waste products can be used meaningfully in the energy sector or in higher value applications – then the losses would be similar to the smaller losses illustrated in the 1. generation biofuels (4b). Our research indicates that:

"…transport demands should be meet by electricity and where direct electricity cannot be used, synthetic fuels using renewable energy should be used due to the limitations in the biomass resources."

The increasing use of biofuels has raised the discussions about their effect on the environment, such as the risk of intervening with food production, deforestation, and changes in land-use. The transport sector faces significant challenges in the future due to its dependency on oil. The question is how much more renewable energy can be integrated into the transport sector? A number of case studies have been performed for Denmark. A holistic approach to create 100% renewable energy scenarios for all transport was introduces in The IDA Energy Plan 2030 [15] using integrated energy system the EnergyPLAN to create a reference model of the 2030 Danish energy system analyses. Steps included maintaining passenger transport demand for vehicles and trains at current levels by moving people and goods onto trains and ships, introducing battery electric vehicles, using more efficient forms of transport, and by introducing biofuels. This study was followed up by a more thorough analysis in the IDA Climate Plan 2050 in 2009 [1]. While both of the case studies used an integrated approach to the transition towards renewable energy in the transport sector and while electrification was prioritised, the use of biomass in parts of the transport sector was crucial for 100% renewable energy for covering transport demands. Biomass is a preferable replacement for fossil fuels in transport as it can be converted to high-density fuels and can be used in the current infrastructure. Bio-fuels have also become more competitive due to the rising prices of fossil fuels.

In 4c in Figure 4 another solution is proposed where electricity is used in electrolysers in combination with gasified biomass to create synthetic fuels covering 50% of the transport demands. With 50% wind power in the electricity grid, such integration reduces the fuel consumption from the 2. generations biofuels although it is still higher than using 1. generation biofuels. The configuration in 4c however enables the use of several storage options and several more flexible electricity consumptions. This makes it possible to increase the renewable energy penetration from 50% and improve the fuel efficiency even higher than with the 1. Generation biofuels. In 4d in Figure 4 a principle diagram shows how the fuel efficiency of the energy system can be increased significantly by increasing the wind power penetration enabled by the additional storage options. With 75% penetration of intermittent renewable energy resources the fuel consumption can be reduced by almost 80% in this ideal principle diagrams (from 1a to 4a or 4c).

In the CEESA research project the results suggest that electricity is the most efficient method of supplying transport fuels in the future. Energy dense fuel are required for the parts of the transport sector that cannot be covered with battery electric vehicles or public transport. Specifically for other applications such as long-distance driving or for heavy-duty transport such as trucks or aviation and ships. Such demands should not be covered by hydrogen due to the cost of hydrogen vehicles and hydrogen storage options. The research indicates that it is likely that some form of gaseous or liquid based fuel will be necessary to supplement electricity in a future 100% renewable energy system. The most attractive option at present is liquid fuel in the form of methanol/DME, as it is a more efficient way to produce fuel than methane when tacking into account the efficiency of the vehicles [28,29]. In either case, this distinction is not as critical as it may seem: both the methanol/DME and methane pathways share a lot of technologies in their pathways so the key message for the short term is that these technologies should be developed further before a final fuel is pursued. Most significantly, these technologies are biomass gasification and electrolysers, and thus can reduce the biomass demands significantly.

Another key point of such infrastructure is not illustrated in Figure 4. The infrastructure to create synthetic fuels as described above give way to the next generations of energy systems where biomass is entirely phased out. The synthetic fuel production could be based on electrolyser technology and CO_2 from other sources than gasified biomass. Further research into such systems is required, however the technology to produce such fuels are available to today, and methanol is produced with using current alkaline electrolysers and chemical synthesis with CO_2 from geothermal sources in Iceland. Such systems also have the CO2 storage option, enabling the same flexibility as described above. New more efficient electrolysers can improve such systems and the system illustrated in 4d in Figure 4, however gasification and chemical synthesis has been done for a number of years. Our research claims that:

"…synthetic fuels based on gasified biomass and electrolysis can pave the way to entirely phasing out biomass if CO_2 sources are available"

GRIDS AND STORAGES IN SMART ENERGY SYSTEMS

In the research ad principle diagrams presented a number of key technologies are included. In smart energy system many new technologies and infrastructures which create new forms of flexibility, primarily in the 'conversion' stage of the energy system are crucial. The radially available fuels in the current energy system due to the high density fossil fuel availability can be achieved in smart energy systems. In Figure 5 grids and storages in Smart Energy Systems are illustrated.

