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Smart Energy Systems for coherent 100% renewable energy and transport solutions

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HIGHLIGHTS

- Integrating smart electricity, smart thermal and smart gas grids to enable 100% RE.
- Cost and fuel synergies across electricity, heating, and transport can be exploited.
- Focusing only on a smart electricity grid reduces the potential for fluctuating RE.
- Smart Energy System design can ensure biomass use is limited to a sustainable level.
- Smart Energy Systems can pave the way for bioenergy-free 100% RES incl. transport.

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ABSTRACT

The hypothesis of this paper is that in order to identify least cost solutions of the integration of fluctuating renewable energy sources into current or future 100% renewable energy supplies one has to take a Smart Energy Systems approach. This paper outline why and how to do so. Traditionally, significant focus is put on the electricity sector alone to solve the renewable energy integration puzzle. Smart grid research traditionally focuses on ICT, smart meters, electricity storage technologies, and local (electric) smart grids. In contrast, the Smart Energy System focuses on merging the electricity, heating and transport sectors, in combination with various intra-hour, hourly, daily, seasonal and biannual storage options, to create the flexibility necessary to integrate large penetrations of fluctuating renewable energy. However, in this paper we present the development and design of coherent Smart Energy Systems as an integrated part of achieving future 100% renewable energy and transport solutions. The transition from fossil fuels towards the integration of more and more renewable energy requires rethinking and redesigning the energy system both on the generation and consumption side. To enable this, the Smart Energy System must have a number of appropriate infrastructures for the different sectors of the energy system, which are smart electricity grids, smart thermal grids (district heating and cooling), smart gas grids and other fuel infrastructures. It enables fluctuating renewable energy (such as wind, solar, wave power and low value heat sources) to utilise new sources of flexibility such as solid, gaseous, and liquid fuel storage, thermal storage and heat pumps and battery electric vehicles. Smart Energy Systems also enable a more sustainable and feasible use of bioenergy than the current types allow. It can potentially pave the way to a bioenergy-free 100% renewable energy and transport system.

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1. Introduction

Currently most energy systems are predominantly based on fossil fuels, but this has to change in the future. The purpose of introducing more and more renewable energy into the energy system is to save fuels, which in the short term are fossil fuels (and nuclear in some contexts). In the longer term bioenergy will become the key concern, as biomass is a limited resource that cannot be expected to replace all fossil fuels used today. Apart from anthropogenic greenhouse gas emissions from the combustion of fossil fuels and the need for a sustainable use of biomass, there are several other reasons for why this transition is important: Security of supply and geopolitical issues, health risks related to combustion of fossil fuels, socio-economic consequences of the energy mixes, ownership and democracy, while business development and job creation are other important parts of the energy system that have been in focus for decades [1,2]. Fossil fuels play a major part in these issues and an unsustainable use of bioenergy may cause similar challenges in the future.

In current fossil based systems, the flexibility is based on the fuels provided for power plants, boilers and vehicles in liquid, gaseous, and solid form. Today's energy systems are based on infrastructure and storage facilities that can cover the demands by means of transporting fossil fuels over large distances in ships and pipelines on the global level, to national or regional energy infrastructure such as coal, gas and oil storage facilities. Hence, a global system is based on large-scale storage of energy-dense fossil fuels that usually can flexibly meet the demands at the right time and place. While this is already a reality for the fossil-fuel based energy system, the challenge now is to create an equally or more flexible energy supply with increasing amounts of fluctuating renewable energy.

While some studies that look at more sectors as part of the path towards 100% renewable energy systems, including electricity, heat and transport have already been developed [3–9], there is still a predominant sectorial focus; specifically on how to integrate fluctuating resources into the electricity sector [10].

More and more focus is being placed on energy savings, renewable energy sources and the handling of fluctuating renewable energy sources. While electricity savings should be promoted heavily, an increasing focus is placed on the integration of fluctuating renewable energy into the electricity system to lower emissions [11–17]. For example, the smart grid community has a strong focus on the use of the following components: ICT, smart meters and smart grids connected to existing electricity demands, EV's and individual heating technologies [10,18–24], flexible demand, storages and electricity storage, distributed generation [25–27], power-to-gas [28] and transmission [29–31]. Some authors are also connecting the smart grids to the concept of smart cities, but continues to have a focus on the electricity grid only and/or on individual buildings [32–34]. Only very few authors look at the transition as a complete redesign of the whole system [10,18].

More recent research shows however that merging the heating and electricity sector from a system level is important in order to create a fuel efficient energy system that is economically and environmentally feasible [35–39]. In fact connecting the electricity and heating sectors can lower overall costs and increase the value of wind power [40]. The heating sector and the electricity sector can be interconnected by using technologies such as large thermal storage and large-scale heat pumps supplying heating for district heating networks.

The great challenge however is the transport sector, and no single technology can solve the transport puzzle [41]. Also the current use of biofuels is heavily debated and the biomass use is controversial, even with new bio-refining technologies also using waste biomass products, due to the connection to food production and land-use [42–44]. At the same time large amounts of bioenergy will have to be used in the heat, power and industrial sectors in the future, and demands from all sectors, including transport, is already on the rise. *In other words it is equally important to limit the use of bioenergy as it is to reduce the use of fossil fuels in the future, as the present use of fossil fuels cannot be substituted by biomass.*

In this paper the aim is to combine the knowledge relating to the integration of renewable energy in the various sectors of the energy system, to minimise overall costs and fuel consumption (fossil or bioenergy). There is a lack of knowledge on (1) what does current research tell us about the integration of renewable energy by combining the different sectors and (2) what does the actual design of such a Smart Energy System look like?

Also in this paper we present our hypothesis, that using a Smart Energy Systems approach, which includes a substantial merging of the different energy sectors, will lead to the identification of a more fuel-efficient and lower-cost solution compared to the traditional approach of individual sectors. This is primarily due to the new synergies enabled in the cross-sectorial approach, which enable higher penetrations of fluctuating renewable resources such as wind power, photovoltaics (PV), wave power and run-of-river hydro power at the expense of fossil fuels or bioenergy. We believe that The Smart Energy System concept is essential for 100% renewable energy systems to harvest storage synergies and exploit low value heat sources. The Smart Energy System approach was defined in 2011 in the CEESA project (see below). The project addressed Danish scenarios with a particular focus on renewable energy in the transport system in a context with limited access

