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Review

Smart energy and smart energy systems

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A B S T R A C T

In recent years, the terms "Smart Energy" and "Smart Energy Systems" have been used to express an approach that reaches broader than the term "Smart grid". Where Smart Grids focus primarily on the electricity sector, Smart Energy Systems take an integrated holistic focus on the inclusion of more sectors (electricity, heating, cooling, industry, buildings and transportation) and allows for the identification of more achievable and affordable solutions to the transformation into future renewable and sustainable energy solutions. This paper first makes a review of the scientific literature within the field. Thereafter it discusses the term Smart Energy Systems with regard to the issues of definition, identification of solutions, modelling, and integration of storage. The conclusion is that the Smart Energy System concept represents a scientific shift in paradigms away from single-sector thinking to a coherent energy systems understanding on how to benefit from the integration of all sectors and infrastructures.

Contents

1. Introduction

In recent years, several new definitions and terms have been put forward to develop new approaches and understandings on how to design future sustainable energy systems such as e.g. *smart grid* [1], *Net Zero Energy Buildings (NZEB)* [2] and *power to gas* [3]. These terms are typically defined and applied within the limits of sub-sectors and sub-infrastructures and therefore often represent a single-sector approach, which cannot be fully understood or analysed if not properly placed in the context of the overall energy

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system.

The term *Smart Energy* or *Smart Energy Systems* was defined and used in order to provide the scientific basis for a paradigm shift away from single-sector thinking into a coherent and integrated understanding of how to design and identify the most achievable and affordable strategies to implement coherent future sustainable energy systems. This way of using the term *Smart Energy Systems* was first introduced in 2012 [4]. Later on it was given a specific definition published in a book in 2014 [5] after being pre-published in a booklet from 2013 [6]. However, as we shall see later on in the literature review, the term *Smart Energy Systems* has also - often within control engineering and management - simply been used synonymously for Smart Grid and/or to express that the control system in question would have a broader application than only within the electricity sector. Moreover, the term integrated energy systems or integrated community energy systems [7] have sometimes been used.

This review paper concerns the scientific basis for a paradigm shift away from single-sector thinking into the use of a coherent cross-sectoral *smart energy systems* concept, by starting with a literature review. Then it makes a state-of-the art description of different single-sector approaches to the transformation towards future sustainable energy solutions within the electricity, gas, building and industrial sectors. Next, it discusses the Smart Energy Systems concept with regard to the issues of definition of the term, identification of renewable systems design, the integration of holistic storage solutions and the modelling of national energy systems.

2. Literature review

A literature review of the use of the term *"Smart Energy Systems"* up until the end of year 2016 has been conducted in the following way. By use of Scopus, 72 journal papers were identified which used the term in either title, abstract, keywords or references. By use of ScienceDirect and GoogleScholar seven more papers from Energy Procedia and similar were added. The search has concentrated on scientific journal articles, conference papers and books, which have made an active use of the concept. A few papers, which have only used the term in keywords or in references, have been excluded from the analysis. In total, the survey includes 69 publications.

The survey shows that the term has been used from 2009 and onwards. In the years 2009–2013, it was only used a few times while in the years 2014–2016 there has been an increasing use of the term.

The use of the term can be categorized into two major groups. In Group 1, the word ***smart*** is the most important. In this group the topics are typically control management and similar. In Group 2 the word **systems** is the most important. In this group, the cross-sectoral approach is in focus.

In Group 1, the use can be divided into the following sub-groups:

- **Similar to Smart Grid (Smart Grid):** The term is used more or less synonymously with the term *Smart Grid* in approximately 19 papers [8–26]. For example, in Ref. [14] the two terms are described in the following way: *"…. in terms of smart energy systems (Smart grid),…"*. Or when the focus is on power transmission, then the term is sometimes used together with the term *"Smart Power Systems"* [18]. In general, these papers have a sole or predominant electricity sector approach. A few of them concentrate on the interactions between control systems and human beings [10,16,26].
- **Smart Grid but Broader (Cross Sector Control):** In other papers the main focus is still on control engineering in the electricity sector, but the term *Smart Energy Systems* seems to refer to that the control systems and/or algorithms that have a broader use also within other sectors [27–31]. Thus, in some papers, such as [27], it is mentioned that the control systems in question could be used in *"a connected electricity and gas meter".*
- **Smart Heating (Heat Control):** In a few papers there is a sole or predominant focus on control and management in the thermal/heating sector [32–35]. In some papers the control and management systems have such a general nature that it is not clear - or relevant - to specify if the application focuses on the 'electricity only' smart grid approach or has a broader application [36].

In several of the papers in Group 1 the term *smart energy systems* refers to a broader use of the control management systems in question beyond the typical smart grid applications or, to describe a more holistic view of generation, transportation as well as the consumption of power, although still within the electricity sector such as in Ref. [17]. As described later, this use of the term fits very well with the term *Smart Grid* as it was originally introduced in 2005.

In Group 2, the use can be divided into the following sub-groups:

- **Cross-Sectoral Integration (System Integration):** In most papers [4,37–68] the term actively refers to a holistic integrated system including all sectors and/or all energy carries. For example, in Ref. [37] the term is referred to in the following way: *"The establishment of smart energy systems should be furthered by combining the heat, cooling, power, gas and transport markets."* Often there is a focus on coordinating the use of different infrastructures and energy carriers such as a reference to *"different energy carriers in smart energy systems"* [47]. Again some of these papers focus on the interactions between the technical systems and human beings and/or broader societal and policy implications [59,60,64]
- **All or More Sectors** (System Viewpoint)**:** In one paper [69] the term is used for a *"global smart energy system"* including all sectors but not in particular emphasizing the cross-sectoral approach. And in another, the term is used to express the interaction from *"homes to network to cities"* [70] or with a reference to smart cities [71,72].
- **RES Integration (Renewable Electricity Integration):** In a few papers the term is used in relation to wind integration into energy systems however still with a focus on the power supply sector [73,74].

In several of the mentioned papers above (from all sub groups), the issue of storage is highlighted. Essential for the papers in Group 2 is that the understanding of the term *smart energy systems* is used to include all sectors and most papers take a focus on the cross-sectoral integration aspect.

Fig. 1 presents an overview of the literature review by counting the number of scientific publications using the term and grouping them into the definedgroups and sub-groups. In Fig. 1, Group 1 and its sub-groups in which the word smart is in focus is shown in blue, while Group 2 and sub-groups are shown in green.

As can be seen from Fig. 1 there has been a steep increase in the use of the term since it was first mentioned in 2009. Especially within the cross-sectoral understanding of the concept (marked with green) the use has increased significantly in recent years.

As already defined, this review paper concentrates on the scientific basis for a paradigm shift away from single-sector thinking into the use of a coherent cross-sectoral *smart energy systems* concept. Therefore, in the following the paper will not include the understanding in which the term has been used more or less synonymously for Smart Grid.

3. State-of-the-art in energy sub-sectors

This section introduces state-of-the art in the different parts of the energy system constituting smart energy systems.

3.1. State-of-the-art within the electricity sector: smart grid

The challenge of integrating fluctuating renewable energy sources into the electric power grid has been recognized and discussed for several years under different labels. The lead author of this paper published on the subject already in 1986 [75–77] including the concept of a regulation hierarchy in order to manage distributed generation without causing feedback in the system. Afterwards, the challenge has been discussed using the label "Distributed generation" [78] or as part of the discussions regarding innovative technological concepts such as Vehicle-to-Grid (V2G) [79] or micro-grids [80] as well as local, regional and national energy systems [81–84].

