Applied Energy 275 (2020) 115331

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

The role of electrification and hydrogen in breaking the biomass bottleneck of the renewable energy system – A study on the Danish energy system

Anders Winther Mortensen[a,*], Brian Vad Mathiesen[b], Anders Bavnhøj Hansen[c], Sigurd Lauge Pedersen[d], Rune Duban Grandal[c], Henrik Wenzel[a]

[a] SDU Life Cycle Engineering, Department of Chemical Engineering, Biotechnology and Environmental Technology, University of Southern Denmark, Campusvej 55, 5230 Odense M, Denmark

[b] Department of Planning, Aalborg University, A. C. Meyers Vænge 15, 2450 Copenhagen, Denmark

[c] Business Support and Development, Energinet, Tonne Kjærsvej 65, 7000 Fredercia, Denmark

[d] Centre of Supply, The Danish Energy Agency, Amaliegade 44, 1256 Copenhagen K, Denmark

HIGHLIGHTS

- Renewable energy system design approaches towards a sustainable biomass consumption.
- Hydrogen integration for electrofuel production to replace biofuels.
- Electrification in renewable energy systems reduces demand for biomass and hydrogen.
- Electrification and hydrogen integration needed to reach sustainable biomass demand.

ARTICLE INFO

Keywords:
Renewable energy systems
Energy system modeling
Electrification
Biomass
Hydrogen

ABSTRACT

The aim of this study is to identify the technical solution space for future fully renewable energy systems that stays within a sustainable biomass demand. In the transition towards non-fossil energy and material systems, biomass is an attractive source of carbon for those demands that also in the non-fossil systems depend on high density, carbon containing fuels and feedstocks. However, extensive land use is already a sustainability challenge and an increase in future demands threat to exceed global sustainable biomass potentials which according to an international expert consensus is around 10 – 30 GJ/person/year in 2050. Our analytical review of 16 scenarios from 8 independent studies of fully renewable energy system designs, and synthesis of 9 generic system designs, reveals the significance of the role of electrification and hydrogen integration for building a fully renewable energy system which respects the global biomass limitations. The biomass demand of different fully renewable energy system designs was found to lie in the range of 0 GJ/person/year for highly integrated, electrified, pure electrofuel scenarios with up to 25 GJ/person/year of hydrogen to above 200 GJ/person/year for poorly integrated, full bioenergy scenarios with no electrification or hydrogen integration. It was found that a high degree of system electrification and hydrogen integration of at least 15 GJ/person/year is required to stay within sustainable biomass limits.

1. Introduction

In 2005, with a global population of less than 7 billion people [1], the so-called Human Acquired Net Primary Production (HANPP) was around 220 EJ per year [2], i.e. the total net biomass harvest due to human activities. Of this harvest, 35–55 EJ per year were used to provide energy services [3], 20–30 EJ/year for roundwood, paper, and cardboard production [4], and the remainder being used mainly for food and animal feed.

In 2019, the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES), released their Global Assessment Report on Biodiversity and Ecosystem Services [5]. According to this large expert review, a million species are threatened with extinction at the present level of HANPP. Demand for biomass and land is, however, likely to increase further due to global developments; the main drivers for land and biomass demand being the projected

* Corresponding author.
E-mail address: awm@kbm.sdu.dk (A.W. Mortensen).

https://doi.org/10.1016/j.apenergy.2020.115331
Received 4 February 2020; Received in revised form 19 May 2020; Accepted 2 June 2020

development in population and welfare in general as well as the development towards bioenergy in particular.

According to the United Nations [6], the world's population is projected to reach 9.8 billion people in 2050 and 11.2 billion in 2100. If this population growth comes alongside a significant general increase in welfare per capita and people shift their diets towards more meat it would result in a dramatic increase in demands for land for animal feed production [7].