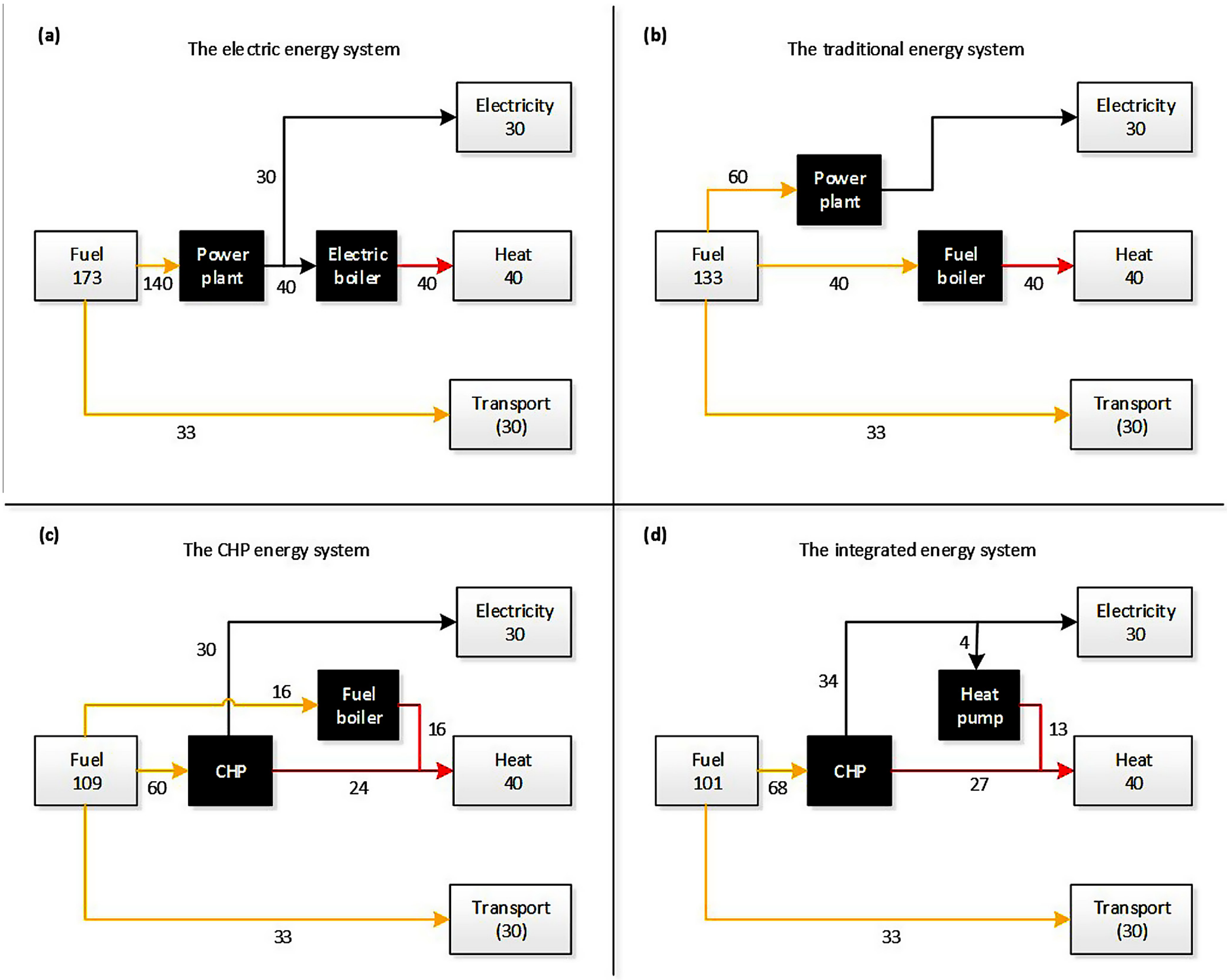

Fig. 1. Energy-flow-diagrams of an electricity based energy system (1a), a traditional energy system (1b), a CHP energy system (1c) and an integrated CHP energy system with heat pumps (1d) – all providing the same energy services.

to bioenergy. The aim in the paper is to present this holistic energy system perspective.

2. Methodology

The Smart Energy System approach is presented in two parts to compile research and also provide a concrete case study:

1. Firstly, energy flow diagrams are presented to illustrate the principle of why the Smart Energy Systems approach will lead to improved solutions compared to sector focused solutions, and
2. Secondly, we will quantify the potential benefits from a Danish case based on the results of the strategic research project CEESA (Coherent Energy and Environmental System Analyses) [45–50].

The energy flow diagrams quantifies the energy flow for different energy supply systems and different penetrations of fluctuating resources. The fluctuating resources are illustrated by wind power, but could in principle also be PV, wave power and/or run-of-river hydro power, etc. For each of the different supply systems in the diagrams, the amount of wind power technical feasible in the system is based on previous research that accounts the hourly variations which need to be accommodated [3–9,45–50]. The energy flow diagrams presented illustrate a specific relation between supplies and demands i.e. wind power and specific electricity and heating demands. The design and results presented however present an approach that can be used on context with more cooling demands or substantial amounts of run-of-river and pumped hydro. The aim here is to highlight the need to have an integrated energy system in order to identify feasible options to replace fossil fuel and biomass.

In Fig. 1 an example of four different energy systems is given. In all energy systems the end demands are the same, but these demands are met through different pathways. All of the energy flow diagrams represent the whole year and illustrate the energy supply and demands. The four energy systems are:

- The system entitled the *'electricity system'* is characterised by electricity being supplied from power plants, while all heating is being supplied by electric boilers or resistance heaters (electric heating).
- In the system entitled the *'traditional system'*, heating is supplied by individual boilers, which are most often fuelled with oil and gas, while electricity is still provided by a power plant.

- In the *'CHP system'*, electricity and heating is integrated by the use of Combined Heat and Power production (CHP).
- Finally, the *'Integrated CHP system'* includes the addition of centralised heat pumps for the heating demands.
- For all four systems transport is separate and includes an approximated refinery loss.

The methodology is to gradually add wind power to each of these systems until they will no longer be able to integrate the wind power produced: this is the point where excess electricity from the fluctuating power production will not be consumed in that particular energy system design. Subsequently, new systems will have to be designed by adding components such as electric vehicles, biofuels, renewable electrofuels[1] and storage capacities, etc. By increasingly connecting sectors and moving towards a Smart Energy System, synergies are identified in a sector integrated approach and by exploiting different storage options.

There is considerable knowledge about most parts of the energy system. In this paper we combine previous research results regarding Smart Energy Systems and in this process describe the research behind. The main findings presented are based on research results from detailed energy systems analyses using the Advanced Energy System Analysis Computer tool EnergyPLAN. The tool includes national or regional energy systems, which includes 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 [51] which is rather unique in comparison with many other tools [52]. The tool is a deterministic input/output tool and general inputs are demands, renewable energy sources, energy technology capacities, costs, and a number of optional regulation strategies for import/export and excess electricity production, all on an hourly basis. The tool is also able to include analyses combining fluctuating renewable energy sources with the production of synthetic gases or liquids in addition to the capability to include different types of biofuels. The analyses in EnergyPLAN is supplemented by GIS (Geographical Information Systems) based mapping and analysis of heat demand and supply options. By means of spatial analysis using highly detailed heat atlases of the building stock by age, use and current heat supply, the economically accessible potentials of energy efficiency, the expansion of energy infrastructure, as well as the locally available renewable energy sources are identified by means of cost-supply curves [53].

The final recommendations regarding the design of Smart Energy Systems build on a case study from the strategic research project CEESA [45,46]. The CEESA project was an interdisciplinary research project and involved more than 20 researchers from seven different universities or research institutions in Denmark. In the CEESA project, various different 100% renewable energy and transport systems were designed and analysed. These form the basis for the development towards the Smart Energy System flow diagrams presented in this paper.

After describing the principle design, the overall results from the CEESA project are presented. Transport is one of the key challenges in society and was given special attention in the 100% renewable energy scenarios developed in the CEESA project. 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.

In the present article, we focus mainly on the technical system aspects of Smart Energy Systems. The political and institutional challenges, market structures [40,50,54–62] and other non-technical framework conditions associated with the drastic transformation of the technical interdependencies when shifting from current energy systems to Smart Energy Systems are not addressed here. Furthermore, the different phases described here, through which energy systems could develop into Smart Energy Systems, do not necessarily follow a chronological order. This sequential set-up is presented for pedagogical reasons – in reality, there will be overlaps between the phases.

3. From electricity systems to Smart Energy Systems

In the existing energy system, 20–25% of fluctuating renewable energy can normally be technically integrated on an annual bases without affecting the reliable operation of the electricity grid [9,10,36,63–68]. The electricity based system is illustrated without fluctuating renewable energy in (1a) of Fig. 1 and with renewable energy in (2a) of Fig. 2. As can be seen in such energy-flow-diagrams, significant losses occur in the conversion phase at the power plant. By introducing renewable energy, such as wind power, a part of the fuel used can be replaced. In Fig. 1, fluctuating renewable energy penetration of 25% annually is assumed to be the limit, since beyond this, the peaks during the year of the fluctuating resources will reach the current electricity peak demands and will increasingly be curtailed. In this section we illustrate how this limit can be increased by changing from a sectorial approach to an integrated approach – going from the focus on electricity, heat and transport systems separately to looking at the sectors coherently.