In recent years, the *Smart Grid* concept has played an important role. This term was first used in 2005 by Amin and Wollenberg in their paper "Towards a Smart grid" [1]. The paper describes how the key elements and principles of operating interconnected power systems were established long before realizing the options arising from today's computer and communication networks. Today, computation and control management is used in all corners of the power sector, but is far from being used to its full potential. As Amin and Wollenberg emphasize, practical methods, tools and technologies are allowing *"power grids and other infrastructures to locally self-regulate, including automatic reconfiguration in the event of failures, threats or disturbances"*. Amin and Wollenberg have not included a formal definition of smart grid, but it can be understood from the paper that a *smart grid* is a power network using modern computer and communication technology to achieve a network, which can better deal with potential failures.

Later, the discussion of the need for changes in future power infrastructures has often been related to the "smart grid" concept in a large number of reports and papers. Many of them argue for the need for smart grids in order to facilitate better integration of fluctuating renewable energy [85]. Several smart grid papers focus on the consumer and how to involve the consumer in the active operation of the power balance by introducing technical operation systems and/or economic incentives to facilitate flexible demands, including the development and design of proper information and communication systems [86], heat pumps and electric vehicles [87,88]. The above-mentioned papers and approaches regarding smart grids all seem to have a sole or predominant focus on the electricity sector, thus, only a few papers emphasise the need for intelligent management of a complete set of energy forms including electricity, heat, hydrogen, biofuels, industry and transport as e.g. Ref. [85] does.

There are four recent definitions in Ref. [5] for Smart Grids (from the United States Department of Energy, the International Energy Agency and the European Union). Even though some inconsistencies exist, all of these clearly define smart grid to be limited to the electricity sector. The typical core of defining a smart grid consists of a bi-directional power flow, i.e. the consumers also produce to the grid, which differs from the traditional grid in which there is a clear separation between producers on the one side and consumers on the other side resulting in a uni-directional power flow. Consequently, former concepts mentioned above such as regulation hierarchies, distributed generation, V2G concepts as well as many micro-grids all become smart grids or part of the smart grid concepts.

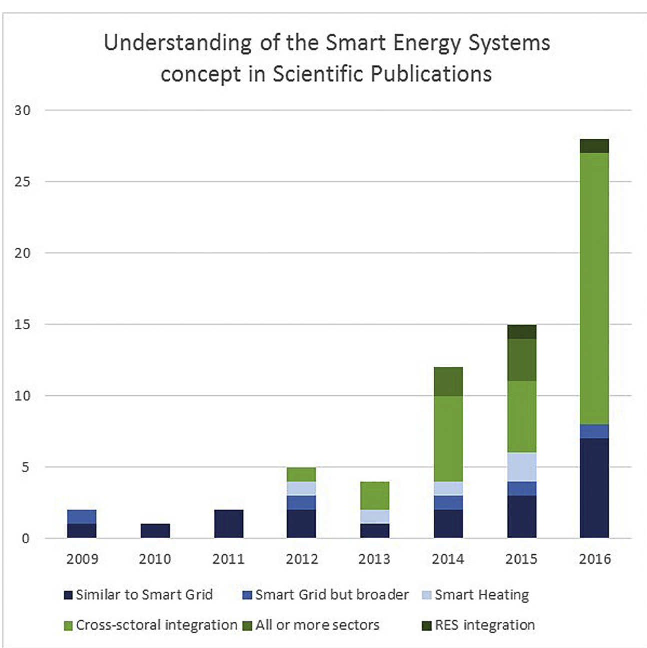

Fig. 1. Overview of the use of the term "Smart Energy Systems" in scientific literature until the end of 2016. The blue colours include papers in which the term is used with a Smart Grid one sector approach or a little broader, while the green colour include papers in which a holistic view of including all sectors (electricity, thermal, gas, industry and transport) are in focus. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

> State-of-the-art of a smart grid is that the concept is defined within the limitations of the electricity sector, thus creating a paradigm in which solutions for the integration of fluctuating renewable energy should be found within the sub-sector itself. Most research is carried out within these limits even though some attempts have been made to take a broader view that includes heating, cooling, industry and transport.
>
> The hypothesis of a Smart Energy Systems approach is that the best solutions cannot be found within these limits. One has to provide a broader scientific understanding and concept.

3.2. State-of-the-art within biomass and transport: EV and power-to-gas

How to switch the transport sector into sustainable energy within the limits of sustainable use of biomass is a great challenge, maybe the greatest challenge of all. All over the world, countries are making more and more ambitious strategies for increasing the amount of renewable energy in transportation. Several studies have been carried out on electric vehicles [7,89] including the potential integration with the electricity sector such as already mentioned under the smart grid section. Electric vehicles can aid the integration of more wind power by simply adjusting the time of their charge according to the renewable electricity generation, or even go a step further by both consuming and producing electricity via vehicle-to-grid (V2G) technology [79]. However, when including all aspects of the transport sector it is evident that no single technology can solve the transport puzzle in a feasible way [90]. Different technologies must be combined and most strategies addressing a transformation of the total transport sector combine electric vehicles with the use of biofuels.

All light vehicles (cars and vans) are typically expected to transition to electric motor vehicles. However, for heavy vehicles and aviation there is a need for gaseous or liquid fuel which could be produced out of carbon from biomass resources. In general the inclusion of biomass involves important benefits. It can act as a direct combustible replacement to fossil fuels, e.g. in dispatchable centralised power stations. Moreover biomass can exist as a solid, liquid, or gaseous fuel and that makes it suitable for 100% renewable energy systems, especially with regard to the transport sector. On the other hand, the major drawback of biomass is its availability and its implications for land use and food production [91].

Previous research has examined the dilemma between, on the one hand, the need for biomass in transport and, on the other hand, the limitations to sustainable use of biomass. Two studies [67,92] have led to the conclusion that power-to-gas is needed to boost the limited biomass resource and such conclusions have led to the definition of the term ***electrofuels*** [55,93,94]. Electrofuels are produced by integrating the electricity, gas and transport sectors through the Power-to-liquid and Power-to-gas concepts [95]. The first step is the conversion of electricity via electrolysis to hydrogen. The hydrogen is then used either for boosting gasified or fermented biomass in a hydrogenation process or merged with CO_2 emissions from point sources such as energy or industrial plants and further converted to desired fuels. These fuels are called electrofuels or more precisely bio-electrofuels and CO_2-electrofuels. The technology complex will consist of:

- Electrolysers: to produce hydrogen
- Gasification and fermentation: to gasify biomass and generate biogas to produce carbon
- Chemical synthesis: to synthesize the electrofuels from the hydrogen and carbon

Parallel to these efforts of integrating the power-to-transport technologies with other parts of the system, extensive research has been carried out in recent years with respect to various aspects of power-to-gas technologies, see e.g. Ref. [3].

> State-of the-art of power-to-gas is that the concept is defined mostly to boost hydrogen and/or green gas and green liquid fuel production within the limitations of the gas, transport and the electricity sectors, thus creating a paradigm in which solutions to the integration of fluctuating renewable energy should be found within these subsectors. Most research is carried out within these limits and the integration of the other sectors e.g. the heating sector is often overlooked. The idea of Smart Energy Systems is that better solutions can be found when the other sectors, especially the heating sectors is included.

3.3. State-of-the-art within the buildings sector: NZEB and savings

The design and importance of introducing low-energy buildings have been the subject of several papers and reports in the academic literature [96–99]. Concepts such as zero carbon [100] and zero emission and Zero Energy Buildings (ZEBs) [101] have been introduced. A ZEB combines savings, i.e. highly energy-efficient building designs, with on-site renewable energy generation such as mostly solar thermal or photo voltaic (PV) systems [102] and sometimes also heat pumps and even small micro cogeneration of heat and power (CHP) based on biomass. Efforts have been made to improve the performance of solar thermal among others by use of exergy analysis [103].