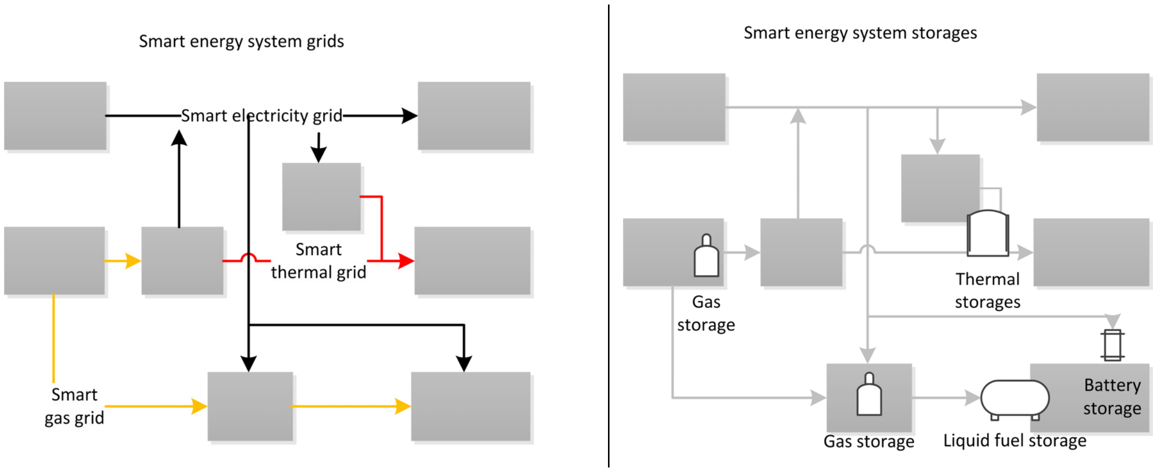


Figure 5, Principle diagrams of the grids (5a) and storages (5b) in smart energy systems.

By combining the electricity, thermal, and transport sectors the grids and storages in these grids can make the energy system flexibility across these and compensate for the lack of flexibility from renewable resources such as wind and solar. In the three grids the storage and sector integration is comprised of:

- Smart Electricity Grids to connect flexible electricity demands such as heat pumps and electric vehicles to the intermittent renewable resources such as wind and solar power.
- Smart Thermal Grids (District Heating and Cooling) to connect the electricity and heating sectors. This enables thermal storage to be utilised for creating additional flexibility and heat losses in the energy system to be recycled.
- Smart Gas Grids to connect the electricity, heating, and transport sectors. This enables gas storage to be utilised for creating additional flexibility. If the gas is refined to a liquid fuel, then liquid fuel storages can also be utilised.

In a stricter sense, these infrastructures can be defined as:

- Smart Electricity Grids are electricity infrastructures that can intelligently integrate the actions of all users connected to it - generators, consumers and those that do both - in order to efficiently deliver sustainable, economic and secure electricity supplies.

- Smart Thermal Grids are a network of pipes connecting the buildings in a neighbourhood, town centre or whole city, so that they can be served from centralised plants as well as from a number of distributed heating or cooling production units including individual contributions from the connected buildings.

- Smart Gas Grids are gas infrastructures that can intelligently integrate the actions of all users connected to it - supplies, consumers and those that do both - in order to efficiently deliver sustainable, economic and secure gas supplies and storage.

Based on these fundamental infrastructures, a Smart Energy System is a design that in which as an approach in which smart Electricity, Thermal and Gas Grids are combined and coordinated to identify synergies between them in order to achieve an optimal solution for each individual sector as well as for the overall energy system. Our research claims that:

"…short and long term storage options able to disconnect the production from the time at which the demand is there using batteries, thermal storages, gas storages and liquid storages are key components in 100% renewable energy systems as are the grids that enable storage"

THE SMART ENERGY SYSTEM CASE: THE CEESA 100% RENEWABLE ENERGY SCENARIOS

From 2006, an end goal of 100% renewable energy system has been debated in in Denmark. To compliment this, in 2006 and in 2009 scenarios were developed which outlined how this target could be reached by 2050 [1,2]. 2050 was recently set as the official target year by the Danish government. This section presents some of the results of systems analyses of a future Danish energy system based on 100% renewable energy by 2050 in the CEESA project. This projects builds on experience with creating the scenarios in 2006 and 2009 mentioned and other research projects, some of which are also described previously here.

