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# Renewable Energy Systems - A Smart Energy Systems Approach to the Choice and Modelling of 100 % Renewable Solutions

Henrik Lund*[a], Brian Vad Mathiesen[b], David Connolly[b], Poul A. Østergaard[a]

[a]Aalborg University, Department of Planning and Development, Vestre Havnepromenade 9, Aalborg
[b]Aalborg University, Department of Planning and Development, A.C. Meyers Vænge 15, Copenhagen
Lund@plan.aau.dk

This paper presents the learning of a series of studies that analyse the problems and perspectives of converting the present energy system into a 100 % renewable energy system using a smart energy systems approach. As opposed to, for instance, the smart grid concept, which takes a sole focus on the electricity sector, smart energy systems include the entire energy system in its approach to identifying suitable energy infrastructure designs and operation strategies. The typical smart grid sole focus on the electricity sector often leads to the conclusion that transmission lines, flexible electricity demands and electricity storage are the primary means to deal with the integration of fluctuating renewable sources. However, the nature of wind power and similar sources has the consequence that these measures are neither very effective nor cost-efficient. The most effective and least-cost solutions are to be found when the electricity sector is combined with the heating and cooling sectors and/or the transportation sector. Moreover, the combination of electricity and gas infrastructures may play an important role in the design of future renewable energy systems. The paper illustrates why electricity smart grids should be seen as part of overall smart energy systems and emphasizes the inclusion of flexible combined heat and power (CHP) production in the electricity balancing and grid stabilization. Furthermore, it highlights how to design and model future sustainable smart energy systems.

## 1. Introduction

In recent years, a number of new terms and definitions of sub-energy systems and infrastructures have been promoted to define and describe new paradigms in the design of future energy systems such as smart grid (Massoud and Wollenberg, 2005), 4th generation district heating (Lund et al., 2014), Vehicle-2-Grid (Lund and Kempton, 2008) and power to gas (Gahleitner, 2013). All these infrastructures are essential new contributions and represent an important shift in paradigm in the design of future renewable energy strategies. However, they are also all sub-systems and sub-infrastructures which cannot be fully understood or analysed if not properly placed in the context of the overall energy system. Moreover, they are not always well defined and/or are defined differently by different institutions.
The issue of sub-systems versus overall energy systems is carefully analysed in (Lund, 2014; Connolly et al., 2013) and are here referred to as the concept of smart energy systems. As opposed to, for instance, the smart grid concept, which takes a sole focus on the electricity sector, smart energy systems include the entire energy system in its approach to identifying suitable energy infrastructure designs and operation strategies. One main point is that in order to do a proper analysis of any smart grid infrastructure, one has to define the overall energy system in which the infrastructure should operate. Another main point is that different sub-sectors influence one another and one has to take such an influence into consideration if the best solutions are to be identified.

Today, the design of the energy system is based on fossil fuels. This makes the energy system very flexible and reliable since large amounts of energy can be stored in liquid, gaseous, and solid form via

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fossil fuels. This means that energy can be provided 'on demand', as long as there is a suitable fossil fuel storage nearby, such as a diesel tank in a car, a gas tank for a boiler, or a coal storage for a power plant. Hence, fossil fuels have provided society with a lot of flexibility: fossil fuels store large amounts of energy so it is available on demand whenever it is required. However, in the future this flexibility will be limited.

## 2. Smart Energy Systems

The future energy system will rely on renewable energy resources such as wind and solar power. These resources do not contain large amounts of stored energy, but instead the energy from the wind, sun, waves and tides must be captured and used immediately. This is one of the key technological challenge facing energy systems in the future. The question is: How can the future energy system, which will be based on renewable energy, operate without the flexibility currently being provided by large amounts of stored energy in fossil fuels, while simultaneously providing affordable energy and utilising a sustainable level of the resources available? The solution will be to find new forms of flexibility within the energy system, which are affordable and utilise renewable energy resources in an efficient manner. This is called a smart energy system.