3.1. The concepts of storage – expanding from a single sector focus

As the debate and research about the integration of fluctuating renewable energy sources grows, sectorial backgrounds of the different actors and stakeholders create sectorial focuses on solving the integration challenge as well. Due to the rapid development of renewable electricity technologies, this sectorial focus often leads to an over emphasis on solutions in the electricity sector for the integration of renewable energy. For example, typical solutions involve direct electricity storage in batteries, flywheels, pumped storage or in fuels used for electricity production, such as hydrogen from electrolysers [69,70].

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 principle of electricity storage is to charge a 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 types of large-scale electricity storage technologies that have been implemented (i.e. >100 MW): pumped hydroelectric energy storage (PHES) and compressed air energy storage (CAES). Both of these technologies lead to significant inherent energy losses, with the two having round-trip efficiencies of approximately 85% and 65% respectively. Hence, when assessing electricity storage, there is a balancing act between integrating more fluctuating renewables and reducing the overall efficiency of the system. Salgi and Lund [71] investigated the feasibility of CAES and compares it 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 electricity production altogether. In a subsequent paper Lund and Salgi [72] compared a fixed investment in CAES to the same investment in alternative sources of flexibility such as electric boilers, large-scale

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[1] Throughout this paper the term *electrofuel* refers to fuel production by combined use of electrolysers with carbon source. If the carbon source is CO_2-emissions the term *CO_2-electrofuel* is used, and in case the carbon source is from the biomass gasification the term *bioelectrofuel* is used. If not indicated differently the produced fuels are DME/methanol.

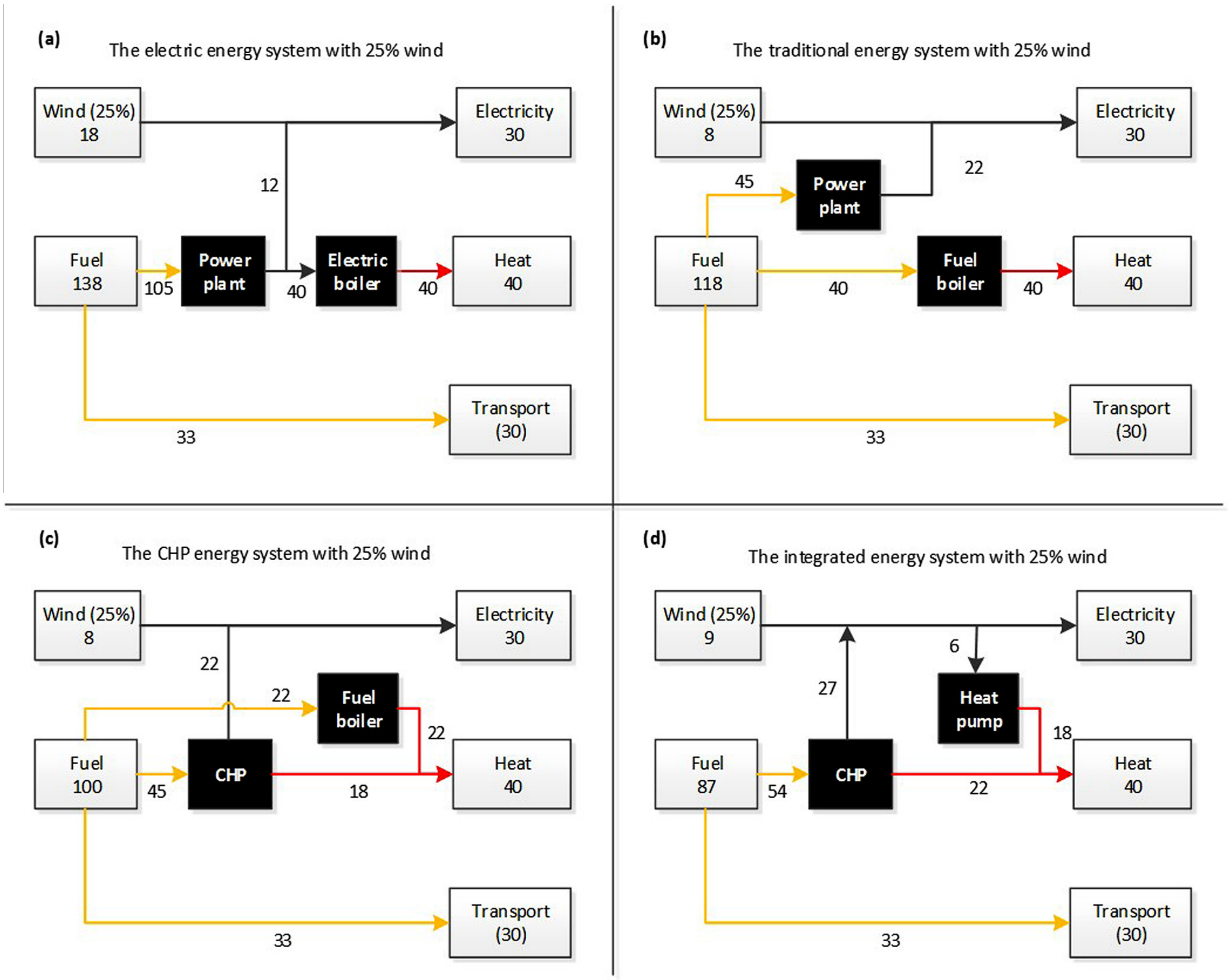

Fig. 2. Energy-flow-diagrams of 25% wind power of the electricity consumption in an electric energy system (2a), a traditional energy system (2b), a CHP energy system (2c) and an integrated CHP energy system with heat pump (2d) providing the same energy services.

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. In fact comparing CAES to other integration options shows, that even free electricity from wind power would not be able to cover the costs of the investments in CAES. However, if CAES plants can save investments in power plant capacities in the system, the CAES technology may become more feasible to the system.

There are some indications that using electric vehicles in so called Vehicle-to-grid (V2G) mode, may serve the energy system with the same characteristics, while also enabling another potential mean to secure overall grid stability as well as in local electricity grids [73–75]. For grid stability however, power electronics also play a role on the power generation side in distributed power generation systems [76]. Østergaard [77] compares different storage options in a local energy system – electricity storage, gas storage and thermal heat storage and identifies a better flexibility in electricity storages than other storages. Therefore, some focus should also be asserted on the electricity system in future Smart Energy Systems, however this does not mean that round trip losses should be implemented. It does however stress the potential role of flexible demands and batteries in maintaining the shorter term grid stability in the different parts of the electricity transmission and distribution system.

Mathiesen investigates the role of fuel cells and hydrogen in future energy systems [36]. 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 while micro-CHP should be avoided completely [35,36]; both in systems with and without CHP plants. Electrolysers should only be implemented in energy systems with very high shares of fluctuating renewable energy (+50%) and other options are significantly more important [36]. In a 100% renewable energy system however, electrolysers constitute a key part for e.g. transport, because they displace fuels derived from biomass, but should still not be using hydrogen for electricity production to the grid [46,78,79].

These case studies about current technologies and potential future technologies highlight the issue of electricity storage as the main mean of integrating fluctuating resources. Electricity storage technologies such as batteries or flywheels may have a function as a means to manage the grid in few extreme situations, but should be avoided as the main mean of integration. In other words, electricity storage can benefit the system in the short term in the form of ancillary services and grid stability (with small impacts on the overall energy losses), but it does not have a major role when it comes to large-scale integration on an annual basis, primarily due to relatively high energy losses and costs compared to the alternatives. What are then the options if we want to increase the fluctuating renewable energy penetration?

3.2. Merging the electricity and heating sectors

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 heating sector's perspective, a number of options can be applied as mentioned already in the case studies above. In Fig. 1 a number of energy-flow-diagrams illustrates how the electricity and heat can be supplied assuming that we need 40 units of heat, 30 units of electricity and 30 units of fuel for transport before we start introducing fluctuating renewable energy sources.