The assumption in CEESA is that the transition towards 100% renewable energy relies highly on the technologies which are to be available within such time horizon and can have different effects on the biomass consumption. To highlight such issues, the CEESA project has identified scenarios based on three different assumptions with regard to the available technologies. This methodology allows a better optimization and understanding of the energy systems. In order to enable a thorough analysis of the different key elements in 100% renewable energy systems, two very different 100% renewable energy scenarios as well as one recommendable scenario have been created:

- **CEESA-2050 Conservative:** The conservative scenario is created using mostly known technologies and technologies which are available today. This scenario assumes that the current market can develop and improve existing technologies. In this scenario, the costs of undeveloped renewable energy technologies are high. Very little effort is made to push the technological development of new renewable energy technologies in Denmark or at a global level. However, the scenario does include certain energy efficiency improvements of existing technologies, such as improved electricity efficiencies of power plants, more efficient cars, trucks and planes, and better wind turbines. Moreover, the scenario assumes further technological developments of electric cars, hybrid vehicles, and bio-DME/methanol production technology (including biomass gasification technology).

- **CEESA-2050 Ideal:** In the ideal scenario, technologies which are still in the development phase are included on a larger scale. The costs of undeveloped renewable energy technologies are low, due to significant efforts to develop, demonstrate and create markets for new technologies. For example, the ideal scenario assumes that fuel cells are available for power plants, and biomass conversion technologies (such as gasification) are available for most biomass types and on different scales. Co-electrolysis is also developed and the transport sector moves further towards electrification compared to the conservative scenario.

- **CEESA-2050:** This scenario aims to be a “realistic and recommendable” scenario based on a balanced assessment of realistic and achievable technology improvements. Less co-electrolysis is used and a balance is implemented between bio-DME/methanol and syn-DME/methanol in the transport sector. This is the main CEESA scenario.

It should be highlighted, that in all scenarios, energy savings in electricity, heating and industry as well as direct electricity consumption are given a high priority. And all scenarios rely on a holistic smart energy system approach as explained above. This includes the use of heat storages and district heating with CHP plants and large heat pumps as well as the integration of transport fuel pathways with the use of gas storage. Also the systems reqiere flexible power plants and CHP plants in the future. All scenarios are hence based on gasification and gas for the power production when the intermittent resources are not able to meet demands. Also in the CEESA scenario special attention has been put on the transport sector. The results of the energy system analyses in the CEESA project regarding the primary energy supply for the three scenarios and the reference energy system is illustrated in Figure 6. Compared to the reference energy system, all the scenarios are able to reduce the primary energy supply to a level of approximately 500 PJ. There are, however, large differences between the scenarios with regard to use of biomass. In the conservative technology scenario, a 100% renewable energy system is possible with a total biomass consumption of approx. 330 PJ. The ideal technology scenario can decrease this consumption to approx. 200 PJ of biomass. In the CEESA 2050 recommendable scenario, the biomass consumption is approx.. 240 PJ.
Figure 6