Since often a ZEB is connected to the ***electricity*** grid is has the option of exchanging electricity. This has led to the definition of a Net Zero Energy Building (NZEB) [2,104]. A NZEB exchange electricity in certain hours but on an annual basis the net exchange becomes zero. Such hourly mismatch between demand and production and how to deal with it have also been subject of discussion [105]. In Ref. [106], it is argued that on-grid NZEBs, which have little or even zero exchange of electricity with the electric grid, are both a very costly solution and sometimes even a counter-productive solution seen in the perspective of the overall energy system. The cost is higher and it will lead to a higher total energy demand and CO_2 emission if each NZEB is trying to adjust on its own compared to when they act as integrated units of the overall system.

With regard to the issue of heating and cooling, heat saving strategies have recently been described in a number of studies focusing on decarbonising the European heating and cooling sectors through a combination of heat savings and district heating [107] and by implementing energy efficiency in buildings across Europe [108,109]. Some studies focus on similar research areas, but on a national scale [41], while others focus on energy savings through improved efficiency in buildings across EU-27 [108]. These studies show that heat savings are vital if a future low-carbon energy system is to be achieved.

Several studies also conclude that heat savings cannot stand alone and that heat supply in the future will also be necessary through efficient heating technologies such as district heating [110] to avoid infeasible investments in building refurbishments [111]. Other studies find that NZEBs must be coordinated with the heat supply networks in order to integrate excess heat e.g. from solar thermal into the remaining energy system [112].

However, only few attempts of quantifying the balance between heat savings and heat supply have been developed so far and only for national systems such as Denmark [41] and the UK [113] or on an urban district scale [114]. These studies therefore only present single-country assessments and do not draw comparisons between multiple countries or comparisons between different methods.

> State-of the-art of buildings including NZEB is that the concept has a starting point defined within the limitations of the building sector and with a focus on new buildings. The predominant paradigm is that solutions for the integration of fluctuating renewable energy should be found within the individual buildings. Most research is carried out within these limits even though several attempts have been made to take a broader view of buildings as integrated units of electricity as well as heating and cooling infrastructures. The idea of Smart Energy Systems is that the best solutions cannot be found within these limits. One will have to provide a broader scientific understanding and concept.

3.4. State-of-the-art within the industrial sector

The transformation of the industrial sector into sustainable energy use is also posing a great challenge. Moreover, the expected changes are substantial. For example, the implementation of the European Union objectives to reduce greenhouse gas emissions by 80–95% in 2050 involves a suggested decrease within the industrial sector of between 83 and 87% [115,116].

State-of-the-art at present is to combine the following three main categories of technical options: Improved material efficiency; improved energy efficiency, and transforming into a less carbon-intensive energy supply or carbon capture and storage (CCS) [116,117].

Within improved material efficiency, the focus is to promote increased use of recycled materials and increased material efficiency. Such measures are central to the circular economy as promoted by the European Union [118] and they are highlighted as important in the Fifth Assessment Report by the Intergovernmental Panel on Climate Change (IPCC), but the resulting mitigation potential is not quantified [119].

Within energy efficiency, applying the best available technology in industry can reduce the energy intensity by an estimated 25% and through innovation by an additional 20% at the most before approaching technological limits in some energy intensive industries. [120] simulate a savings potential of 35% for industry globally by 2030 vs. frozen 2005 efficiency, a result which they note is in line with other studies.

In Ref. [116], the future potential for and the implications of electrifying the production of basic materials in the European Union are investigated. The production of steel, cement, glass, lime, petrochemicals, chlorine and ammonia required 125 TWh of electricity and 851 TWh of fossil fuels for energy purposes and 671 TWh of fossil fuels as feedstock in 2010. A complete shift of the energy demand as well as the resource base of feedstocks to electricity would result in an electricity demand of 1713 TWh, about 1200 TWh of which would be for producing hydrogen and hydrocarbons for feedstock and energy purposes. With increased material efficiency and some share of bio-based materials and biofuels, the electricity demand could be lower.

Most studies search for solutions within the industrial and electricity sectors based on replacing fossil fuels with electricity (which can then be supplied by renewable energy), and no studies so far have analysed the potential benefits of integrating the industrial sector with the heating and cooling sectors, nor as an active part for the integration of fluctuating sources in a smart energy system. However, in a recent study made by the Danish Society of Engineers, a first attempt has been made to estimate some of the benefits of integrating the industrial sector as an active component in the coherency of a smart energy system [67]. Such an integration involve utilizing industrial waste heat for district heating as well as covering cooling and low-temperature heat demands in industry using district heating and cooling. Moreover, the study estimates the potential demand for green gas versus green electricity depending on the specific needs. However, this study is only for the Danish industry (with a modest energy intensity compared to other countries) and does not explore the significant potential for making use of gas – and thermal storage capacities arising from such an integration of the industrial sector.

> State-of-the-art within industry shows relatively few studies compared to other sectors, especially the electricity sector. The few available studies focus on efficiency measures and the replacement of fossil fuels by electricity within the limits of the industrial and electricity sectors. No studies have quantified the synergies and benefits arising from a joint integration of industry with the heating, cooling and electricity sectors. The idea of Smart Energy Systems is that better solutions can be found when the other sectors are included.

4. Smart energy systems

As described in Section 3, the, scientific state-of-the-art is that solutions for the integration of renewable energy are in focus within the limits of energy sub-sectors based on concepts such as, e.g., *"smart grid"*, *"Zero energy buildings"* and *"Power-to-Heat"*, while until now the industrial sector and the heating and cooling sectors have been largely overlooked.

The concept of *smart energy systems* was introduced in order to identify the potential synergies between sub-sectors. As opposed to, for instance, the *smart grid* and similar concepts, which takes a sole focus on the sub-sector in question, *smart energy systems* include the entire energy system in its approach to identifying suitable energy infrastructure designs and operation strategies. The hypothesis is that the most effective and least-cost solutions are to be found when each sub-sector is combined with the other sectors.

One main point is that the analysis of individual technologies and sectors are contextual and, to do a proper analysis, 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.

4.1. Definition

In 2013, [5,6] made a formal definition of a smart energy system consisting of *"new technologies and infrastructures which create new forms of flexibility, primarily in the 'conversion' stage of the energy system. 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 built around three grid infrastructures:*

- ***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 the utilisation of thermal storage for creating additional flexibility and the recycling of heat losses in the energy system.*
- ***Smart Gas Grids*** *to connect the electricity, heating, and transport sectors. This enables the utilisation of gas storage for creating additional flexibility. If the gas is refined to a liquid fuel, then liquid fuel storages can also be utilised."*

Based on these fundamental infrastructures a Smart Energy Systems was given the following definition:

> A **Smart Energy System** is defined as an approach in which smart electricity, thermal and gas grids are combined with storage technologies 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 [5,6].

Several synergies can be achieved by 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 [5,6]:

- Excess heat from industry and electricity production can be used to heat buildings via district heating.
- Electricity for heating purposes makes it possible to use heat storage instead of electricity storage, which is both cheaper and more efficient as detailed further in the following. Moreover, it provides a more flexible CHP production.
- Heat pumps for heating can be used to provide cooling for district cooling networks and vice versa.
- Electricity for heating may be used for balancing power and electric grid services: for example, in regulating power markets.
- 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 as detailed further in the following.
- 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.

4.2. Energy system analysis modelling aspects

Simulation and design of smart energy systems calls for tools and models that extend across all parts of the energy system with focus on electricity, heating, cooling and transportation and thus across infrastructures connected by electric, thermal and gas grids. Secondly, due to the exploitation of fluctuating renewable energy sources, tools appropriate for simulation and design of smart energy systems must have a high temporal resolution while also being able to model across seasons to account for seasonal variations and properly reflect the utilisation of storage. Especially with regard to the analysis of energy storage, it is important that models and tools have the option of including different types or storage representing different energy carriers such as electricity, hydrogen, hot and cold water, green gas, and green liquid fuels. Furthermore, it is important that the tools and models can calculate the input, output, and contents of each storage option chronologically, for each step of the calculation period.