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 fluctuating resources. The energy-flow-diagrams illustrate how redesigning the energy system can improve the fuel efficiency by 30–40% from the worst case to the best case. Although the diagrams represent ideal situations they do 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. By going from the CHP system to the integrated system with large heat pumps (1d), the balance between the electricity demand and the heat demand becomes apparent as a part of the design of the supply system. The energy-flow-diagrams assume a high electric efficiency in the gas engine or gas turbine CHP plants and hence some of heat supply has to be met by a boiler in (1c). Going towards the integrated system with heat pumps from the CHP system (1c to 1d) does not improve the fuel efficiency significantly. This redesign from the CHP system towards the integrated system is more important for the integration of fluctuating renewable energy.

In Fig. 2 and 25% of the electricity demand is covered by wind power in the four energy systems presented previously on an annual basis. The wind power production is calculated as 25% of the total electricity demand, e.g. in (2a) the electricity demand is 70 as electricity is also used to supply heat by using electric boilers. Wind power produces 25% of this demand (approximately 18) while the power plant generate the remainder (52) to cover the demand. These energy systems represent ideal situations as for example, the heat pumps would not cover all demands in (2d) but would be supplemented by some boiler operation.

As highlighted, merging the heating (and/or cooling) sector with the electricity sector becomes increasingly important to improve the fuel efficiency of the energy system. Again, if the purpose is to increase the amount of fluctuating resources to reduce the use of fuels, it is also important to redesign the energy system to facilitate this. Large-scale heat pumps are one option since they reduce the use of boilers, while at the same time enable the fuel-efficient integration of fluctuating renewable energy. As displayed in Fig. 2, introducing heat pumps reduces fuel consumption in the energy system with 25% wind power, but additional to that, research shows that heat pumps can facilitate up to 40% fluctuating renewable energy without reducing the fuel efficiency of the system. Our research shows that for large-scale integration of fluctuating resources [34–37,80–92]:

> *…merging the electricity sector and the heating sector should be carried out using CHP plants and large heat pumps with thermal storages in district heating systems where possible…*

In several case studies, the use of district heating, thermal storages and heat pumps has been highlighted as the more feasible and fuel efficient option compared to individual solutions. District heating is normally seen as feasible in locations with a high geographical heat demand density, a concept which is currently challenged as district heating pipes get more efficient and heat supply sources become more accessible. Clearly, various factors influence the feasibility and the extent of district heating. Where district heating is not possible under such constraints, individual heat pumps should be used [36,37,89–95] if the building stock allows it. In Dyrelund et al. [92] and Lund et al. [37], various heating technologies under three distinct scenarios for the Danish energy system were analysed in a feasibility study and a study about the suitability of heating systems in energy systems with large amounts of renewable energy. Almost 50% of the Danish net heat demand is currently supplied by district heating. GIS-based analysis using a heat atlas [37,53,88,96] shows that by identifying existing district heating areas and by connecting areas currently supplied with natural gas for individual heating, 63–73% of the heat demand could be covered by district heating. Through energy systems analysis it was investigated whether the current level should be maintained and combined with individual solutions, or whether the district heating systems should be expanded to these levels. 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 in natural gas areas adjacent to district heating networks were converted and finally, in the third scenario, all buildings in areas that are 2nd degree neighbours to district heating areas, or that were otherwise within reach of district heating networks, were converted. To provide a complete picture, five alternatives to district heating sources 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 progresses towards a 100% renewable energy system by 2060, the electricity consuming options (heat pumps and electric heating) and district heating are still the most environmentally and economically attractive alternatives. In contrast, the electricity producing alternatives (micro CHP) are less attractive, which was primarily due to the additional excess electricity production in the system from fluctuating renewable energy sources. Other studies confirm such results. Recently, similar studies have been conducted on the European scale [84–87,97] confirming that district heating and thermal heat storages can increase the fuel efficiency significantly, while simultaneously decreasing costs and the greenhouse gas emissions. In areas where the heat density is too low for district heating, ground source heat pumps are feasible [37,83] – individual buildings are however not able to provide the same flexibility by simply applying heat storages or batteries in the houses as district heating systems [34,35,83].

By introducing heat savings in buildings low-value energy sources can also be utilised in district heating networks [98,99]. When looking at heavily refurbished or new dwellings, district heating and ground source heat pumps should be in focus [81], especially when considering that consumer behaviour may change over time and is not similar from family to family, and that comfort levels may also change [81,100]. The perspectives of low-energy dwellings have been analysed and described in several studies [61,101–104], including zero emission buildings [80,105–107]

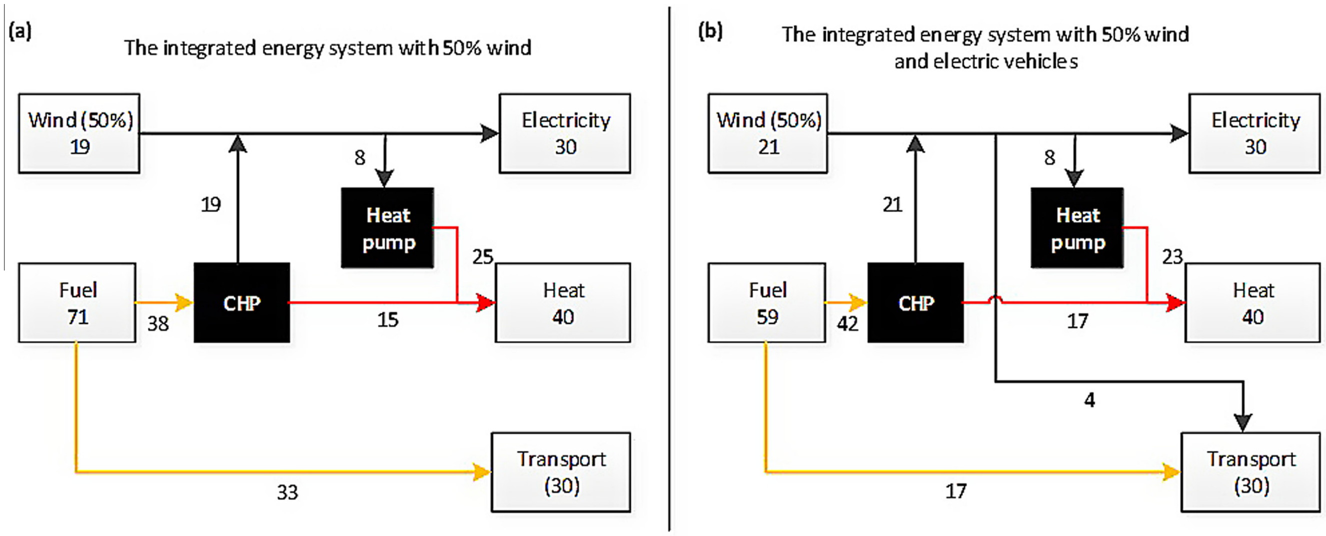

Fig. 3. Energy-flow-diagrams of the integrated CHP energy system with 50% wind power and heat pumps (3a) and the same systems combined with electric vehicles (3b) covering 50% of the transport demand.

and the challenges related to this concept [34]. These studies show to some extent that heavy refurbishment and implementation of energy savings in dwellings are feasible [102,103], however the analyses on the European and other energy systems presented above show that a balance should be found between how much to refurbish, and at which stage renewable energy heating systems should be implemented. Both in the Danish case and in the European study heat savings of approximately 50% of the current heat demand should be implemented.

Merging the electricity and heating sector using CHP plants, thermal heat storages and heat pumps enables fuel efficient integration of more fluctuating renewable energy and lower biomass consumption as this enables a displacement of boiler heat production [35,37,82]. In Fig. 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.