Many studies have attempted to estimate the global biomass potential, i.e. how much biomass can be available for bioenergy in the future. Currently, there is a high agreement among the scientific community that the sustainable technical potential for bioenergy by 2050 is up to at least a 100 EJ/year; being equivalent to 10 GJ/person/year in 2050 if everybody should have their equal share. An comprehensive review found the potential deployment levels of biomass for energy by 2050 to range between 100 and 300 EJ/year, the range being based on the judgment by a large group of experts behind the latest consensus report by the Intergovernmental Panel on Climate Change (IPCC) [2]. A range of 160–270 EJ/year of bioenergy is reported in another study, where sustainability criteria are specifically considered [8]. A maximum physical potential for bioenergy of 190 EJ/year is reported in yet another study [9] and the International Energy Agency operates with a limit of 150 EJ/year of sustainable biomass feedstocks for their scenarios [10]. Some researchers find even higher potentials above 300 EJ/year, equivalent to 30 GJ/person/year in 2050, but with a low agreement among other experts [11]. Based on the expert consensus and the other studies, we find it unlikely that more than 200 EJ/person/year equivalent to 20 GJ/person/year of biomass would be available for the energy system in 2050.

An extensive deployment of bioenergy is one potential action that could be taken to lowering global greenhouse gas emissions as agreed in the Paris agreement [12]. In 2015, the world's total primary energy supply was around 570 EJ, of which around 470 EJ were fossil fuels [13]. This is more than a doubling of the world's total primary energy supply since 1973 [13] and for current policy scenarios, the number is projected to increase to more than 800 EJ by 2040 [14] and around 900 EJ by 2050 [15], equivalent to 90 GJ/person/year. From these numbers, it is evident that biomass alone cannot fully substitute fossil fuels. Other technologies and strategies are needed for fossil fuel substitution to avoid biomass and land constraints being a bottleneck of the renewable energy system.

The overall aim of this paper is to explore the scale of biomass demand of the fully renewable energy system and to reveal both the potential and the necessity of non-carbon solutions such as energy system electrification and hydrogen integration in breaking the biomass bottleneck.

1.1. The role of hydrogen in energy system designs

Hydrogen can be produced from electricity based on renewable energy sources such as hydro power, wind, and solar energy, via electrolysis splitting water into hydrogen and oxygen. Hydrogen can then be used in fuel cells to propel vehicles or to produce electricity which can replace biofuels or electricity produced from bioenergy. Hydrogen can also be an intermediate energy carrier that can be reacted with carbon to form carbon containing fuels and feedstocks with much higher volumetric densities and better storage and handling properties than hydrogen in its pure state. These fuels could be methane, methanol, gasoline, diesel, jet fuel, etc. which can be used in existing engines and motors.

It is possible to significantly enhance the yield of hydrocarbon/fuel per biomass input to the system by upgrading biomass carbon with hydrogen, and thus reduce overall biomass demands and land area demands. Hydrogen can be reacted with carbon from biomass in various forms. For example, as carbon monoxide in syngas from biomass pyrolysis/gasification, as CO_2 in biogas, or as CO_2 captured in flue gas from biomass incineration (e.g. at heat and power plants). Upgrading CO_2 with hydrogen into hydrocarbons or other carbon containing fuels also enables CO_2 captured directly from the air by so-called direct air capture (DAC) to be used as a carbon feedstock for fuel production. By using DAC, no carbon source other than the air is needed to produce the necessary hydrocarbons to satisfy future energy systems, because the carbon is again released to the atmosphere, when the fuels are burned. It is, thus, in principle possible to displace biomass completely from the energy system by upgrading carbon dioxide from the atmosphere with hydrogen. Throughout this article, fuels where carbon is upgraded with hydrogen produced from renewable energy sources are defined as *electrofuels* [16]. An efficient way to produce electrofuels could be through co-electrolysis and Fischer-Tropsh synthesis [17].

Hydrogen is not the only energy carrier that has the potential for breaking or relaxing the biomass bottleneck. Other non-carbon fuels or energy carriers, such as ammonia made from hydrogen and atmospheric nitrogen, and energy storage solutions and flexible demand solutions can also be utilized. However, as illustrated later in the article, the demand for high density fuels is a dimensioning demand in renewable energy system designs, and here hydrogen in combination with carbon has its merits.