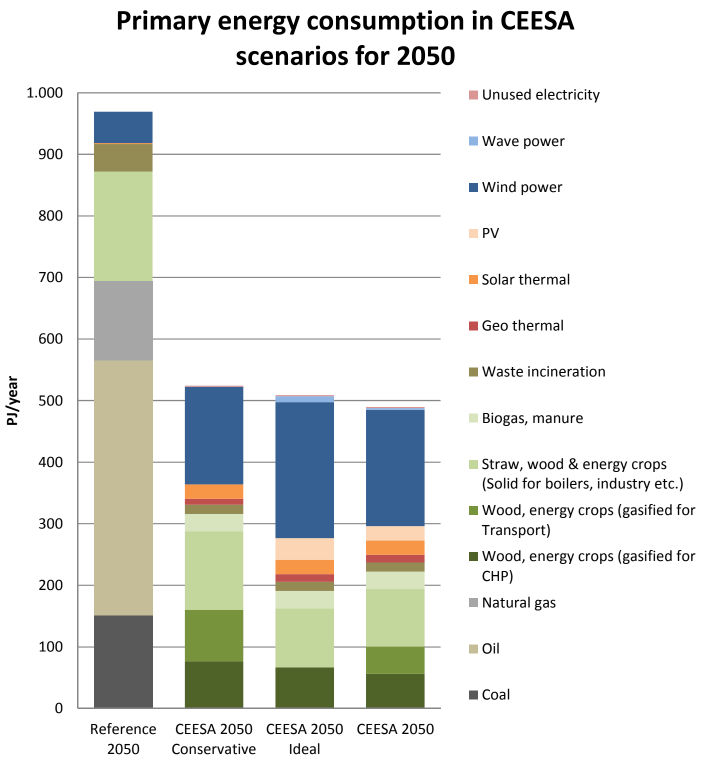


Figure 6, The primary energy supply in the CEESA 100% renewable energy scenarios for 2050.

The CEESA project includes a careful examination of the pathways to provide biomass resources. A shift in forest management practices and cereal cultivars ensure a potential of approx.. 240 PJ/year by 2050. Such potential represents the use of residual resources only. This means that the CEESA 2050 recommendable scenario is kept within the boundaries of residual resources, and the CEESA 2050 conservative scenario illustrates that an active energy and transport policy is required to stay within these limits. It should be noted that a target of 240 PJ/year by 2050 implies a number of potential conflicts due to many different demands and expectations of ecosystem services, as this requires the conversion of agricultural land otherwise allocated to food crop production to energy crop production, potentially reducing food and feed production. All crop residues must be harvested, potentially reducing the carbon pool in soils. A way to reduce this conflict potential is to reduce the demand for biomass for energy or to further develop agriculture and forestry in order to increase the biomass production per unit of land.

In all three scenarios, hour-by-hour energy system analyses have been used to increase the amount of wind turbines to an amount ensuring that the unused electricity consumption is low. These analyses also ensure that the heat supply and gas supply is balanced. In order to achieve such balance a smart energy systems approach have been carried out.

The integration of sectors is very important in 100% renewable energy systems to increase fuel efficiency and decrease costs. The most important step and the first step is the integration between the heating and the electricity sectors. In Denmark, this is already implemented to a large extent and approximately 50 % of the electricity demand is produced by CHP plants. Such integration requires thermal storages of today's sizes (about 8 hours in average production), a boiler and district heating networks to enable the flexible operation of the CHP plants as already implemented in the Danish energy system. This can reduce the fuel consumption and help integrate fluctuating wind power effectively. As mentioned 20-25% of the wind power can normally be integrated without significant changes in the energy system.

With more than 20-25% wind power, the next step in the integration is to install large heat pumps. In the CEESA scenarios, a significant amount of onshore and offshore wind power is installed by 2020. About then 50% of the electricity demand is covered from these sources. This results in some imbalance in the electricity grid, and heat pumps alone are not able to ensure the balance. The transport sector needs to be integrated into the energy system with more than 40-45% wind power. As a consequence, some electric vehicles are implemented and flexible demand is included in households and industry. This, however, is not sufficient. Thus, small amounts of electrolysers based on known alkaline technology are also implemented to facilitate wind power integration and for the production of bio-DME/Methanol in combination with gasified biomass. This also enables the integration of larger amounts of renewable energy into the transport sector.

In 2030, a larger proportion of electric vehicles are included in a solution in which they are able to charge according to a price mechanism. In order to make sure that electric vehicles can fulfil this function, the low voltage grid needs to be enforced in some areas. The electricity production from onshore and offshore wind power in combination with photovoltaic is approximately 60% in 2030. In order to facilitate this, transport needs to be integrated further. In CEESA, this is achieved by implementing electric cars on a larger scale, i.e., from 2020 onwards.

In CEESA 2050, more and new technologies are necessary to make sure that the renewable energy is integrated efficiently into the system and that fossil fuels are being replaced totally. Hence after 2030, electrolysers for hydrogen production for bio-DME/methanol are gradually increased to provide larger amounts of liquid fuels to the transport sector and the electrolysers are more efficient. Also co-electrolysers are contributing to produce syn-DME/Methanol without using biomass, but by using carbon sequestration from the electricity sector or other sources.