3.3. Merging the electricity, heating and transport sectors

For a 50% renewable electricity penetration, flexible electricity demands based on current electricity use and intelligent operation of new demands in individual heat pumps have some role in the integration, although it is smaller than large-scale heat pumps [35]. The next major step is the integration of fluctuating renewables of the transport sector [35]. In Fig. 3 an energy-flow-diagram of how the transport sector could be partly transformed is illustrated (3b). It is assumed that 50% of the total end transport demand is covered by electric vehicles for private cars. Electric vehicles can significantly improve the fuel efficiency and increase the penetration of fluctuating 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 [3,4,35,41,46,73,74,108–110]:

> *…connecting the electricity and transport sectors enables more fluctuating renewable energy to be utilised… and the transport sector should be electrified to the largest extent possible…*

In constructing 100% renewable energy and transport systems, a key challenge is to introduce more renewable energy in a manner where most fossil fuels are replaced. Previous analyses in hour-by-hour energy system analyses have shown that this is possible by increasing the amount of battery electric vehicles or hybrid battery electric vehicles [35,73,74,109,111], as well as in dynamic simulations within the hour [108]. In Mathiesen and Lund [35] an analysis of seven different technologies is presented for integrating renewable energy indicating that battery electric vehicles constitute the most promising transport integration technology when compared with hydrogen fuel cell vehicles. Hydrogen vehicles introduces losses into the system, and apart from using fluctuating resources, electrolysers will increase the use of power plants as well [73]. Also increasing the use of electric trains can improve the fuel efficiency compared to individual vehicles [3,4,41] and overall much more electricity needs to be utilised in the transport sector [46,110].

3.4. Towards Smart Energy Systems

There are limitations to the extent of transport demand that can be covered by direct electricity consumption in trains or similar and in battery electric vehicles. The remaining part of the transport demand, such as trucks and planes, needs to be covered by fuels that can be transported on board. There are different kinds of biofuels available for this. In Fig. 4 different options for connecting the transport sector with the other sectors are illustrated in energy-flow-diagrams in systems with large penetrations of renewable energy.

The transport sector faces significant challenges in the future due to its dependency on oil products. 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 creating 100% renewable energy scenarios for all transport was introduced in the Danish Society of Engineers (IDA) in the IDA Energy Plan 2030 [41] using the integrated energy systems analysis tool EnergyPLAN. The steps in the study 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 [3]. While both of the case studies used an integrated approach for 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 achieving 100%

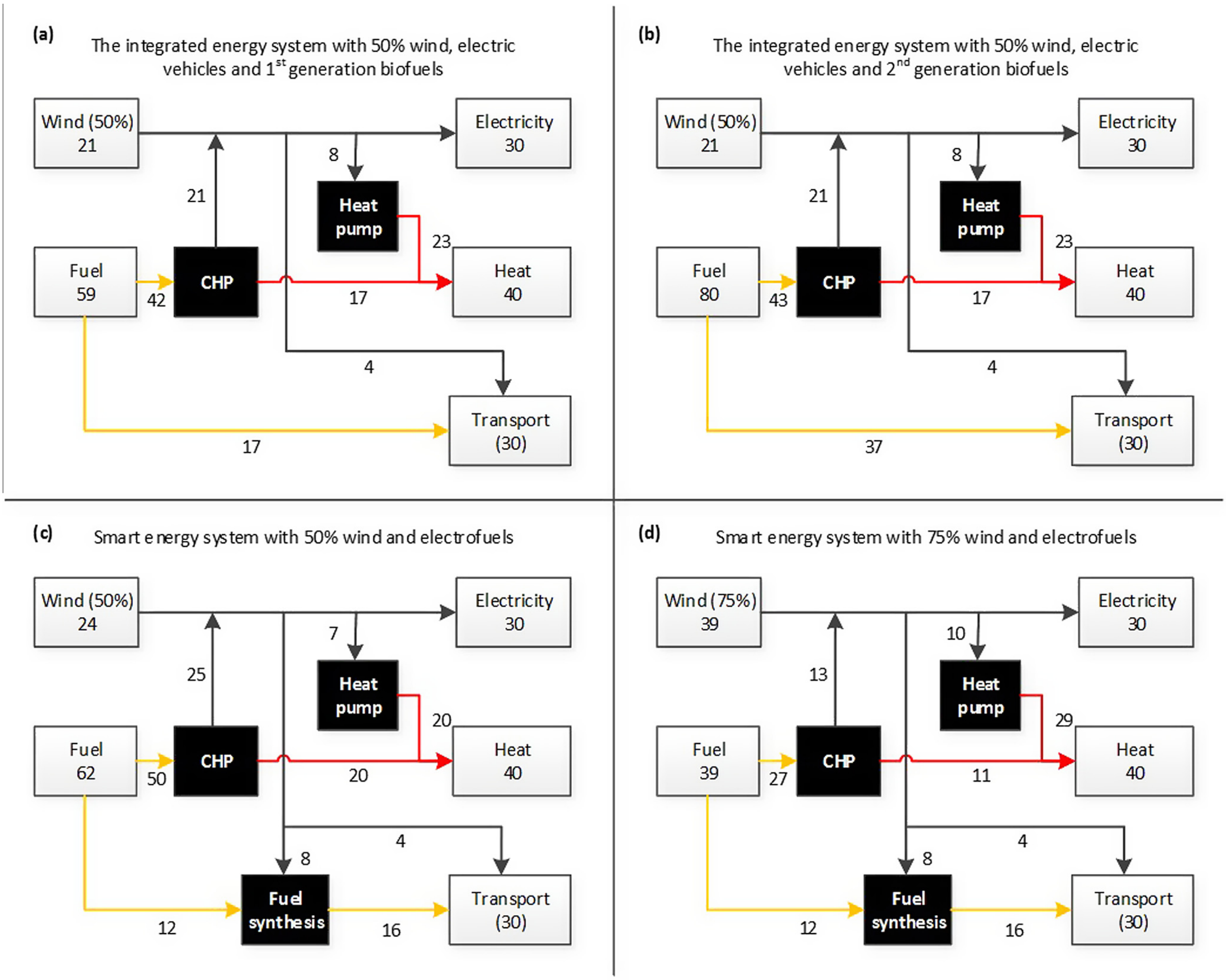

Fig. 4. Energy-flow-diagrams of integrated energy and transport systems with 1st and 2nd generation biofuels (4a) and (4b) and the Smart Energy System (4c) and its storage options (4d).

renewable energy for covering transport demands. Biomass is the preferable replacement for fossil fuels in the transport sector as it can be converted to high-density fuels and can be used within the current infrastructure system. Biofuels have also become more competitive due to the rising prices of fossil fuels.

Assuming that half of the transport demand (represented by 15 units of transport in the energy-flow-diagrams) 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, then the conversion losses are rather small as illustrated in (4a) of Fig. 4. 1st generation biofuels 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 2nd generation biofuels are proposed and why research is growing in this area. In (4b) of Fig. 4 the conversion to transport fuels is included in an example of a 2nd generation biofuel (with 40% biomass to fuel efficiency). As illustrated 2nd generation biofuels introduce large conversion losses, thus increasing the demand for biomass significantly (i.e. fuel). Even if the waste products from the production of biofuels can be used in other sectors for higher value applications (such as food production or further energy applications), then these conversion losses will still be similar to those for 1st generation biofuels (4b). In a 100% renewable energy context, this will result in an overreliance on bioenergy. Our research shows that [3,41,46,73,78,79,110]:

> *…transport demands should be met by electricity and for demands where direct electricity cannot be used, renewable electrofuels using electrolysis based on electricity from fluctuating renewable energy sources should be used, due to limitations in the bioenergy resource…*

The increasing use of biofuels has raised discussions about their effect on the environment, such as the risk of intervening with food production, deforestation, and changes in land-use [42]. In Connolly et al. [110], a number of alternative electrofuels pathways are described and compared as alternatives to support or replace biofuels in 100% renewable energy systems. The methanol/DME pathway from this paper is proposed here in (4c) of Fig. 4 to supply 50% of the transport demand. These renewable electrofuels are produced by converting electricity via electrolysers to hydrogen that is bound with carbon source from CO_2 recycling or biomass gasification Surplus heat can be used for district heating in order to integrate the heat and transport sector. Renewable electrofuels are described further below. With 50% wind power in the electricity