Connolly et al. have investigated a wide range of energy system models that could analyse the large-scale integration of renewable energy. In total, 37 different energy models are included in the study, but due to various limitations, many of these cannot be used to evaluate the Smart Energy System concept. Primarily, this is due to the traditional ‘single-sector’ approach especially towards the electricity sector. Out of the 37 energy models considered, only 10 stated that they include all sectors of the energy system, defined as electricity, heating, and transport. Seven of these models considered all sectors, but they analysed the energy system on an annual basis over long-term time horizons such as multiple decades. Therefore, these tools are not suitable for analysing the integration of intermittent renewable energy and various energy storages, since they cannot consider the short-term changes. Out of the three remaining models, only EnergyPLAN (www.EnergyPLAN.eu) uses an hourly time-step over the entire analyses while the others use sample periods such as typical days. This is an improvement on annual energy models, but again it is not ideal when analysing the benefits of cross-sectoral links to intermittent renewable energy. Therefore, EnergyPLAN is used here as one example of how the Smart Energy System can be analysed since it is identified as one that is both holistic and has a one hour temporal resolution over a complete one year period [121]. In EnergyPLAN, conversion between different energy carriers and the integration between sectors are two of the core characteristics. Here it thus serves as an example of the kind of tool required for smart energy system simulation and design.

EnergyPLAN is not an endogenous investment optimization model but provides a framework for simulating alternative user-defined scenarios or user-defined investment strategies for the energy system. Analyses may be performed from a technical optimization perspective where the model simulates optimal behaviour of dispatchable units (i.e. conversion units, storages and demand that may be controlled) with respect to energy efficiency and the systems load-following capability. Systems may also be simulated from a business-economic perspective, where units are dispatched according to short-term marginal costs, taking an external electricity market into account. While the latter approach relies on valid system costs and market prices for simulation results to reliably reflect system operation, the former approach is influenced by technical energy unit characteristics. The latter is thus an appropriate approach for the more explorative analyses that extend beyond the known market and costs structures. It may also form a part of the an analytical approach where first technical feasibility is established and afterwards, appropriate markets and institutions are designed to move towards the preferred technical solution [37,40,92,122,123].

In regards to cross-sector integration, units are included that enable the conversion between a number of relevant energy carriers and energy sources including electricity, heating, cooling, hydrogen, synthetic gases/fuels and biofuels. This includes well-established technologies like CHP units, compression heat pumps and absorption heat pumps as well as electrolysers and other more novel technologies for the production of synthetic fuels/electrofuels. To ensure that proper technical feasibility may be assessed, hourly balances for all energy carriers are provided, including electricity, heating, cooling, hydrogen, and gas including natural gas, biogas, biomass gasification, and synthetic/electro gas. EnergyPLAN enables the user to assess the balance through a number of metrics including e.g. import, export, excess production, and production on condensing mode power stations and boilers [124].

EnergyPLAN has been applied in more than 100 journal articles [125], and is thus a well-established tool. The majority of these articles deal with integrating the various sectors, but there are also articles with single-sector focus. Published analyses range from urban systems to multi-country studies with a prevalence of studies on the national level aiming to assist in the design of long-term energy strategies.

4.3. A holistic approach to the storage aspects

Treating and simulating the energy system as an integrated entity rather than as a series of distinct and separate sectors, provides possibilities for flexibility that will assist in the integration of fluctuating renewable energy sources. Where an electricity sector-specific analysis of renewable energy systems thus frequently calls for significant storage capacity, more holistic energy system analyses results in less demand for electricity storage. Apart from the additional flexibility provided by dispatchable conversions between energy carriers and between different parts of the energy system, a cross-sectoral smart energy system approach also enables the utilization of storage options within heating, cooling and synthetic fuels which are less costly and more efficient than electricity storage [49]. While round-trip efficiencies back to electricity would be prohibitively low, this is inconsequential: the intention by using these storages is not to convert back to electricity, but mainly to form a very flexible electricity demand that also caters for demands within heating, cooling, industry, and transport in the future. It is possible or even likely, that electricity storage cannot be avoided altogether, however by using the efficient and low-cost options elsewhere in the energy systems, electricity storage requirements may me significantly reduced.

4.4. Smart energy Europe and country studies

The smart energy systems concept and approach has been used in cases both at the European level [55] as well as at the country level [67].

The report "IDA's Energy Vision 2050 - A smart energy system strategy for 100% renewable Denmark" [67] is a case from 2015 of using the approach at the country level. The report refers to the long-term goal supported by several consecutive Danish governments to have an energy supply in Denmark by 2050 based on 100% renewable energy. The Danish Society of Engineers (IDA) define the IDA Energy Vision 2050 as an input in the debate on how to implement this goal in the best way. The IDA Energy Vision 2050 shows that *"a conversion to 100% renewable energy is a technical option within economic reach; that an integrated Smart Energy System design can create a more robust and resilient system; and that there is a potential for creating more jobs than in a fossil fuel based energy system as well as lower health related costs due to a reduction in emissions from the energy supply"*.

The IDA Energy Vision 2050 is explicitly based on the Smart Energy Systems concept. It designs a scenario and a roadmap to implement a 100% renewable energy system in 2050, called "IDA 2050". When performing the economic and environmental assessments, this scenario is compared to two reference scenarios published by the Danish Energy Agency (DEA). The one, called the "DEA Fossil 2050" scenario represents a Business as Usual scenario based on fossil fuels while the other, called "DEA Wind 2050", representing one way of implementing the 2050 goals of 100% renewable energy. The "DEA Wind 2050" solutions represent what is often in Denmark considered the consensus solution.

The IDA Energy Vision follow two previous energy strategies from IDA, namely the "IDA Energy Plan 2030" from 2006 [126] and the "IDA Climate Plan 2050" from 2009 [127]. All three have provided important inputs to Danish energy policy. The IDA Energy Vision 2050 shows that a 100% renewable energy system is technically and physically possible for Denmark as well as economically feasible compared to the alternative fossil fuel energy system.

By use of the smart energy systems concept, IDA's Energy Vision identifies a cross-sectoral integrated energy system in which a 100% renewable energy supply may be reached for all sectors by combining thermal, gas and liquid fuel storage capacities along with a limited use of electricity storage, which is primarily in connection to electric vehicles in the transport sector. By use of the EnergyPLAN model all storage and energy balances are accounted for at an hourly level throughout the entire year.

The report and paper "Smart Energy Europe: The technical and economic impact of one potential 100% renewable energy scenario for the European Union" [55] is a case study that applies the same smart energy systems principles to the European level. The study puts forward one potential way of transforming the European energy system into 100% renewable energy by the year 2050. The study is based on the smart energy systems concept and includes the complete energy system (i.e. electricity, heating, cooling, industry, and transport). Based on the use of this concept the transition is highlighted in nine steps. The corresponding impact of each step is quantified in terms of primary energy supply, carbon emissions and total annual socio-economic cost.

The results *"indicate that to reach the EU targets of 80% less CO_2 in 2050 compared to 1990 levels, the total annual cost of the EU energy system will be approximately 3% higher than the fossil fuel alternative, and 12% higher to reach a 100% renewable energy system. However, considering the uncertainties in relation to many of the cost assumptions for the year 2050, these differences could be considered negligible."* However, more importantly, the general cost structure may shift. Due to the many investments in energy efficiency and renewable energy sources major cost will be converted from imported fuel into investments in Europe. The total number of additional direct jobs from this transition is estimated in the paper at approximately 10 million. This could result in an overall gain for the EU economy in the *Smart Energy Europe* scenario, even though it is more costly to produce the energy.

The final *Smart Energy Europe* scenario in Ref. [55] ends up with no fossil fuel usage, no energy imports, and no carbon dioxide emissions (<1% of the reference). The key technological changes are: wind power, solar power, electric vehicles, heat savings, individual heat pumps, district heating, large-scale thermal storage, biomass gasification, carbon capture and recovery, electrolysers, chemical synthesis, and fuel storage (i.e. for electrofuels). Many of these technologies are already sufficiently mature to be implemented today, especially those in the electricity and heat sectors.