1.2. Energy system analysis

An energy system analysis (ESA) can be used to understand the balancing of the energy system between the primary inputs to the energy system and the final service demands. ESAs are demand–supply match-making studies with a high temporal resolution, typically matching demand with supply hour-by-hour. ESAs support the understanding of the interrelations between the renewable energy technologies, energy efficiency, energy storages and the energy infrastructure i.e. electricity grids, district heating, and gas grids. Thus, an ESA can be used to understand the biomass demands of renewable energy systems which enable a comparison with sustainably available biomass potentials. When comparing different principles and approaches to the energy system design, it is then possible to reveal the dependency of biomass demands on the design approach, including the dependency on the degree of electrification and hydrogen integration into the system.

An integrated, cross-sectoral or so-called 'smart energy system' approach is pivotal to understand the correlation between biomass needs, hydrogen integration, and electrification in future energy systems. For renewable energy systems, hour-by-hour analyses are preferable due to the fluctuating nature of wind and solar power. Some tools do not use this approach, but rather have a focus on the balance in investments in combination with analyses of critical time-slices to identify balancing and storage needs.

There is a tendency to focus on the concept of 'smart grids' when it comes to research on handling fluctuating renewable energy sources in the energy system [18]. The smart grid focus has the outset in the electricity sector and looks at the issues from the electricity producer/consumer perspective e.g. micro grids, vehicle-to-grid, heat pumps, virtual power plants, super grids, and interconnections.

Lately, the terms 'smart energy' and 'smart energy systems' have gained research momentum [19]. These concepts focus on the interactions between more sectors going beyond the electricity sector. This expands the possible infrastructures and energy storages as well as the primary energy supply modeled from the electricity sector, which typically is between 20 and 40% of end-demands. Going from a focus on integration as a problem seen from the electricity side [20] to a system perspective enables synergies between sectors allowing for the increase of overall energy system efficiency and storage costs, as well as the overall need for primary energy including biomass [21,22]. An expanded focus further helps to understand the interrelations towards the gas sector and district heating sectors.

1.3. Aims and hypothesis

The overall aim of this study is to identify the sustainable ‘solution space’ for renewable energy system designs understood as technical system design options that meet all energy system service demands while staying within a sustainable use of biomass resources. This aim shall be met by the following objectives: 1) identify the best consensus estimate of future global biomass potentials, 2) review existing ESA’s for the case of the future Danish renewable energy system and identify key boundary conditions for their biomass demand, 3) identify and assess key system design principles and their implications for the biomass demand of the system, 4) reveal the significance of electrification and hydrogen to the system and their correlation with the system biomass demand. Our study is thus not a techno-economic assessment of each individual technology, but a holistic approach to quantifying the amounts of hydrogen integration and electrification needed to keep the biomass demand of a fully renewable energy system at a sustainable level.

Our hypothesis is that there is a significant negative correlation between biomass demands, electrification, and hydrogen integration in the energy system. Further, that electrification alone cannot bring biomass demand to a sustainable level, but that large-scale hydrogen integration is required.

To our knowledge, this study is the first to quantify biomass demands of fully renewable energy system designs, to reveal and quantify the correlation between biomass demand, electrification, and hydrogen integration, and to identify a generic solution space for renewable energy system designs which stays within a sustainable biomass demand.

1.4. The scope and the eight studies

Denmark has been chosen as the geographical scope of this study. This has been done since Denmark is one of few countries with a variety of very detailed hour-by-hour simulations of future fully renewable energy systems considering all sectors of the energy system. For this specific study eight of the newest comprehensive studies on how to transition the Danish energy system into a fully renewable energy system have been analyzed. The studies have been conducted by different Danish energy system stakeholders and researchers, i.e. the Danish Energy Agency (DEA), University of Southern Denmark (SDU), the Danish Society of Engineers (IDA), Aalborg University, and Energinet (the Danish electricity and gas grid TSO). The number of scenarios analyzed in this paper is 16 as some of the eight studies include several scenarios each based on different system design approaches e.g. some scenarios do not include hydrogen and electrification of heat and transport, while others assume high degrees of electrification. The 16 scenarios, thus, represent 16 different pathways and approaches to transition the Danish energy system into a fully renewable energy system. See Table 1 for an overview of studies and scenarios and Section 2.3 for a further explanation of the scenarios. All studies and scenarios are aiming at a full transition by 2050. Therefore, demands and results presented in this paper are for 2050. More details on the scope and the scenarios can be found in the methodology section.