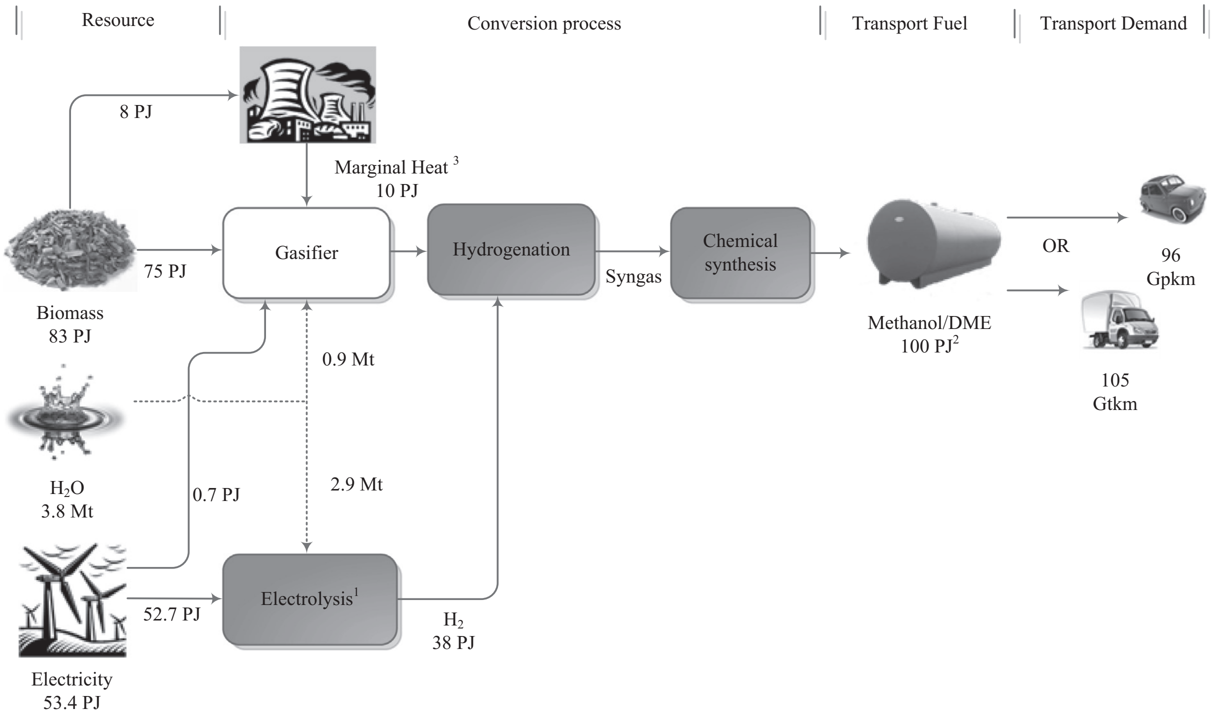

Fig. 5. Steam gasification of biomass which is subsequently hydrogenated to form bioelectrofuel [110]. ^{1}Assumed an electrolyser efficiency of 73% for the steam electrolysis [119]. ^{2}A loss of 5% was applied to the fuel produced to account for losses in the chemical synthesis and fuel storage. ^{3}Assuming a marginal efficiency of 125% and a steam share of 13% relative to the biomass input.

grid, such technologies reduces the fuel consumption from the 2nd generation biofuels, although the fuel consumption is still higher than using 1st 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 1st generation biofuels. In (4d) of Fig. 4 an energy-flow-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 a 75% penetration of fluctuating renewable energy resources, the fuel consumption can be reduced by almost 80% in these ideal energy-flow-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 [46,110]. Energy dense fuels are required for the parts of the transport sector that cannot be covered with battery electric vehicles or electricity powered public transport. Specifically for applications such as long-distance driving or for heavy-duty transport such as trucks, aviation, and ships, electricity is not technically feasible. These demands should not be covered by hydrogen because of to the cost of hydrogen vehicles and hydrogen storage options as the main carrier either [73,112]. 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 seems to be liquid fuel in the form of methanol/DME, as it is a more efficient way to produce fuels compared to methane when taking into account the efficiency of the vehicles [78,79,110,113], however there are many other options [114,115]. 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 so the key message in the short term is that these technologies should be developed further before a final fuel is pursued. Chemical synthesis is well developed, while biomass gasification and electrolysers have the potential to improve [79,114–119]. An example of the process of creating bioelectrofuels based on renewable energy in the form of methanol is illustrated in Fig. 5.

Another key point of such infrastructure is not illustrated in Fig. 4. This infrastructure enables the next phase of the energy system, i.e. to create CO_2-electrofuels, where all types of biomass is entirely phased out. Our research shows that [78,79,110]:

> *...electrofuels based on gasified biomass and electrolysis can pave the way to entirely phasing out biomass if CO_2 sources are available...*

The renewable electrofuel production can also be based on CO_2 from other sources than gasified biomass [120], such as carbon capture and recycling (CCR) from stationary source ambient air [121]. This is very promising for the transport sector, particularly when there is a limited biomass resource [120], but this does not mean that Carbon Capture and Storage (CCS) is a good option for power plants. In fact analyses show that it is not suitable for a longer term high penetration of renewable energy [122].

Further research into such systems is required; however the technology to produce such transport fuels is available today in the form of bioenergy and electrolysers. Similarly, methanol is already produced using current alkaline electrolysers and chemical synthesis with CO_2 from geothermal sources in Iceland [123]. Such systems also have the CO_2 storage option, enabling the same flexibility as described above. New more efficient electrolysers can improve the system illustrated in (4d) of Fig. 4, however it is important to understand that while gasification and chemical synthesis has already been going on for a number of years for producing electrofuel.

4. Grids and storages in Smart Energy Systems

As stated earlier, direct electricity storage with the aim of putting electricity back onto the grid should be avoided [35,36,71,72]. There are many other options to create flexibility in the system as well as to integrate fluctuating renewable energy resources fuel- and cost-effectively. Our research shows that:

> *…electricity storage, i.e. converting electricity to other energy forms including fuels, or chemical storage with the aim of putting it back on the electricity grid, should be avoided as a strategy for balancing fluctuating electricity production…*

In other words, the round trip losses of such electricity storage should be avoided as other solutions focusing on the end use are better options. In areas where there are many possibilities to develop pumped storage, it may make sense from a cost perspective compared to increasing the use of biomass and oil (e.g. on Islands). Grid stability issues may also merit such electricity storage, such as in local distribution grids with bottlenecks. In the long term however, the heating, cooling and transport sectors can be merged to form synergies in storage options occurring due to connections between sectors. By prioritising electricity conversion to heat pumps, electric vehicles and transport fuels through electrolysis, a much higher penetration of fluctuating power is feasible due to their flexibility, and periods of power deficit are reduced. This changes the role of dispatchable electricity supply since they now produce a much smaller part of the annual electricity supply (10–20%) compared to today (typically >75%) [45]. The operation time is thus reduced to 800–2000 h each year. However, a large capacity of dispatchable plant is still needed for periods when there is a low production from fluctuating renewable electricity resources. The demand for dispatchable power supply may then in turn be provided by gaseous fuels stored in the system. Demands can be met by biogas and gasified biomass using gas-based flexible technologies such as gas engines or combined cycle gas turbines, or even MW size fuels cells if these should be developed [36,45]. In a transition period natural gas may play a key role in the energy systems. It should be noted, that in such systems we may have years, seasons, weeks or hours with very low amount of e.g. wind power and/or PV. Hence, in the future we will need power generation capacity standing by [45]. The capacity installed should not be much different than today, however the amount of operation hours will decrease significantly. By having such a design, security of supply from seconds to years can be ensured. On the other hand there may be years, seasons or weeks with very high amounts of fluctuating renewable energy production. In such periods, a Smart Energy System design is able to absorb and store these resources for later use in various forms.