The study considers itself as an option for debate rather than a final solution. It is highlighted that additional steps exists which could be implemented to reduce the cost, such as increasing the sustainable biomass limit. However, this was beyond the scope of the study [40]. Based on existing policies, the EU energy system is likely to be somewhere between the *Smart Energy Europe* scenario proposed in the study and where it is today. The results suggest that the progress towards a 100% renewable energy system will most likely be defined by political desire and society's ability to implement suitable technologies, rather than the availability of cost-effective solutions.

Both cases illustrate how an integrated approach based on the smart energy systems concept lead to the identification of suitable cross-sectoral storage and infrastructure solutions.

5. Conclusion

Typically, the *scientific state-of-the-art* is that solutions for the integration of renewable energy are searched for within the limits of individual energy sub-sectors based on concepts such as *"smart grid"*, *"Zero energy buildings"* and *"Power-to-Heat"*, while until now the industrial sector and the heating and cooling sectors have largely been overlooked.

A literature review reveals a steep increase in the use of the term *Smart Energy Systems* in scientific literature since it was first mentioned in 2009. In recent years, the term has been used mostly to express a holistic systems approach as opposed to a single sector approach while previously it has also been used synonymously with Smart Grid. Especially within the cross-sectoral understanding of the concept the use has increased significantly in recent years. Essential for the increase is that the understanding of the *smart energy systems* concept includes all sectors and takes a cross-sectoral integration aspect.

The *idea* of the Smart Energy Systems concept is to provide the scientific basis for a paradigm shift away from single-sector thinking to a coherent smart energy systems understanding of how to design, analyse and discuss the benefits of including all sectors and infrastructures.

The *hypothesis* of the *Smart Energy Systems* concept is that the most feasible least-cost strategies cannot be found within the limits of the individual sub-sectors. One has to put each of the sub-sectors into the coherency of an overall energy system looking for synergies between the individual sub-sectors in order to be able to identify the best options. Especially with regard to the design of suitable storage and infrastructure, the *Smart Energy Systems* approach has the potential to identify more efficient and affordable solutions.

This paper describes how the concept of Smart Energy Systems represent a radical shift in approach and understanding of how to design achievable and affordable solutions during the transition to future renewable and sustainable energy systems. This shift influences the design of studies and the use of tools, methodologies and modelling as well as the results in terms of the need for storage and infrastructures.

Case studies at the country and European level illustrate how a Smart Energy Systems approach can lead to the identification of future Sustainable and 100% Renewable Energy Solutions with a focus on holistic, integrated and affordable solutions to the storage and infrastructure needs.

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References

[1] Amin SM, Wollenberg BF. Towards a smart grid. Power Energy Mag IEEE 2005;3:34–41. http://dx.doi.org/10.1109/MPAE.2005.1507024.
[2] Mohamed A, Hasan A, Sirén K. Fulfillment of net-zero energy building (NZEB) with four metrics in a single family house with different heating alternatives. Appl Energy 2014;114:385–99. http://dx.doi.org/10.1016/j.apenergy.2013.09.065.
[3] Gahleitner G. Hydrogen from renewable electricity: an international review of power-to-gas pilot plants for stationary applications. Int J Hydrogen Energy 2013;38:2039–61. http://dx.doi.org/10.1016/j.ijhydene.2012.12.010.
[4] 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. http://dx.doi.org/10.1016/j.energy.2012.04.003.
[5] Lund H. Renewable energy systems - a smart energy systems approach to the choice and modeling of 100% renewable solutions. second ed. Academic Press; 2014.
[6] Connolly D, Lund H, Mathiesen BV, Østergaard PA, Möller B, Nielsen S, et al. Smart energy systems: holistic and integrated energy systems for the era of 100% renewable energy. Aalborg: Aalborg University; 2013.
[7] Mendes G, Ioakimidis C, Ferrão P. On the planning and analysis of Integrated Community Energy Systems: a review and survey of available tools. Renew Sustain Energy Rev 2011;15:4836–54. http://dx.doi.org/10.1016/j.rser.2011.07.067.
[8] Qadri MT, Khan MNI. Totally integrated smart energy system through data acquisition via remote location. World Acad Sci Eng Technol 2009:38.
[9] Crossley P, Beviz A. Smart energy systems: transitioning renewables onto the grid. Renew Energy Focus 2010:11. http://dx.doi.org/10.1016/S1755-0084(10)70118-6.
[10] Cummings ML, Thornburg KM. Paying attention to the man behind the curtain. IEEE Pervasive Comput 2011:10. http://dx.doi.org/10.1109/MPRV.2011.7.
[11] Simonov M, Mussetta M, Grimaccia F, Leva S, Zich RE. Artificial intelligence forecast of PV plant production for integration in smart energy systems. Int Rev Electr Eng 2012:7.
[12] Mrazovac B, Bjelica M, Kukolj D, Todorovic B, Samardzija D. A human detection method for residential smart energy systems based on Zigbee RSSI changes. IEEE Trans Consum Electron 2012:58. http://dx.doi.org/10.1109/TCE.2012.6311323.
[13] Storage battery systems for smart community. Furukawa Rev; 2013.
[14] Volkova IO, Gubko MV, Salnikova EA. Active consumer: optimization problems of power consumption and self-generation. Autom Remote Control 2014:75. http://dx.doi.org/10.1134/S0005117914030114.
[15] Naumann A, Bielchev I, Voropai N, Styczynski Z. Smart grid automation using IEC 61850 and CIM standards. Control Eng Pract 2014:25. http://dx.doi.org/10.1016/j.conengprac.2013.12.001.
[16] Hammer S, Wißner M, André E. Trust-based decision-making for smart and adaptive environments. User Model User-Adapt Interact 2015:25. http://dx.doi.org/10.1007/s11257-015-9160-8.
[17] Sytnikov VE, Bemert SE, Krivetsky IV, Karpov VN, Romashov MA, Shakarian YG, et al. The test results of AC and DC HTS cables in Russia. IEEE Trans Appl Supercond 2016:26. http://dx.doi.org/10.1109/TASC.2016.2535150.
[18] Sytnikov VE, Bemert SE, Krivetsky IV, Romashov MA, Popov DA, Fedotov EV, et al. The creation of high-temperature superconducting cables of megawatt range in Russia. Phys A. T Nucl 2015:78. http://dx.doi.org/10.1134/S1063778815140112.
[19] Halvgaard R, Vandenberghe L, Poulsen NK, Madsen H, JÃ,rgensen JB. Distributed model predictive control for smart energy systems. IEEE Trans Smart Grid 2016:7. http://dx.doi.org/10.1109/TSG.2016.2526077.
[20] Derakhshan G, Shayanfar HA, Kazemi A. The optimization of demand response programs in smart grids. Energy Policy 2016:94. http://dx.doi.org/10.1016/j.enpol.2016.04.009.
[21] Bulkeley H, McGuirk PM, Dowling R. Making a smart city for the smart grid? The urban material politics of actualising smart electricity networks. Environ Plan A 2016:48. http://dx.doi.org/10.1177/0308518X16648152.
[22] Babonneau F, Caramanis M, Haurie A. A linear programming model for power distribution with demand response and variable renewable energy. Appl Energy 2016:181. http://dx.doi.org/10.1016/j.apenergy.2016.08.028.
[23] Alamaniotis M, Bargiotas D, Tsoukalas LH. Towards smart energy systems: application of kernel machine regression for medium term electricity load forecasting. Springerplus 2016:5. http://dx.doi.org/10.1186/s40064-016-1665-z.
[24] Miller WJ. Internet of things (IoT) for smart energy systems. 2016. http://dx.doi.org/10.1016/B978-0-12-805343-0.00011-5.
[25] Jafari-Marandi R, Hu M, Chowdhury S. A system of system approach for smart complex energy system operation decision. In: Int Des Eng Tech Conf Comput Inf Eng ConfVol 1B; 2015. http://dx.doi.org/10.1115/DETC2015-47415. p. V01BT02A044.
[26] Amft O, Medland R, Foth M, Petkov P, Abreu J, Pereira FC, et al. Smart energy systems. IEEE Pervasive Comput 2011;(10):63–5. http://dx.doi.org/10.1109/MPRV.2011.10.
[27] Bohlig B. ZigBee meets ip. Sensors (Peterborough, NH). 2009. p. 26.
[28] Saito K, Jeong J. Development of general purpose energy system simulator. Energy Procedia 2012;14:1595–600. http://dx.doi.org/10.1016/j.egypro.2011.12.887.
[29] Aduda K, Thomassen T, Zeiler W, Labeodan T, Boxem G, van der Velden J, et al. The human in the loop: an approach to individualize smart process control. Procedia Environ Sci 2014;22:302–12. http://dx.doi.org/10.1016/j.proenv.2014.11.029.
[30] Bulut MB, Odlare M, Stigson P, Wallin F, Vassileva I. Buildings in the future energy system - perspectives of the Swedish energy and buildings sectors on current energy challenges. Energy Build 2015:107. http://dx.doi.org/10.1016/j.enbuild.2015.08.027.
[31] Nasiakou A, Vavalis M, Zimeris D. Smart energy for smart irrigation. Comput Electron Agric 2016:129. http://dx.doi.org/10.1016/j.compag.2016.09.008.
[32] Halvgaard R, Bacher P, Perers B, Andersen E, Furbo S, J??rgensen JB, et al. Model predictive control for a smart solar tank based on weather and consumption forecasts. Energy Procedia 2012;30:270–8. http://dx.doi.org/10.1016/j.egypro.2012.11.032.
[33] Yun J, Kim J. Deployment support for sensor networks in indoor climate monitoring. Int J Distrib Sens Netw 2013:2013. http://dx.doi.org/10.1155/2013/875802.
[34] Van Pruissen O, Van Der Togt A, Werkman E. Energy efficiency comparison of a centralized and a multi-agent market based heating system in a field test. Energy Procedia 2014;62:170–9. http://dx.doi.org/10.1016/j.egypro.2014.12.378.
[35] Ooka R, Ikeda S. A review on optimization techniques for active thermal energy storage control. Energy Build 2015:106. http://dx.doi.org/10.1016/j.enbuild.2015.07.031.
[36] Naus J, Van Vliet BJM, Hendriksen A. Households as change agents in a Dutch smart energy transition: on power, privacy and participation. Energy Res Soc Sci 2015:9. http://dx.doi.org/10.1016/j.erss.2015.08.025.
[37] Hvelplund F, Möller B, Sperling K. Local ownership, smart energy systems and better wind power economy. Energy Strateg Rev 2013;1:164–70. http://dx.doi.org/10.1016/j.esr.2013.02.001.
[38] Batas Bjelić I, Rajaković N, Ćosić B, Duić N. Increasing wind power penetration into the existing Serbian energy system. Energy 2013;57:30–7. http://dx.doi.org/10.1016/j.energy.2013.03.043.
[39] Connolly D, Mathiesen BV. A technical and economic analysis of one potential pathway to a 100% renewable energy system. Int J Sustain Energy Plan Manag 2014;1:7–28. http://dx.doi.org/10.5278/ijsepm.2014.1.2.
[40] Meyer NI, Mathiesen BV, Hvelplund F. Barriers and potential solutions for energy renovation of buildings in Denmark. Int J Sustain Energy Plan Manag 2014:1. http://dx.doi.org/10.5278/ijsepm.2014.1.5.
[41] Lund H, Thellufsen JZ, Aggerholm S, Wichtten KB, Nielsen S, Mathiesen BV, et al. Heat saving strategies in sustainable smart energy systems. Int J Sustain Energy Plan Manag 2014;4:3–16. http://dx.doi.org/10.5278/ijsepm.2014.4.2.
[42] Lund H, Werner S, Wiltshire R, Svendsen S, Thorsen JE, Hvelplund F, et al. 4th Generation District Heating (4GDH). Integrating smart thermal grids into