2. Methodology

Fig. 1 below illustrates the methodological approach which consists of two parts, 1) an analytical review of all the scenarios listed in Table 1 and 2) a synthesis of generic system design strategies to clarify the significance of different design principles on biomass demand of the system. These two approaches are, then, merged to support the identification of a solution space for the design of a renewable energy system that stays within the limits of sustainably available biomass.

2.1. The stepwise approach

Energy systems are big and complex and so are their simulations. Since the 16 scenarios come from 8 different studies, they have been conducted at different times, in different ways, by different practitioners, and focusing on different aspects. To make the scenarios comparable, a uniform energy system template and data structure was developed in order to a) enable a comparison of overall inputs and delivered services, and b) study the energy flows within the system. The review of the 16 scenarios was more specifically conducted according to the following steps:

1) Scenario review: We set out to review and compare the scenarios in order to understand the relationship between the biomass demand of the fully renewable energy system, framework conditions/assumptions and design principles. The scenarios were scrutinized, and a thorough account was made of all differences and similarities and their influence on the results.
2) Common data structure: A common and uniform data structure was developed – in this case designed as a spreadsheet template.
3) Data expression: Data from the reviewed scenarios were fitted into the uniform template for careful inventory of all energy flows, conversion steps, conversion efficiencies, etc. in the different scenarios.
4) Comparison: Scenarios were compared and dependencies between framework conditions, assumptions, design principles, and biomass demand were clarified while using the uniform template. Framework conditions include end-demand services which can be found in Table 1. Assumptions include conversion efficiencies for each process and conversion step of the energy system. A simplified overview of median conversion efficiencies can be found in Table 2, but a total overview of all conversion efficiencies for each individual step for the 16 scenarios is not presented in this paper, as it would be too voluminous. Refer to each individual study for further details. Design principles include electrification in heat and transport, biomass conversion processes, hydrogen integration, demand flexibility, energy storage, modal shifts in transportation, etc. An indication of the degree of electrification can be found in Table 1, while the other aspects are discussed in the Results section. An important difference between the studied scenarios is that they do not supply the same energy system end-services, but have different assumptions on trends in transport, heat, and electricity demand resulting in some differences in scale of demand of end-services by 2050.
5) Normalization: Results were, then, normalized to the same demands for energy system end-services. End-demands of transportation (divided on the various modes of transport), heat (divided on district heating, domestic heating and industry), and conventional electricity were normalized to one and the same reference setting by adjusting the supplies from the prevailing supply technologies within the scenario. Data from the DEA study (2014) has been used to guide the normalization, cf. Table 1 for exact figures and end-demand data for the other studies before normalization. This study was used as the guideline for several reasons; 1) DEA is the Danish authority in the area, 2) the study has become a broadly used reference for the Danish energy system, 3) assumptions on the degree of modal shifts in transport is moderate. The process of adjusting the end-services was undertaken with great caution not to skew the original characteristics of the system designs. The normalization had to take place manually in the uniform template, as it was not possible to simulate all the scenarios once again with new demand assumptions. The manual normalization was conducted as follows; 1) end-demands where changed to the reference values (cf. Table 1), 2) the supply of propellants for transportation were changed to satisfy the new demands, 3) the supply of heat were changed to satisfy the new heat demand after considering any changes in excess heat from

Table 1
Overview of the 8 studies and the 16 scenarios scrutinized in this paper together with an overview of the end-demand for electricity, heat, and transportation before and after normalization of the end-service demands. Electricity inputs for heat and transport are included in the table to give an indication of the degree of electrification. These electricity inputs are not directly part of the end-demands, as they are converted to transport and heat respectively. The scenarios are divided in groups according to the study authors. The heat demands after normalization differs slightly between the scenarios due to different assumptions on the efficiencies and use of district heating.