If the penetration of fluctuating renewable energy from wind power and PV etc. should go towards 100% of the electricity supply in a future Smart Energy System, then some form of energy storage may be necessary. However, moving from ~75% fluctuating renewable energy to 100% may prove very costly. Hydrogen from electrolysis could be produced and mixed with carbon to form storable gaseous or liquid fuels, not with the aim of providing fuels for the transport sector, but with the aim of producing electricity. Previous research however shows from studying the CAES technology compared to other integration options, that even free electricity from wind power would not be able to cover the costs of the investments in CAES [72]. If all of the flexibility from connecting the sectors has been used, then, it may even prove more cost-effective to over-invest in fluctuating renewable energy (such as wind power), and simply waste some of the peak production and critical excess electricity production, instead of trying to balance such small demands with large investments in electricity storage. The exact economic optimization in such a situation depends on future boundary conditions and in particular the availability of biomass compared to technology costs.

The readily available fuels that create the flexibility in the current energy system, can be achieved in Smart Energy Systems. In the research and energy-flow-diagrams presented, a number of key technologies are included. In Smart Energy Systems many new technologies and infrastructures, which create new forms of flexibility primarily in the conversion stage of the energy system, are crucial. In Fig. 6 grids and storages in Smart Energy Systems are illustrated.

By combining the electricity, thermal, and transport sectors, the grids and storages in these sectors can improve the energy system flexibility and compensate for the lack of flexibility from renewable resources such as wind and solar.

In the three grids, the storage and connections between sectors is comprised of:

- Smart electricity grids to connect flexible electricity demands such as heat pumps and electric vehicles to the fluctuating 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 as well as the integration of fluctuating renewable heat sources.
- 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 networks 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 – suppliers, 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 in which smart Electricity, Thermal and Gas Grids are combined and coordinated to exploit synergies to achieve an optimal solution for each individual sector as well as for the overall energy system. Our research finds that:

> *…short and long term storage options, such as batteries and large thermal storages, as well as solid, gaseous and liquid storages are key components in 100% renewable energy systems and so are the infrastructures and grids that enable such storage…*

5. The Smart Energy System case: The CEESA 100% renewable energy scenarios

Beginning in 2006, an end goal of a 100% renewable energy system has been debated in Denmark in the political forum. To complement this, in 2006 and 2009 scenarios were developed which outlined how this target could be reached by 2050 [3,4]. Later 2050 was 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 project builds on experience from

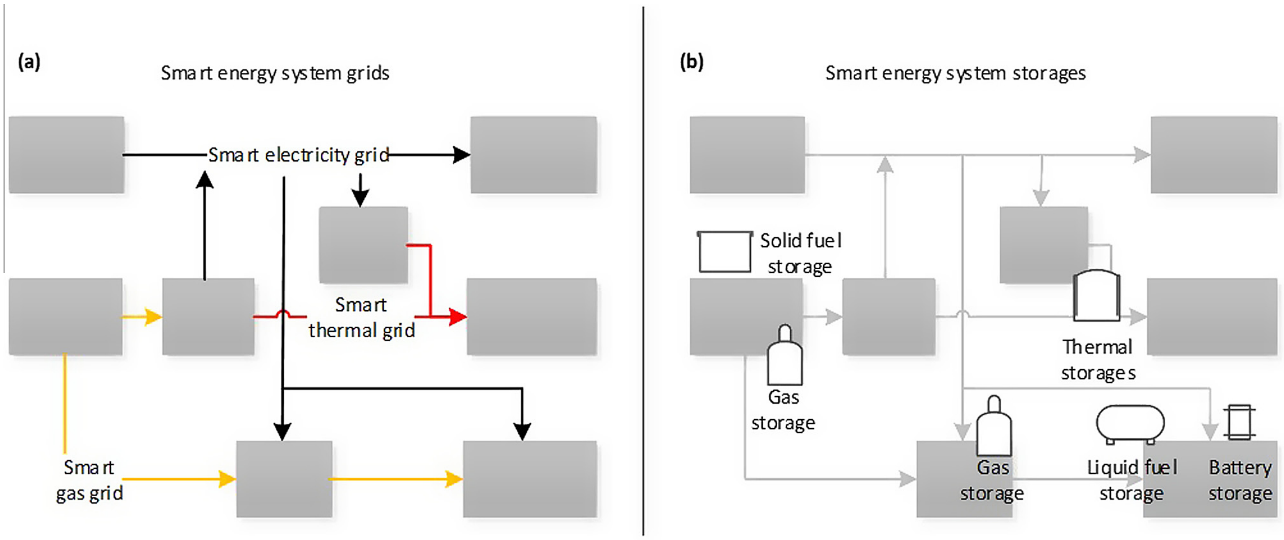

Fig. 6. Energy-flow-diagrams of the grids (6a) and storages (6b) in Smart Energy Systems.

creating the scenarios in 2006 and 2009 and other research projects, some of which are also described previously here.

5.1. Three different Smart Energy System options in the case study

The assumption in CEESA is that the transition towards 100% renewable energy relies highly on the technologies which will 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 for 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 mostly using 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 for 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 more efficient wind turbines. Moreover, the scenario assumes further technological development of electric cars, hybrid vehicles, and bioelectrofuel 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_2-electrofuelis also implemented and the transport sector moves further towards electrification compared to the conservative scenario.

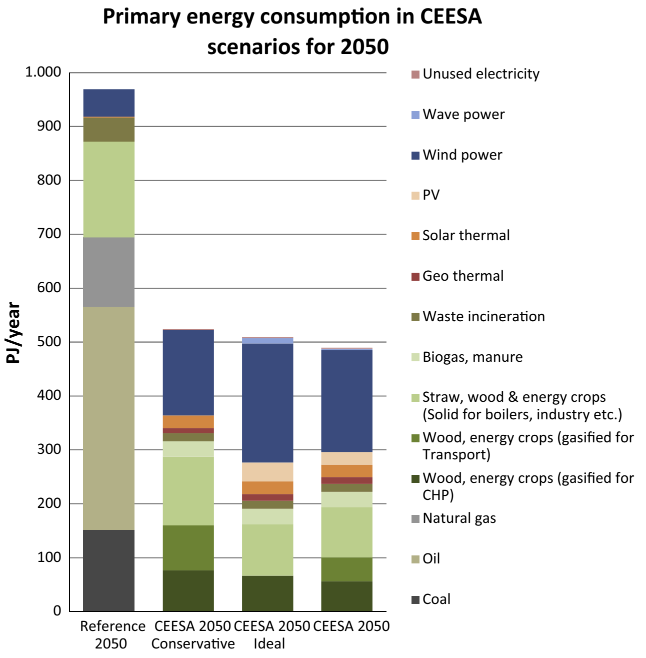

Fig. 7. The primary energy supply in the CEESA 100% renewable energy scenarios for 2050.

- *CEESA-2050:* This scenario aims to be a “realistic and recommendable” scenario based on a balanced assessment of realistic and achievable technology improvements. A balance between bioelectrofuel and CO_2-electrofuel produced DME/methanol is implemented in the transport sector. This is the main CEESA scenario.

It should be highlighted, that in all scenarios, energy savings in electricity, heating and industrial sectors as well as direct electricity consumption are given a high priority. All scenarios rely on a holistic Smart Energy System approach as explained above. This includes the use of thermal heat storages and district heating with CHP plants and large heat pumps as well as transport fuel pathways with the use of gas storage. Also the systems require flexible power plants and CHP plants in the future. All scenarios are hence based on gasification and gas for the power production when the fluctuating resources are not able to meet demands. Furthermore, special attention has been put on the transport sector in the CEESA scenarios. 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 Fig. 7. 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 approximately 330 PJ. The ideal technology scenario can decrease this consumption to approximately 200 PJ of biomass while in the CEESA 2050 recommendable scenario, the biomass consumption is approximately 240 PJ.

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 approximately 240 PJ/year by 2050 which 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 from food-crop production to energy-crop production. All crop residues must be harvested, potentially reducing the carbon pool in soils. This potential conflict can be solved by either reducing the demand for biomass for energy, or by further developing agriculture and forestry yields 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 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.