future sustainable energy systems. Energy 2014;68:1–11. http://dx.doi.org/10.1016/j.energy.2014.02.089.
[43] Lund R, Mathiesen BV. Large combined heat and power plants in sustainable energy systems. Appl Energy 2015;142:389–95. http://dx.doi.org/10.1016/j.apenergy.2015.01.013.
[44] Mathiesen BV, Lund H, Connolly D, Wenzel H, Østergaard PA, Möller B, et al. Smart Energy Systems for coherent 100% renewable energy and transport solutions. Appl Energy 2015;145:139–54. http://dx.doi.org/10.1016/j.apenergy.2015.01.075.
[45] Duić N. Is the success of clean energy guaranteed? Clean Technol Environ Policy 2015:17. http://dx.doi.org/10.1007/s10098-015-0969-y.
[46] Blaauwbroek N, Nguyen PH, Konsman MJ, Shi H, Kamphuis RIG, Kling WL. Decentralized resource allocation and load scheduling for multicommodity smart energy systems. IEEE Trans Sustain Energy 2015:6. http://dx.doi.org/10.1109/TSTE.2015.2441107.
[47] Kipping A, Trømborg E. Hourly electricity consumption in Norwegian households - assessing the impacts of different heating systems. Energy 2015:93. http://dx.doi.org/10.1016/j.energy.2015.09.013.
[48] Prina MG, Cozzini M, Garegnani G, Moser D, Oberegger UF, Vaccaro R, et al. Smart energy systems applied at urban level: the case of the municipality of Bressanone-Brixen. Int J Sustain Energy Plan Manag 2016:10. http://dx.doi.org/10.5278/ijsepm.2016.10.3.
[49] Lund H, Østergaard PA, Connolly D, Ridjan I, Mathiesen BV, Hvelplund F, et al. Energy storage and smart energy systems. Int J Sustain Energy Plan Manag 2016:11. http://dx.doi.org/10.5278/ijsepm.2016.11.2.
[50] Østergaard PA, Lund H, Mathiesen BV. Smart energy systems and 4th generation district heating. Int J Sustain Energy Plan Manag 2016;10:1–2. http://dx.doi.org/10.5278/ijsepm.2016.10.1.
[51] Thorsen JE, Cudmundsson O, Brand M, Funder-Kristensen T. Electric and thermal energy flexibility: utilizing excess heat from a supermarket refrigeration system in a district heating grid. Euroheat Power (English Ed 2016:13.
[52] Lunde M, Røpke I, Heiskanen E. Smart grid: hope or hype? Energy Effic 2016:9. http://dx.doi.org/10.1007/s12053-015-9385-8.
[53] Shi H, Blaauwbroek N, Nguyen PH, Kamphuis RIG. Energy management in multi-commodity smart energy systems with a greedy approach. Appl Energy 2016:167. http://dx.doi.org/10.1016/j.apenergy.2015.11.101.
[54] Lund R, Mohammadi S. Choice of insulation standard for pipe networks in 4th generation district heating systems. Appl Therm Eng 2016:98. http://dx.doi.org/10.1016/j.applthermaleng.2015.12.015.
[55] Connolly D, Lund H, Mathiesen BV. Smart Energy Europe: the technical and economic impact of one potential 100% renewable energy scenario for the European Union. Renew Sustain Energy Rev 2016;60:1634–53. http://dx.doi.org/10.1016/j.rser.2016.02.025.
[56] Nastasi B, Lo Basso G. Hydrogen to link heat and electricity in the transition towards future Smart Energy Systems. Energy 2016;110:5–22. http://dx.doi.org/10.1016/j.energy.2016.03.097.
[57] Lythcke-Jørgensen C, Ensinas AV, Münster M, Haglind F. A methodology for designing flexible multi-generation systems. Energy 2016;110:34–54. http://dx.doi.org/10.1016/j.energy.2016.01.084.
[58] Dumas PA. European perspective of the development of deep geothermal in urban areas: smart thermal grids, geothermal integration into smart cities. Geomech Und Tunnelbau 2016:9. http://dx.doi.org/10.1002/geot.201600030.
[59] Withanage C, Hölttä-Otto K, Otto K, Wood K. Design for sustainable use of appliances: a framework based on user behavior observations. J Mech Des Trans ASME 2016:138. http://dx.doi.org/10.1115/1.4034084.
[60] Noppers EH, Keizer K, Milovanovic M, Steg L. The importance of instrumental, symbolic, and environmental attributes for the adoption of smart energy systems. Energy Policy 2016:98. http://dx.doi.org/10.1016/j.enpol.2016.08.007.
[61] Grundahl L, Nielsen S, Lund H, Möller B. Comparison of district heating expansion potential based on consumer-economy or socio-economy. Energy 2016;115:1771–8. http://dx.doi.org/10.1016/j.energy.2016.05.094.
[62] Markovska N, Duić N, Mathiesen BV, Guzović Z, Piacentino A, Schlör H, et al. Addressing the main challenges of energy security in the twenty-first century – contributions of the conferences on Sustainable Development of Energy. Water Environ Syst Energy 2016;115(Part 3):1504–12. http://dx.doi.org/10.1016/j.energy.2016.10.086.
[63] Maier S. Smart energy systems for smart city districts: case study Reininghaus District. Energy Sustain Soc 2016;6:23. http://dx.doi.org/10.1186/s13705-016-0085-9.
[64] van der Werff E, Steg L. The psychology of participation and interest in smart energy systems: comparing the value-belief-norm theory and the value-identity-personal norm model. Energy Res Soc Sci 2016;22:107–14. http://dx.doi.org/10.1016/j.erss.2016.08.022.
[65] Dominković DF, Bačeković I, Ćosić B, Krajačić G, Pukšec T, Duić N, et al. Zero carbon energy system of south east Europe in 2050. Appl Energy 2016:184. http://dx.doi.org/10.1016/j.apenergy.2016.03.046.
[66] Gerboni R, Grosso D. Testing future hydrogen penetration at local scale through an optimisation tool. Int J Hydrogen Energy 2016:41. http://dx.doi.org/10.1016/j.ijhydene.2016.10.094.
[67] Mathiesen BV, Lund H, Hansen K, Ridjan I, Djørup S, Nielsen S, et al. IDA's energy vision 2050. A smart energy system strategy for 100% renewable. Denmark. Aalborg. 2015.