	Before normalization						After normalization					
Scenario names	**End-demand for conventional electricity**	**End-demand for heat**	**End-demand for mechanical energy for transport**	**Electricity input for transport**	**Electricity input for heat**	**Summation of electricity input for heat and transport**	**End-demand for conventional electricity**	**End-demand for heat**	**End-demand for mechanical energy for transport**	**Electricity input for transport**	**Electricity input for heat**	**Summation of electricity input for heat and transport**
[GJ/pers./year]												
The Danish Energy Agency (DEA)												
Report: *Energy scenarios towards 2020, 2035, and 2050* [34]												
DEA (2014), Bio+	18.23	41.37	14.82	0.98	1.62	2.60	19.13	41.54	14.82	0.98	1.65	2.64
DEA (2014), Bio [a]	18.23	41.05	14.82	6.05	3.92	9.97	19.13	41.23	14.82	6.05	3.96	10.01
DEA (2014), Wind	18.23	40.33	14.82	7.53	4.58	12.11	19.13	40.50	14.82	7.53	4.62	12.14
DEA (2014), Hydrogen	18.23	39.80	14.82	7.79	5.59	13.38	19.13	39.98	14.82	7.79	5.63	13.42
University of Southern Denmark (SDU)												
Report: *Carbon footprint of bioenergy pathways for the future Danish energy system* [4]												
SDU (2014), Bio [b]	17.12	44.29	14.32	0.87	0.00	0.87	19.13	41.76	14.82	0.87	0.00	0.87
SDU (2014), Electric	16.18	43.81	12.34	5.15	8.59	13.74	19.13	40.88	14.82	6.09	7.98	14.07
SDU (2014), Electrolysis	17.69	42.63	11.73	5.15	13.41	18.56	19.13	40.88	14.82	6.42	12.73	19.15
SDU (2014), BCCR [c]	16.61	43.10	12.21	5.15	16.59	21.74	19.13	40.87	14.82	6.19	16.30	22.49
The Danish Society of Engineers (IDA)												
Reports: *The Danish Society of Engineers' energy plan 2030* [29], *The IDA climate plan 2030* [30], and *IDA's Energy Vision 2050* [36]												
IDA(2006)	18.97	32.54	9.80	3.13	2.50	5.64	19.13	42.96	14.82	4.74	3.27	8.01
IDA(2009)	15.24	45.03	12.81	7.53	3.54	11.07	19.13	41.43	14.82	8.62	3.09	11.71
IDA(2015)	21.74	38.99	12.94	5.53	6.67	12.20	19.13	39.50	14.82	7.18	6.61	13.78
Aalborg University												
Report: *Coherent Energy and Environmental System Analysis* [33]												
CEESA(2011), Cons.[d]	16.31	41.78	11.95	3.61	2.64	6.25	19.13	41.21	14.82	4.38	2.42	6.81
CEESA (2011), Rec.[e]	16.37	41.78	11.95	5.12	2.95	8.06	19.13	41.21	14.82	6.21	2.74	8.94
CEESA(2011), Ideal	16.53	41.78	11.95	5.20	2.98	8.18	19.13	41.21	14.82	6.31	2.77	9.09
Energinet												
Reports: *Energy concept 2030* [35] and *System perspective 2035* [37]												
Energinet (2015)	19.07	37.02	14.31	6.11	5.40	11.51	19.13	40.07	14.82	6.33	5.93	12.26
Energinet (2018)	23.92	38.27	14.82	10.93	8.18	19.11	19.13	40.01	14.82	10.93	8.68	19.61

[a] Original name in study - *'Biomass'*.
[b] Original name in study - *'Standard bioenergy'*.
[c] Original name in study - *'Bio-Carbon Capture and Recycling'*.
[d] Original name in study - *'CEESA-2050 Conservative'*.
[e] Original name in study - *'CEESA-2050 Recommendable'*.