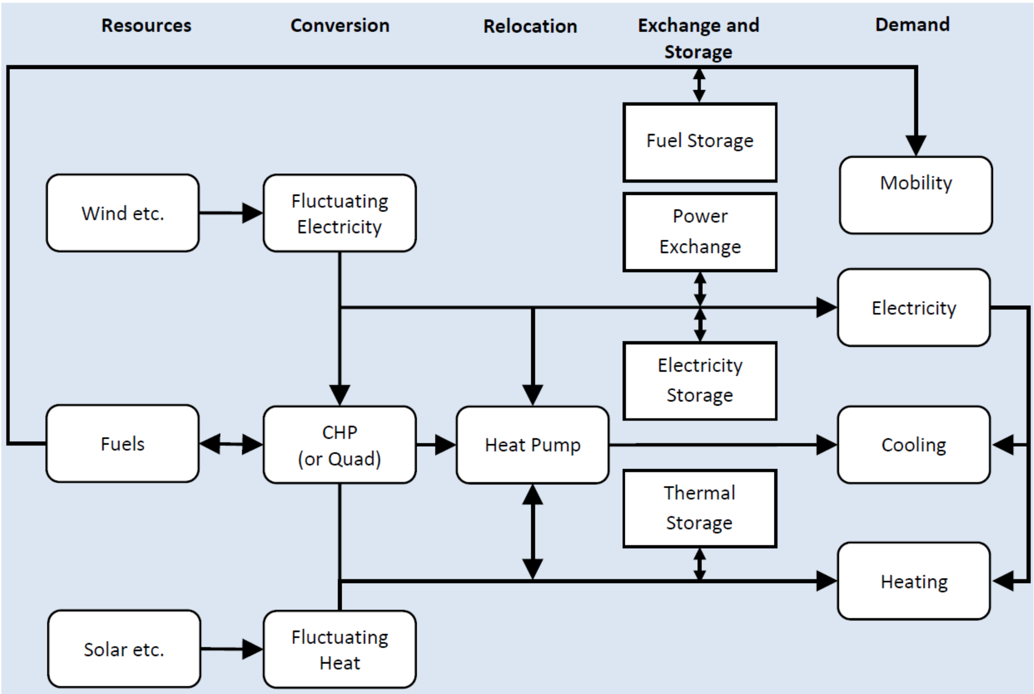


*Figure 1: Illustration of a Smart Energy System based on the integration of the power, heating, cooling, gas and transportation sectors and infrastructures*

A smart energy system consists of new technologies and infrastructures which create new forms of flexibility, primarily in the 'conversion' stage of the energy system. This is achieved by transforming from a simple linear approach in today's energy systems (i.e. fuel to conversion to end-use), to a more interconnected approach. In simple terms, this means combining the electricity, thermal, and transport sectors so that the flexibility across these different areas can compensate for the lack of flexibility from renewable resources such as wind and solar. The smart energy system is illustrated in Figure 1 and uses technologies such as:

- **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.

**2.1 Power-to-Transport**

Additional to the storage issue mentioned above, future energy systems also has to face the challenge of meeting transport demands without exceeding the sustainable biomass potential.