In the CEESA 2050 energy system, gasified biomass and the gas grid storages are also utilised in combination with the electric vehicles and fuel production in the transport sector as well as the district heating systems. This creates an energy system in which smart energy systems are integrated and the storage options are used in combination to enable the final scenario. CHP plants and power plants are based on gas making the production able to react fast.

The CEESA project has taken a closer look at the balancing of gas supply and demand. The hourly activities of all gas consuming units such as boilers, CHP and power plants as well as productions such as biogas and gasification (syngas) units (including hydrogenation) has been calculated and analyses with regard to the need for import/export, gas storage or flexibility and extra capacities in the gas producing units. First was calculated the annual need for import/export in the case of no gas storage and no extra capacities on the production units. Then similar analyses were made with storage capacities gradually being increased from zero to 4000 GWh. In all such situations the need for import is equal to the need export on an annual basis, since the systems are designed to have a net-import of zero. However the need for import/export decrease along with increases in the domestic storage capacity. A storage capacity of about 3000 GWh are able to completely remove the need for import/export. The current Danish natural gas storage facility have a gas content of 17.000 GWh in Stenlille in

Jylland and 7.600 GWh in Lille Torup on Zealand. The work-content of the storages are smaller, approx. 6.500 and 4.800 GWh respectively. This means that the total current storage capacity assuming natural gas quality is 11.350 GWh. If the gas quality in the entire grid is lowered to biogas standard, the storage would be reduced to around 6.800 GWh assuming the capacity is reduced by 40%. This indicates that the current storage capacity is more than twice as large as required in the CEESA-2050 scenario even assuming no extra capacity at the gasification plant, i.e. no flexibility in the production of syngas.

Next, to analyse the influence on adding flexibility and extra capacity on the gas producing units the analysis of gas storage was repeated while gradually increasing the production capacities. An increase in production flexibility and capacity decrease the need for storage capacities. In the CEESA 2050 scenario it was chosen to include about 25% over capacity of in combination with a storage above 3000 GWh.

The analysis has also been used to evaluate peak loads on the gas grid. In the CEESA-2050 scenario, the peak demand is approx. 10.000 MW. At present the peak in Danish natural gas consumption in the winter is about 360 GWh and the maximum gas production is about 260 GWh. On an average the peak load hour in such a day is 15.000 MW and the maximum hourly production is about 11.000 MW from a daily average point of view. This means that even assuming the capacity is used for gas with biogas energy density, the current grid could also be used in the peak situation.

One important learning from such hourly analysis of the complete system including both electricity and gas balances is that relatively cheap gas storage capacities (which in the Danish case are already there) can be used to balance the integration of wind power into the electricity grid. Consequently in the CEESA 2050 scenario it is possible to decrease excess electricity productions to nearly zero at the same time at achieving high fuel efficiencies by using heat and gas storages and having integrated the transport sector. No electricity storage is included and – as such investment would form far be profitable due to the very small utilization hours. Also it would add inefficiency to the system due to round trip losses.

In the principle diagrams in Figure 1 to Figure 5 ideal diagrams of the transition from a simple supply demand system to the integrated Smart Energy System was illustrated from an ideal point of view. The CEESA 2050 scenario losses and hour-by-hour calculations have been performed. The resulting Smart Energy System is illustrated in the sankey diagram in Figure 7.