[68] Lund H. Renewable energy systems: the choice and modeling of 100% renewable solutions. Chem Eng Trans 2014;39:1–6. http://dx.doi.org/10.3303/CET1439001.
[69] Pickard WF. Smart grids versus the achilles' heel of renewable energy: can the needed storage infrastructure be constructed before the fossil fuel runs out? Proc IEEE 2014:102. http://dx.doi.org/10.1109/JPROC.2014.2316359.
[70] Balta-Ozkan N, Boteler B, Amerighi O. European smart home market development: public views on technical and economic aspects across the United Kingdom, Germany and Italy. Energy Res Soc Sci 2014;3:65–77. http://dx.doi.org/10.1016/j.erss.2014.07.007.
[71] Lund PD, Mikkola J, Ypyä J. Smart energy system design for large clean power schemes in urban areas. J Clean Prod 2014;103:437–45. http://dx.doi.org/10.1016/j.jclepro.2014.06.005.
[72] Hu M-C, Wu C-Y, Shih T. Creating a new socio-technical regime in China: evidence from the Sino-Singapore tianjin eco-city. Futures 2015:70. http://dx.doi.org/10.1016/j.futures.2015.04.001.
[73] Zakeri B, Rinne S, Syri S. Wind integration into energy systems with a high share of nuclear power-what are the compromises? Energies 2015:8. http://dx.doi.org/10.3390/en8042493.
[74] Söder L. Simplified analysis of balancing challenges in sustainable and smart energy systems with 100% renewable power supply. Wiley Interdiscip Rev Energy Environ 2016:5. http://dx.doi.org/10.1002/wene.194.
[75] Rosager F, Lund H. Analyse af eloverløbs- og elkvalitetsproblemer. 1986.
[76] Lund H. Implementaring af bæredygtige energisystemer (Implementation of sustainable energy systems). PhD dissertation. Aalborg University; 1990.
[77] Illum K, Lund H. LOCUS-systems: local cogeneration utility systems for efficient utilization of windpower, Rome: European wind energy conference (7–9 October 1986); 1986, p. 329–331.
[78] El-khattam W, Hegazy YG, Salama MM. An integrated distributed generation optimization model for distribution system planning. Power Syst IEEE Trans 2005;(20):1158–65. http://dx.doi.org/10.1109/TPWRS.2005.846114.
[79] Lund H, Kempton W. Integration of renewable energy into the transport and electricity sectors through V2G. Energy Policy 2008;36:3578–87. http://dx.doi.org/10.1016/j.enpol.2008.06.007.
[80] Jiayi H, Chuanwen J, Rong X. A review on distributed energy resources and MicroGrid. Renew Sustain Energy Rev 2008;12:2465–76. http://dx.doi.org/10.1016/j.rser.2007.06.004.
[81] Østergaard PA, Lund H. A renewable energy system in Frederikshavn using low-temperature geothermal energy for district heating. Appl Energy 2011;88:479–87. http://dx.doi.org/10.1016/j.apenergy.2010.03.018.
[82] Alberg Østergaard P, Mathiesen BV, Möller B, Lund H. A renewable energy scenario for Aalborg Municipality based on low-temperature geothermal heat, wind power and biomass. Energy 2010;35:4892–901. http://dx.doi.org/10.1016/j.energy.2010.08.041.
[83] Lund H, Østergaard PA. Sustainable towns: the case of Frederikshavn – 100% renewable energy. In: Clark WW, editor. Sustain. Communities. New York, USA: Springer New York; 2010. p. 155–68. http://dx.doi.org/10.1007/978-1-4419-0219-1_11.
[84] Østergaard PA, Lund H. Climate change mitigation from a bottom-up community approach. In: Clark WW, editor. Sustain. communities des. handb. Amsterdam: Elsevier Butterworth-Heinemann; 2010. p. 247–65. http://dx.doi.org/10.1016/B978-1-85617-804-4.00014-8.
[85] Orecchini F, Santiangeli A. Beyond smart grids – the need of intelligent energy networks for a higher global efficiency through energy vectors integration. Int J Hydrogen Energy 2011;36:8126–33. http://dx.doi.org/10.1016/j.ijhydene.2011.01.160.
[86] Wu YN, Chen J, Liu LR. Construction of Chinas smart grid information system analysis. Renew Sustain Energy Rev 2011;15:4236–41. http://dx.doi.org/10.1016/j.rser.2011.07.129.
[87] Ahn C, Li CT, Peng H. Optimal decentralized charging control algorithm for electrified vehicles connected to smart grid. J Power Sources 2011;196:10369–79. http://dx.doi.org/10.1016/j.jpowsour.2011.06.093.
[88] Kempton W, Tomić J. Vehicle-to-grid power implementation: from stabilizing the grid to supporting large-scale renewable energy. J Power Sources 2005;144:280–94. http://dx.doi.org/10.1016/j.jpowsour.2004.12.022.
[89] Pina A, Ioakimidis CS, Ferrão P. Introduction of electric vehicles in an island as a driver to increase renewable energy penetration. In: 2008 IEEE Int. Conf. Sustain. Energy Technol. ICSET; 2008. p. 1108–13. http://dx.doi.org/10.1109/ICSET.2008.4747172.
[90] Mathiesen BV, Lund H, Norgaard P. Integrated transport and renewable energy systems. Util Policy 2008;16:107–16. http://dx.doi.org/10.1016/j.jup.2007.11.007.
[91] Fresco LO, Dijk D, de Ridder W. Biomass, food & sustainability: is there a dilemma?. 2007.
[92] Lund H, Mathiesen BVV, Hvelplund FKK, Østergaard PAA, Christensen P, Connolly D, et al. Coherent energy and environmental system analysis. Aalborg. 2011.
[93] Ridjan I. Integrated electrofuel and renewable energy systems. 2015. p. 136.
[94] Ridjan I, Mathiesen BV, Connolly D. Terminology used for renewable liquid and gaseous fuels based on the conversion of electricity: a review. J Clean Prod 2016;112:3709–20. http://dx.doi.org/10.1016/j.jclepro.2015.05.117.
[95] Connolly D, Mathiesen BV, Ridjan I. A comparison between renewable transport fuels that can supplement or replace biofuels in a 100% renewable energy system. Energy 2014;73:110–25. http://dx.doi.org/10.1016/j.energy.2014.05.104.
[96] Abel E. Low-energy buildings. Energy Build 1994;21:169–74. http://