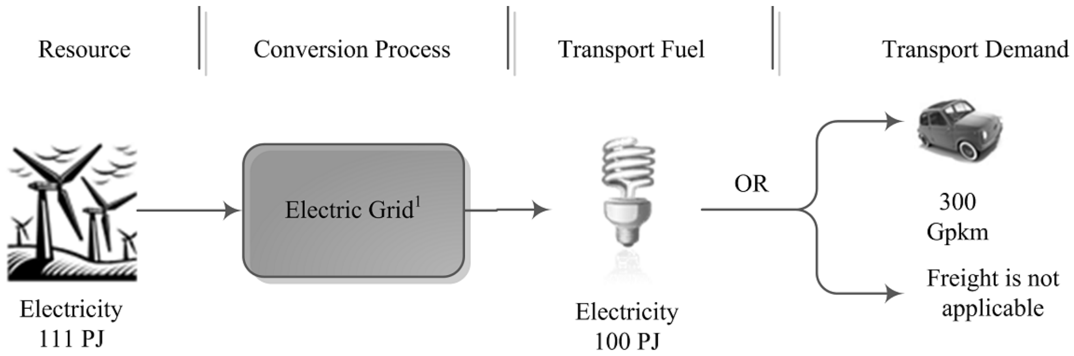


*Figure 2: Direct use of electricity for transportation using battery storage*

From a system point of view the best solution is direct use of electricity as illustrated in Figure 2. However, direct use of electricity cannot cover all the transportation demands. Some will have to be covered by the use of biomass, but the biomass resources available for energy purposes are limited due to demands for food and materials as well as biodiversity. Furthermore, they are limited to such a degree that it is hard to see how biomass alone could cover current energy demands in the transportation sector. Moreover, a transportation system based solely on renewable energy requires some sort of biomass-based gas and/or liquid fuel to supplement the direct use of electricity. The point is that, for the sake of transportation, power will have to be used directly in batteries to supplement some biomass which needs to be turned into either gas or liquid fuel. Moreover, biomass in the form of gas helps in achieving better flexibility and efficiencies in future CHP and power plants.

**2.2 Power-to-Gas**

However, not only biomass is relevant to gas production; but electricity in "power to gas" systems may also be highly relevant to boost and supplement the limited biomass resources. Such "power to gas" technologies may have substantial synergies if they are combined with the production of gas from biomass in technologies such as fermentation, gasification and hydrogenation. In order to create enough gas and liquid fuel for the complete renewable energy system within the biomass resources available, one will have to boost the synthetic gas and liquid fuel from the biomass by hydrogenation, i.e. power-to-gas in the form of producing hydrogen on electrolysers. Different pathways exists for different biomass resources and end use. Figure 3 illustrates one such pathway.

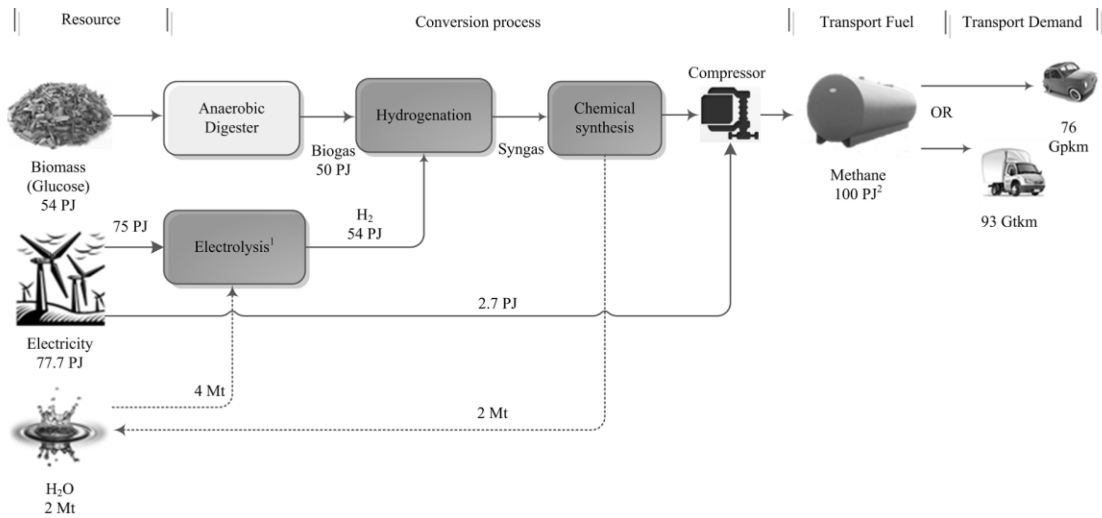


*Figure 3: Example of a pathway using power-to-gas in hydrogenation to boost the amounts of biomass based synthetic gas.*

### 2.3 Power-to-Heat

The design of future renewable energy systems is typically based on a combination of fluctuating renewable energy sources such as wind and solar power on the one hand and residual resources such as waste and biomass on the other. As mentioned above, a pressure on the waste and biomass resources is expected due to the environmental impacts and future alternative demands for food and material. To ease the pressure on the biomass resources and the investments in renewable energy, feasible solutions to future renewable energy systems involve substantial elements of energy conservation and energy efficiency measures (Lund et al., 2012).

District heating has an important role to play in the task of making these scarce resources meet the demands (Connolly et al., 2014). The inclusion of district heating in future renewable energy systems allows the use of CHP together with the utilization of heat from waste-to-energy and various industrial surplus heat sources as well as the inclusion of geothermal and large-scale solar thermal heat. In the future, the industrial processes may involve various procedures of converting solid biomass fractions into bio(syn)gas and/or different types of liquid biofuels for transportation fuel purposes among other things.