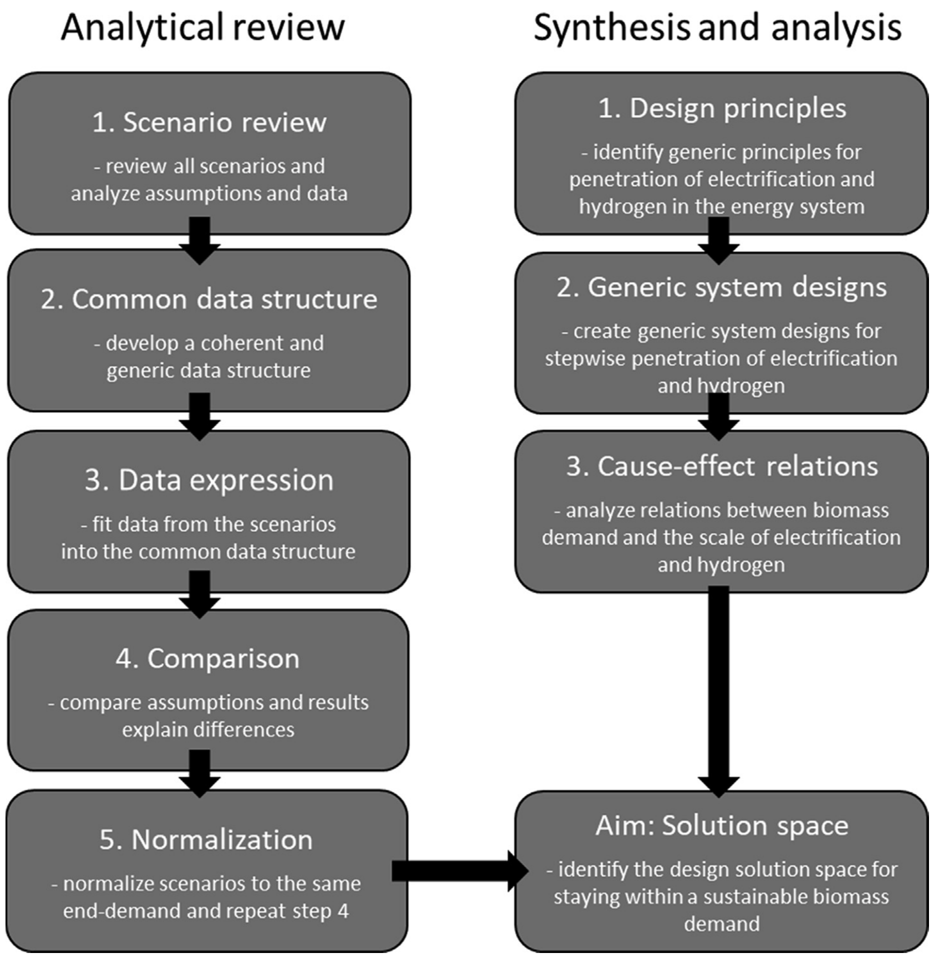

Fig. 1. Flowchart illustrating the methodological approach.

fuel production deriving from the adjustments of fuel supply, 4) supply of electricity were changed to satisfy the new electricity demand after considering any changes in electricity production or consumption due to the changes in transport and heat. Step 4, Comparison, is then repeated based on the normalized datasets.

Synthesis and analysis: In order to support the interpretation of the cause-effect relations behind the differences in biomass demand of the 16 scenarios, a set of 9 generic system designs was developed. Each of these system designs represent a singular principle step towards increasing system efficiency, system integration, and electrification as well as increasing use of CO_2 sources for electrofuel production and hydrogen integration. Whereas the analyzed 16 scenarios all represent a mix of design principles, these generic system design more clearly reveals the significance of a singular measure on the overall system biomass demand. The individual steps are shown in Fig. 1, and the details of each generic system design are given in section 2.4.