5.2. Steps to achieve 100% renewable energy systems

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

With more than 20–25% wind power of the electricity demand, the next step is to install large-scale and individual heat pumps. In the CEESA scenarios, a significant amount of onshore and offshore wind power is installed by 2020 where around 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 with the other sectors if the wind power production reaches a share of more than 40–45% of the electricity demand. As a consequence, some electric vehicles are implemented and flexible demand measures are implemented in households and industry. This is however not sufficient. Thus, small amounts of electrolysers based on known alkaline technology are implemented to facilitate wind power integration and for the production of bioelectrofuel in combination with gasified biomass. This 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% of the electricity demand 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 new technologies are necessary to make sure that the renewable energy is integrated efficiently into the system and that fossil fuels are being replaced completely. Hence after 2030, electrolysers for hydrogen production for bioelectrofuel are gradually increased to provide larger amounts of liquid fuels to the transport sector. It is assumed that the electrolysers are more efficient. CO_2-electrofuel are used to limit the use of biomass. Instead they use carbon recycling from the electricity sector or other stationary 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 recommendable scenario. CHP plants and power plants are based on gas, allowing dispatchable plants to react faster than current technologies.

The CEESA project has taken a closer look on 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 analysed with regard to the need for import/export, gas storage or flexibility and extra capacities in the gas producing units. Firstly, the annual need for import/export in the case of no gas storage and no extra capacities on the production units was calculated. Then similar analyses were carried out for storage capacities gradually being increased from 0 to 4000 GW h. In all such situations the need for import is equal to the need of export on an annual basis, since the systems are designed to have a net import of zero. However, the need for import/export decreases along with increases in the domestic storage capacity. A storage capacity of about 3000 GW h is able to completely remove the need for import/export. The current Danish natural gas storage facility have a gas content of 17,000 GW h in Stenlille near Copenhagen and 7600 GW h in Western Denmark. The work-content of the storages are smaller, approximately 6500 and 4800 GW h respectively. This means that the total current storage capacity, assuming natural gas quality, is 11,350 GW h. If the gas quality in the entire grid is lowered to biogas standard, the storage would be reduced to around 6800 GW h 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 when assuming no extra capacity at the gasification plant, i.e. no flexibility in the production of syngas.

Until now, it was assumed that all gas production facilities operated at baseload, so here the benefits of flexibility at the gas producing plants is investigated by increasing their capacities. The results indicate that an increase in gas production capacity reduces the need for storage capacities. In the CEESA 2050 scenario

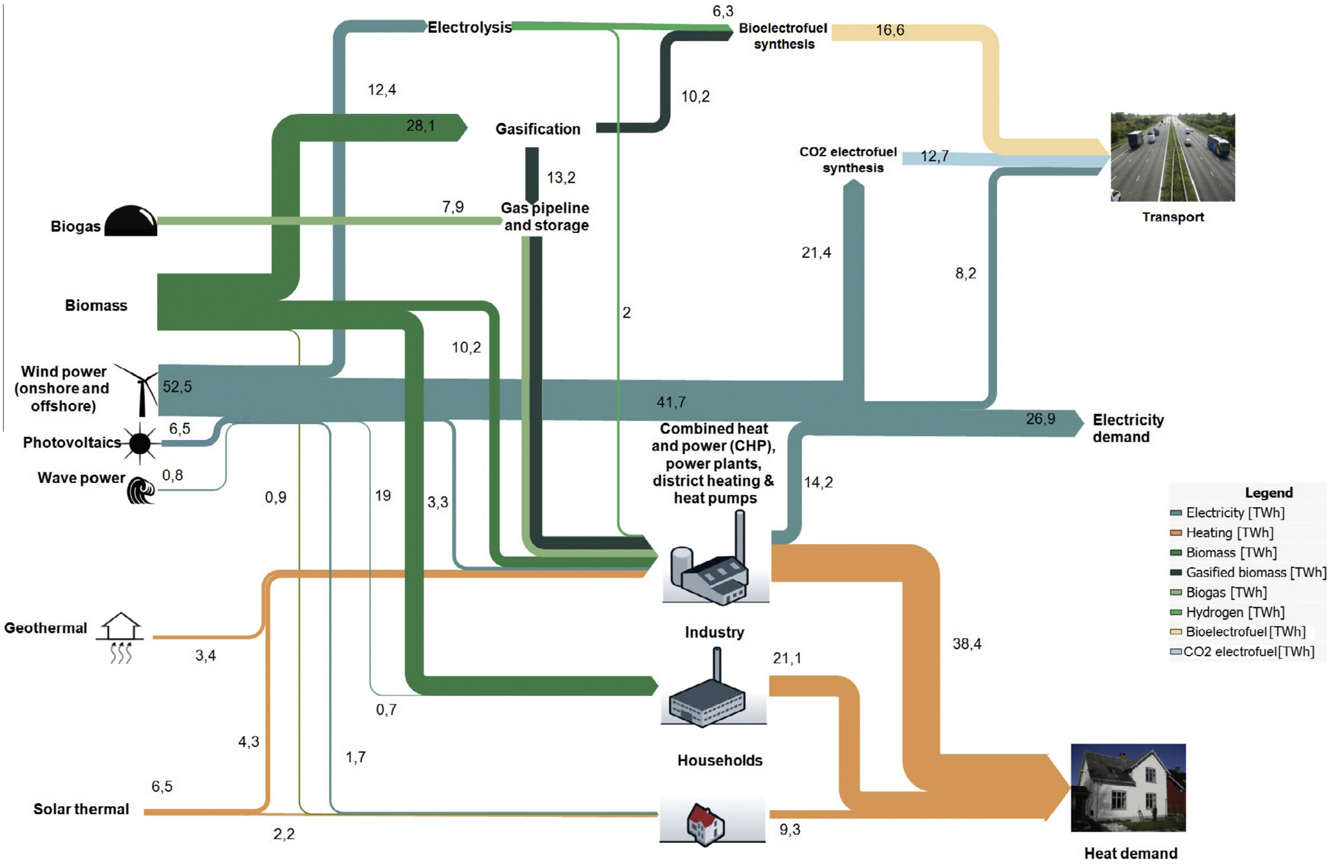

Fig. 8. Energy flows in the CEESA 2050 100% renewable energy scenario. The flows represent the annual aggregated values; however every single hour for all demands and production technologies is accounted for in the energy system analyses.

it was chosen to include about 25% over-capacity for the gas production units, in combination with gas storages above 3000 GW h.

The analysis has also been used to evaluate peak loads on the gas grid. In the CEESA 2050 scenario the peak demand is approximately 10,000 MW. At present, the peak in Danish natural gas consumption in the winter is about 360 GW h and the maximum gas production is about 260 GW h. On 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 when assuming the capacity is used for gas with biogas energy density, the current grid could also be used in the peak situation.

One important lesson from the hourly analysis of the entire 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 production to nearly zero while at the same time achieving high fuel efficiencies by using heat and gas storages and connecting the transport sector. No electricity storage is included as such investments would not be economical, due to the very small utilization hours and the inefficiency in the system from the round trip losses.

The energy-flow-diagrams presented above represent the transition from a simple supply demand system to the integrated Smart Energy System from an ideal point of view. For the CEESA 2050 scenario, losses and hour-by-hour calculations have been accounted for when designing the scenarios. The resulting Smart Energy System is illustrated in the Sankey diagram in Fig. 8.

6. Conclusions

Suboptimal solutions with sectorial 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 and cost effective option. In particular, the study combines the analysis of gasified biomass and gas grid storages in conjunction with electric vehicles and electrofuel 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 an hour-by-hour balance in the gas supply and demand. It should be noted that synergies and feasible solutions are not achieved simply by combining these infrastructures and storage options automatically. The design and configuration has to be carefully investigated. Also it should be noted that energy savings are extremely important as the primary energy demands otherwise would increase significantly and increase the need for fluctuating resources and biomass.

Our hypothesis is, that this approach is generally applicable and appropriate in designing 100% renewable energy systems that are technically feasible, economically have similar cost to fossil fuel alternatives and can have sustainable consumption of bioenergy.

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