To be able to fulfil its role in future renewable energy systems, the present district heating system must undergo a radical change into low-temperature district heating networks interacting with low-energy buildings as well as smart electricity grids. These future district heating technologies have been defined as 4th Generation District Heating Technologies and Systems - 4GDH (Lund et al., 2014).

### 2.4 Power-to-Cooling

For obvious reasons, district heating has higher potential in countries with cold climates than countries with warm climates. However, in warm climates, district cooling may be an option and, in some countries, both types of networks and/or a combination would be desirable. In principle, district cooling can be applied in two different ways. One solution is to use a district heating network to distribute heat, which then by individual absorption units is turned into cooling in the individual building. This option is well suited for locations at which both heating and cooling of buildings is required during different seasons of the year. Moreover, the network can be used to supply both cooling and hot water to the building at the same time. The other solution is to produce central cooling and distribute the cold water. This option has the advantage of being able to include “natural” cooling, such as cold water from rivers or harbours.

## 3. Smart Energy Systems Synergies

As illustrated above, all smart grids are important contributors to future renewable energy systems. However, each individual smart grid should not be seen as separate from the others or separate from the other parts of the overall energy system. Firstly, it does not make much sense to convert, e.g., the electricity supply to renewable energy if this is not coordinated with a similar conversion of the other parts of the energy system. Secondly, better solutions arise for the implementation of the smart energy system and the individual sectors if their implementation is coordinated.

In other words, there are several synergies connected to taking a coherent approach to the complete smart energy system compared to looking at only one sector. This does not only apply to finding the best solution for the total system, but also to finding the best solutions for each individual sub-sector. Such synergies include the following:

- Electricity for heating purposes makes it possible to use heat storage instead of electricity storage, which is both cheaper and more efficient. Moreover, it provides a more flexible CHP production.
- Electricity for heating may be used for balancing in regulating power markets, etc.
- Biomass conversion to gas and liquid fuel needs steam, which may be produced on CHP plants, and produces low-temperature heat, which may be utilized by district heating and cooling grids.
- Biogas production needs low-temperature heat which may be supplied more efficiently by district heating compared to being produced at the plant.
- Electricity for gas such as hydrogenation makes it possible to use gas storage instead of electricity storage which is cheaper and more efficient.
- Energy savings in the space heating of buildings make it possible to use low-temperature district heating which, in addition, makes it possible to utilize better low-temperature sources from industrial surplus heat and CHP.
- Electricity for vehicles can be used to replace fuel and provide for electricity balancing.