The cause-effect relationships derived from the generic designs are, then, finally compared to the analytical review of the 16 scenarios and a solution space is derived, thereby meeting the aim of the study. The illustration of this is given in Figs. 4 and 5.

2.2. Spatial and temporal scope of the analytical review

As mentioned, Denmark has been used as geographical area for this study. In relation to energy systems, Denmark is characterized by the following : 1) since the 1980′s large energy savings including tightening of the building regulations have stopped the energy demand increase and led to a constant primary energy supply even though transportation demands have increased significantly, 2) high system integration with well-developed district heating networks, where e.g. heat from combined heat and power (CHP) production is recovered and used for

Table 2
Overview of conversion efficiencies used in developing the generic design strategies. The efficiencies in italic are percentage points of the total conversion efficiency for that specific process.

Conversion of:	Total conversion efficiency	*Conversion efficiency to fuel or electricity*	*Conversion efficiency to heat*
Electricity to hydrogen (Electrolysis)	70%		
Hydrogen and carbon to fuels	90%	*75%*	*15%*
Biomass to fuels	80%	*65%*	*15%*
Biomass or fuels to CHP	90%	*40%*	*50%*
Biomass or fuels to electricity	40%		
Biomass or fuels to heat	95%		
Electricity to mechanical energy	90%		
Fuels to mechanical energy	35%		

district heating (around 64% of all Danish households are connected to a district heating grid [23]), 3) large wind resources that since the 1990′s have been harvested in increasing scale, 4) a relatively high bioenergy potential especially from agriculture adding up to around 40 GJ/person/year [24,25], which is approximately twice as high as the aforementioned global average, 5) a significant heating demand during the wintertime, 6) a small cooling demand, 7) the Danish electrical power transmission network is interconnected with many of the neighboring countries i.e. Norway, Sweden, Germany, and the Netherlands. An electrical interconnector between Denmark and Great Britain is being planned [26]. These interconnectors enable Denmark and the neighboring countries to trade electricity with each other. Furthermore, 8) the Danish natural gas grid is well developed and has two large storage facilities and interconnections to the neighboring countries, and finally 9) a full implementation of all non-recyclable, combustible waste incineration with heat and power generation.

More than ten studies on how to transition the Danish energy system into a fully renewable energy system have been conducted over the years. These studies include among others *'Energy for the future – alternative energy plan 1983'* from 1983 [27], *'The future renewable energy system – a light green and a dark green scenario'* from 1994 [28], *'The Danish Society of Engineers Energy Plan 2030'* from 2006 [29], *'The Danish Society of Engineers Climate Plan 2050' from 2009* [30], *'Green energy – the road to a Danish energy system without fossil fuels'* from 2010 [31], *'Energy 2050 – development pathways for the energy system' from 2010* [32], *'Coherent Energy and Environmental System Analysis'* from 2011 [33], *'Energy scenarios towards 2020, 2035, and 2050'* from 2014 [34], *'Carbon footprint of bioenergy pathways for the future Danish energy system'* from 2014 [4], *'Energy concept 2030'* from 2015 [35], ·*'IDA's Energy Vision'* from 2015 [36], and *'System perspective 2035'* from 2018 [37]. Most of the studies have a goal of designing and analyzing scenarios making Denmark completely free of fossil fuels by 2050, which is also the goal set by the Danish government [38]. All scenarios chosen for this study are aiming at being fossil-free by 2050 and thus all energy flows and results are 2050 numbers.

Denmark is, thus, a suitable study area for this paper, since the Danish energy system is relatively advanced, and many studies have been conducted on how to make a fully renewable energy system in Denmark. By using Denmark as a concrete case, we ensure that the analysis can be compared to framework conditions applying for a concrete energy system. The studies are comprehensive and quite advanced, many of them hour-by-hour supply–demand balancing studies and some of them also economic optimization studies. All studies explore and include, the role of storage, dispatchable loads, demands response, and transmission infrastructure have been considered in all scenarios. This will also be discussed further in the Results section. The subsequent extrapolation to conditions in other countries is, then, further discussed in the perspectivation section later in this article.