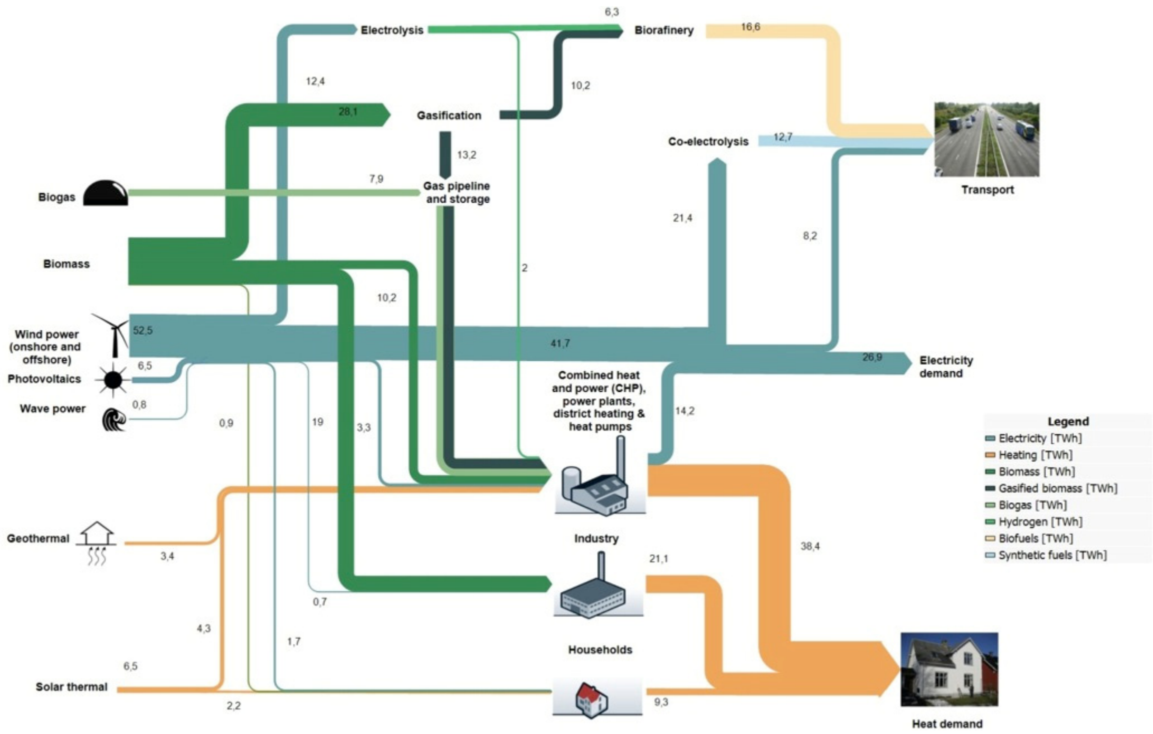


Figure 7, Energy flows in the CEESA 2050 100% renewable energy scenario. The flows represent the annual aggregated values; however every single hour for all demands and production technologies is accounted for in energy system analyses.

CONCLUSIONS

Suboptimal solutions with sectorial focuses or single technology focuses can hamper the way for fuel efficient and feasible future 100% renewable energy systems. By analysing all sectors of the energy system, innovative solutions can be identified in which all sectors are included and in which many technologies each play an important role. By applying a smart energy systems approach to the identification of suitable 100% renewable energy systems design the CEESA scenarios show how system integration is a fuel efficient option and also a cost effect option. In particular the study combine the analysis of gasified biomass and gas grid storages in combination with the electric vehicles and synthetic fuel production in the transport sector as well as the district heating systems. This creates an energy system in which smart energy systems are integrated and the storage options are used in combination to enable the final scenario. The analyses ensure that there is a balance hour-by-hour in the gas supply and demand and that document that the capacity of current Danish salt cavern storage facilities are more than sufficient to facilitate this balancing. It should be noted that synergies and feasible solutions are not achieved simply by combining these infrastructures automatically. The design and configuration has to be carefully investigated. Also it should be noted energy savings are extremely important. Otherwise the primary energy demands would increase significantly.

REFERENCES

[1] Mathiesen BV, Lund H, Karlsson K. 100% Renewable energy systems, climate mitigation and economic growth. Applied Energy 2011.

[2] Lund H, Mathiesen BV. Energy system analysis of 100% renewable energy systems - The case of Denmark in years 2030 and 2050. Energy 2009/5;34:524-31.

[3] Ćosić B, Krajačić G, Duić N. A 100% renewable energy system in the year 2050: The case of Macedonia. Energy 2012;48:80-7.

[4] Peter S, Doleschek A, Lehmann H, Mirales J, Puig J, Corominas J et al. A Pathway to a 100% Renewable Energy System for Catalonia. Institute of Sustainable Solutions and Innovations. 2007. Available from: http://www.isusi.de/downloads/Solar_Catalonia_2007_en.pdf.

[5] David Connolly, Henrik Lund, Brian Vad Mathiesen and Martin Leahy. Ireland's Pathway Towards a 100% Renewable Energy System: the First Step. Dubrovnik, Croatia, 987-953-6313-97-6. 2009/9.

[6] Cédric C. Smart grids: Another step towards competition, energy security and climate change objectives. Energy Policy 2011;39:5399-408.

[7] Orecchini F, Santiangeli A. Beyond smart grids - The need of intelligent energy networks for a higher global efficiency through energy vectors integration. International Journal of Hydrogen Energy 2011;36:8126-33.