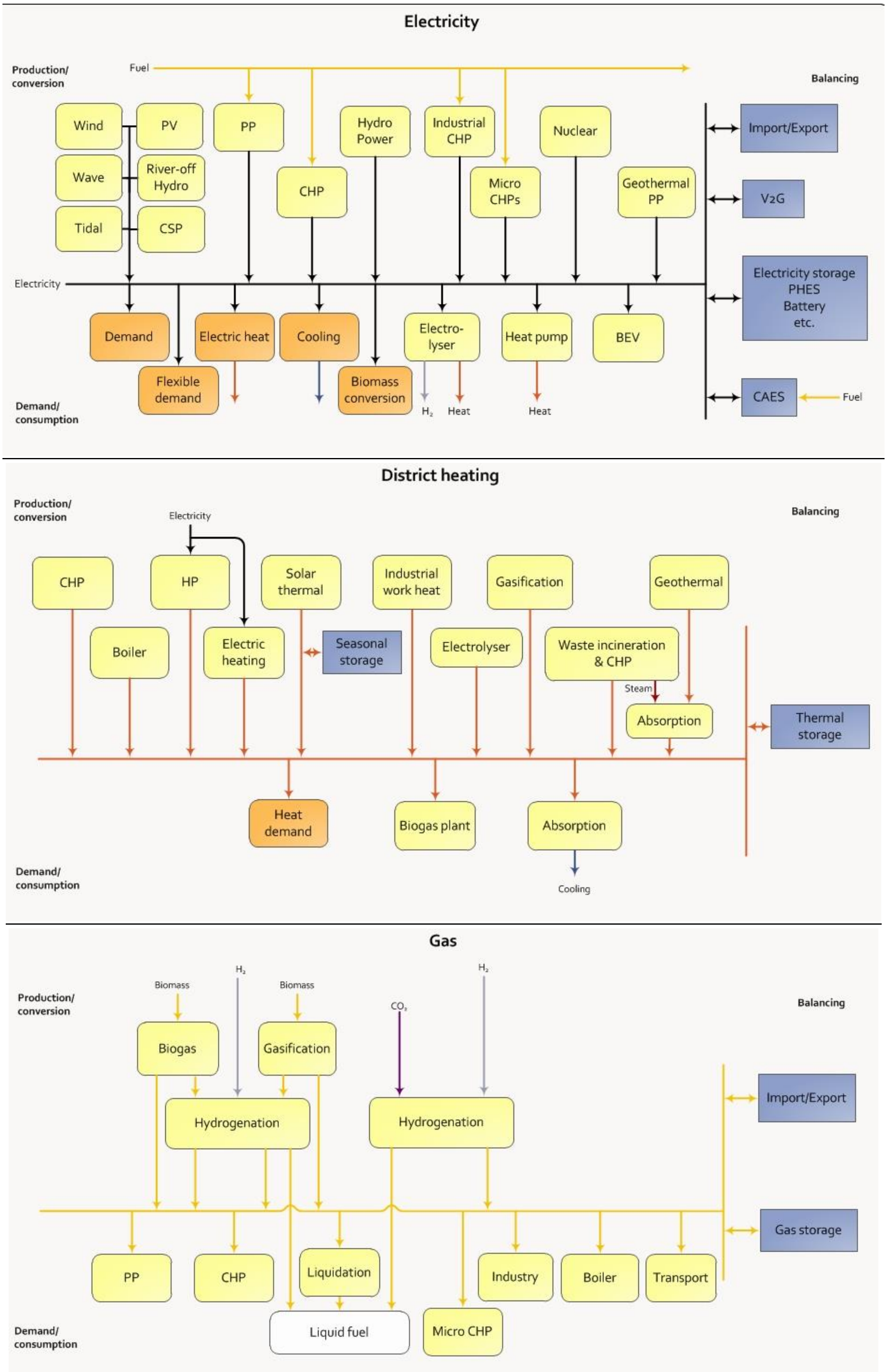


*Figure 4: Illustration of three infrastructures and their components analyses on an hourly basis in EnergyPLAN. EnergyPLAN also include hourly analyses of district cooling, hydrogen and desalination*

## 4. Smart Energy Systems Modelling

The analysis of smart energy systems calls for tools and models which can provide similar and parallel analyses of electricity, thermal and gas grids. The advanced energy systems analysis model, EnergyPLAN, has been developed to fulfil such purpose on an hourly basis (www.EnergyPLAN.eu), so that optimal solutions can be identified. The main purpose of the model is to assist the design of national energy planning strategies on the basis of technical and economic analyses of the consequences of different national energy systems and investments. However, the model has also been applied to the European level as well as to a local level such as towns and/or municipalities. The design of EnergyPLAN emphasises the option of looking at the complete energy system as a whole. Therefore, EnergyPLAN is designed to be a tool in which, e.g., electricity smart grids can be coordinated with the utilisation of renewable energy for other purposes than electricity production.

In the tool, renewable energy is converted into other forms of carriers than electricity, including heat, hydrogen, synthetic gases and biofuels, as well as energy conservation and efficiency improvements, such as CHP and improved efficiencies, e.g., in the form of fuel cells. All such measures have the potential for replacing fossil fuels or improving the fuel efficiency of the system. The long-term relevant systems are those in which such measures are combined with energy conservation and system efficiency improvements. As a consequence, the EnergyPLAN tool does not only calculate an hourly electricity balance, but also hourly balances of district heating, cooling, hydrogen and natural gas, including contributions from biogas, gasification as well as electrolysis and hydrogenation. The diagrammes in Figure 4. present a view of the production and conversion units involved in the balancing of the different grid structures.

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