dx.doi.org/10.1016/0378-7788(94)90032-9.
[97] Thomsen KE, Schultz JM, Poel B. Measured performance of 12 demonstration projects—IEA Task 13 "advanced solar low energy buildings. Energy Build 2005;37:111–9. http://dx.doi.org/10.1016/j.enbuild.2004.01.036.
[98] Heiselberg P, Brohus H, Hesselholt A, Rasmussen H, Seinre E, Thomas S. Application of sensitivity analysis in design of sustainable buildings. Renew Energy 2009;34:2030–6. http://dx.doi.org/10.1016/j.renene.2009.02.016.
[99] Deng S, Wang RZ, Dai YJ. How to evaluate performance of net zero energy building - a literature research. Energy 2014;71:1–16. http://dx.doi.org/10.1016/j.energy.2014.05.007.
[100] Webb R. Towards zero-carbon buildings. Refocus 2001;2:28–31. http://dx.doi.org/10.1016/S1471-0846(01)80046-9.
[101] Marszal AJ, Heiselberg P. Zero Energy Building (ZEB) definitions – a literature review. Aalborg Univ; 2009.
[102] Torcellini PA, Crawley DB. Understanding zero-energy buildings. ASHRAE J 2006:48.
[103] Kalogirou SA, Karellas S, Badescu V, Braimakis K. Exergy analysis on solar thermal systems: a better understanding of their sustainability. Renew Energy 2015:1–6. http://dx.doi.org/10.1016/j.renene.2015.05.037.
[104] Hu M, Weir JD, Wu T. Decentralized operation strategies for an integrated building energy system using a memetic algorithm. Eur J Oper Res 2012;217: 185–97. http://dx.doi.org/10.1016/j.ejor.2011.09.008.
[105] Khouzam KY. The load matching approach to sizing photovoltaic systems with short-term energy storage. Sol Energy 1994;53:403–9. http://dx.doi.org/10.1016/0038-092X(94)90055-8.
[106] Lund H. Marszal a., Heiselberg P. Zero energy buildings and mismatch compensation factors. Energy Build 2011;43:1646–54. http://dx.doi.org/10.1016/j.enbuild.2011.03.006.
[107] Persson U, Möller B, Werner S. Heat Roadmap Europe: identifying strategic heat synergy regions. Energy Policy 2014;74:663–81. http://dx.doi.org/10.1016/j.enpol.2014.07.015.
[108] Broin EÓ, Mata É, Göransson A, Johnsson F. The effect of improved efficiency on energy savings in EU-27 buildings. Energy 2013;57:134–48. http://dx.doi.org/10.1016/j.energy.2013.01.016.
[109] Alev Ü, Eskola L, Arumägi E, Jokisalo J, Donarelli A, Siren K, et al. Renovation alternatives to improve energy performance of historic rural houses in the Baltic Sea region. Energy Build 2014;77:58–66. http://dx.doi.org/10.1016/j.enbuild.2014.03.049.
[110] Lund H, Möller B, Mathiesen BV, Dyrelund A. The role of district heating in future renewable energy systems. Energy 2010;35:1381–90. http://dx.doi.org/10.1016/j.energy.2009.11.023.
[111] Popescu D, Ungureanu F, Hernández-Guerrero A. Simulation models for the analysis of space heat consumption of buildings. Energy 2009;34:1447–53. http://dx.doi.org/10.1016/j.energy.2009.05.035.
[112] Nielsen S, Möller B. Excess heat production of future net zero energy buildings within district heating areas in Denmark. Energy 2012;48:23–31. http://dx.doi.org/10.1016/j.energy.2012.04.012.
[113] Wilson IAG, Rennie AJR, Ding Y, Eames PC, Hall PJ, Kelly NJ. Historical daily gas and electrical energy flows through Great Britain's transmission networks and the decarbonisation of domestic heat. Energy Policy 2013;61: 301–5. http://dx.doi.org/10.1016/j.enpol.2013.05.110.
[114] Best RE, Flager F, Lepech MD. Modeling and optimization of building mix and energy supply technology for urban districts. Appl Energy 2015;159:161–77. http://dx.doi.org/10.1016/j.apenergy.2015.08.076.
[115] European Commission. COM(2011) 112 Final. Communication from the commision: a Roadmap for moving to a competitive low carbon economy in 2050, vol. 34; 2011. p. 1–34. http://dx.doi.org/10.1002/jsc.572.
[116] Aahman M, Nilsson L. Decarbonising industry in the EU - climate, trade and industrial policy strategies. In: Oberthur S, Dupont C, editors. Decarbonisation in the European Union: internal policies and external strategies. Palgrave Macmillan; 2015. p. 92–114.
[117] Edenhofer O, Pichs-Madruga R, Sokona Y, Minx JC, Farahani E, Susanne K, et al. Climate change 2014: mitigation of climate change. 2014. http://dx.doi.org/10.1017/CBO9781107415416.
[118] EU Commission. Towards a circular economy: a zero waste programme for Europe. 2014. http://dx.doi.org/10.1017/CBO9781107415324.004.
[119] IPCC. Climate change 2013-the physical science basis. 2013. http://dx.doi.org/10.1038/446727a.
[120] Akashi O, Hanaoka T, Matsuoka Y, Kainuma M. A projection for global CO2 emissions from the industrial sector through 2030 based on activity level and technology changes. Energy 2011;36:1855–67. http://dx.doi.org/10.1016/j.energy.2010.08.016.
[121] Connolly D, Lund H, Mathiesen BV, Leahy M. A review of computer tools for analysing the integration of renewable energy into various energy systems. Appl Energy 2010;87:1059–82. http://dx.doi.org/10.1016/j.apenergy.2009.09.026.
[122] 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.
[123] Hvelplund F. Renewable energy governance systems. 2001. Plan.auc.dk.
[124] Østergaard PA. Reviewing optimisation criteria for energy systems analyses of renewable energy integration. Energy 2009;34:1236–45. http://dx.doi.org/10.1016/j.energy.2009.05.004.
[125] Østergaard PA. Reviewing EnergyPLAN simulations and performance indicator applications in EnergyPLAN simulations. Appl Energy 2015;154: 921–33. http://dx.doi.org/10.1016/j.apenergy.2015.05.086.
[126] Lund H, Mathiesen BV, Lund H, Mathiesen BV. IDAs energy plan 2030. Copenhagen: Danish Society of Engineers. IDA; 2006.
[127] Mathiesen BV, Lund H, Karlsson K. IDA's climate plan 2050. Copenhagen: Danish Society of Engineers. IDA; 2009.