[8] Lund H, Andersen AN, Østergaard PA, Mathiesen BV, Connolly D. From electricity smart grids to smart energy systems - A market operation based approach and understanding. Energy 2012;42:96-102.

[9] Matthias W. The Smart Grid - A saucerful of secrets? Appl Energy 2011;88:2509-18.

[10] Lund H. Choice awareness: The development of technological and institutional choice in the public debate of Danish energy planning. Journal of Environmental Policy and Planning 2000;2:249-59.

[11] Lund H, Hvelplund F. The economic crisis and sustainable development: The design of job creation strategies by use of concrete institutional economics. Energy 2012;43:192-200.

[12] Mathiesen BV, Lund H. Comparative analyses of seven technologies to facilitate the integration of fluctuating renewable energy sources. IET Renewable Power Generation 2009/6;3:190-204.

[13] Brian Vad Mathiesen. Fuel cells and electrolysers in future energy systems. Ph.D., Department of Development and Planning, Aalborg University, Aalborg, 2008/12. ISSN/ISBN: 1397 3169. Available from: http://people.plan.aau.dk/~bvm/ .

[14] Lund H, Möller B, Mathiesen BV, Dyrelund A. The Role of District Heating in Future Renewable Energy Systems. Energy 2010/3;35:1381-90.

[15] Mathiesen BV, Lund H, Norgaard P. Integrated transport and renewable energy systems. Utilities Policy 2008/6;16:107-16.

[16] Möller B. A heat atlas for demand and supply management in Denmark. Management of Environmental Quality 2008;19:467-79.

[17] Aalborg University. H. Lund. EnergyPLAN - Advanced energy system analysis computer model, documentation version 9.0. 2011.

[18] Salgi G, Lund H. System behaviour of compressed-air energy-storage in Denmark with a high penetration of renewable energy sources. Applied Energy 2008/4;85:182-9.

[19] Lund H, Salgi G. The role of compressed air energy storage (CAES) in future sustainable energy systems. Energy Conversion and Management 2009;50:1172-9.

[20] A. Dyrelund, Henrik Lund, Bernd Möller,Brian Vad Mathiesen. Heat plan Denmark, Varmeplan Danmark [In Danish]. 2008. Available from: http://www.fjernvarmen.dk/Faneblade/ForskningFANE6/FogU/~/media/FogU%20Konto/2008%2001%20Varmeplan%20Danmark%20Rapport%20091008.ashx.

[21] Lund H. Large-scale integration of wind power into different energy systems. Energy 2005/10;30:2402-12.

[22] Connolly D, Mathiesen BV, Østergaard PA, Möller B, Nielsen S, Lund H et al. Heat Roadmap Europe: First pre-study for EU27. Aalborg University, Halmstad University, and Euroheat & Power. 2012. Available from: http://vbn.aau.dk/.

[23] Connolly D, Mathiesen BV, Østergaard PA, Möller B, Nielsen S, Lund H et al. Heat Roadmap Europe: Second pre-study. Aalborg University, Halmstad University, Ecofys Germany GmbH, PlanEnergi, and Euroheat & Power. 2013. Available from: http://vbn.aau.dk/.

[24] Hedegaard K, Mathiesen BV, Lund H, Heiselberg P. Wind power integration using individual heat pumps – Analysis of different heat storage options. Energy 2012;47:284-93.

[25] Lund H, Marszal A, Heiselberg P. Zero energy buildings and mismatch compensation factors. Energy and Buildings 2011;43:1646-54.

[26] Lund H, Munster E. Integrated transportation and energy sector CO2 emission control strategies. Transport Policy 2006/9;13:426-33.

[27] Energinet.dk. B. V. Mathiesen. Analysis of Power Balancing with Fuel Cells & Hydrogenproduction Plants in Denmark. 2009.

[28] J. Kappel,B. V. Mathiesen. Screening of tank-to-wheel efficiencies for CNG, DME and methanol-ethanol fuel blend in road transport. 978-87-91404-49-8. 2013.

[29] Iva Ridjan, Brian Vad Mathiesen, David Connolly and N. Duić. Feasibility of synthetic fuels in renewable energy systems. In: poster session at the Austrian-Croatian-Hungarian Combustion Meeting. Zagreb, Croatia, 2012. Available from: http://vbn.aau.dk.