2.3. The 16 scenarios

For an overview of the studies and the 16 reviewed scenarios, refer to Table 1. For studies containing several scenarios, the scenario names or abbreviations of these from the studies themselves have been added to the entity and year. Each scenario has been designed to meet an expected future Danish energy demand for 2050. This demand can in general be allocated to three types of energy system end-services: electricity, heat, and transportation.

All reviewed scenarios are based on hour by hour simulations of the demand versus the supply of electricity, heat, and gas including transport and industry. The balancing of the grids is modeled in conceptually the same way as they are operated today, but the systems represent much more complex fully integrated energy systems.

All scenarios include import and export of electricity via the transmission interconnectors as part of the balancing of the energy system. This is in line with the real-life operation of the Danish energy system today, where the already existing significant interconnection of Denmark to its neighboring countries helps to balance the Danish electricity grid. This lowers the costs of back-up power production in situations with low amounts of renewable energy in the electricity grid but does not as such lower the need for dispatchable capacity within the energy system.

Simulating the energy systems with electricity trade reveals the best understanding of optimizing the future Danish energy system. However, scenarios simulated mainly in so-called 'island mode' with no electricity transmission interconnectors to neighboring countries can also be informative, as they represent a 'worst case' supply risk assessment, where all issues arising from balancing fluctuating production would have to be solved within the national system boundary. Such scenarios are not optimized or optimal if interconnectors are available, but they provide a picture of an upper limit of the need for domestic system balancing, and they can help to understand how the components of the energy system are connected.

For simulating the transportation sector, the optimal point of departure would be to define the number of people and the amount of goods that had to be transported over given distances. But this is often hard to assess, therefore many of the scenarios scrutinized in this study have based their transport demand on delivered mechanical energy, which can then be converted to a demand for fuels and propellants. The term *propellant* is used as the common denominator, since not only fuels can propel different means of transportation. Electricity from overhead lines or batteries are two such examples of non-fuel propellants. Not all studies have had a detailed elaboration of transport services, which means they only consider the final demands for propellants.

Many of the scenarios have been designed to stay within the Danish potential for biomass, which is around 40 GJ/person/year or approximately twice as high as the global average [24,25]. Others are constructed to show the effect of current policies and trends. See Fig. 3 for details of how each biomass demand relates to the Danish and global potential for biomass.

Generally, for all scenarios, biomass has been preferentially allocated to provide fuels for covering the demand for aviation, long distance sea transport, and heavy-duty vehicles for both private, commercial, and military purposes, secondarily for providing high-temperature process heat for industry, thirdly for back-up electricity for balancing fluctuating wind power and solar power. Biomass for food, medical purposes, and material production has not been considered in the system designs, but only as a background demand.

2.4. Synthesis of generic system designs

After conducting the analytical review of the 16 scenarios, a range of underlying system design principles had been identified which all contributed to reducing the biomass demand, including e.g. energy savings, sector integration, electrification, hydrogen integration with electrofuel production from different CO_2 sources, etc. These design principles have been refined and synthesized into 9 generic design strategies to reveal the significance of each design principle in relation to biomass demand. A similar approach has been used before to study 100% renewable energy systems [21]. No fossil fuels are used in any of the 9 generic design strategies, i.e. they are all fully renewable energy systems just like the reviewed scenarios.

A simplistic energy system model was developed to synthesize and develop these principles into generic design strategies. The term 'generic design strategies' is used to clearly distinguish these generic system designs from the 16 reviewed scenarios. The term is also used since the design principles are seen as generic steps in the ESA development. The model consists of an input side with two energy inputs; 1) renewable electricity and 2) biomass, an output side with three end-services; 1) electricity, 2) heat, and 3) transport, and an intermediate energy conversion with five production units; 1) hydrogen production, 2) fuels production, 3) electricity production, 4) combined heat and electricity

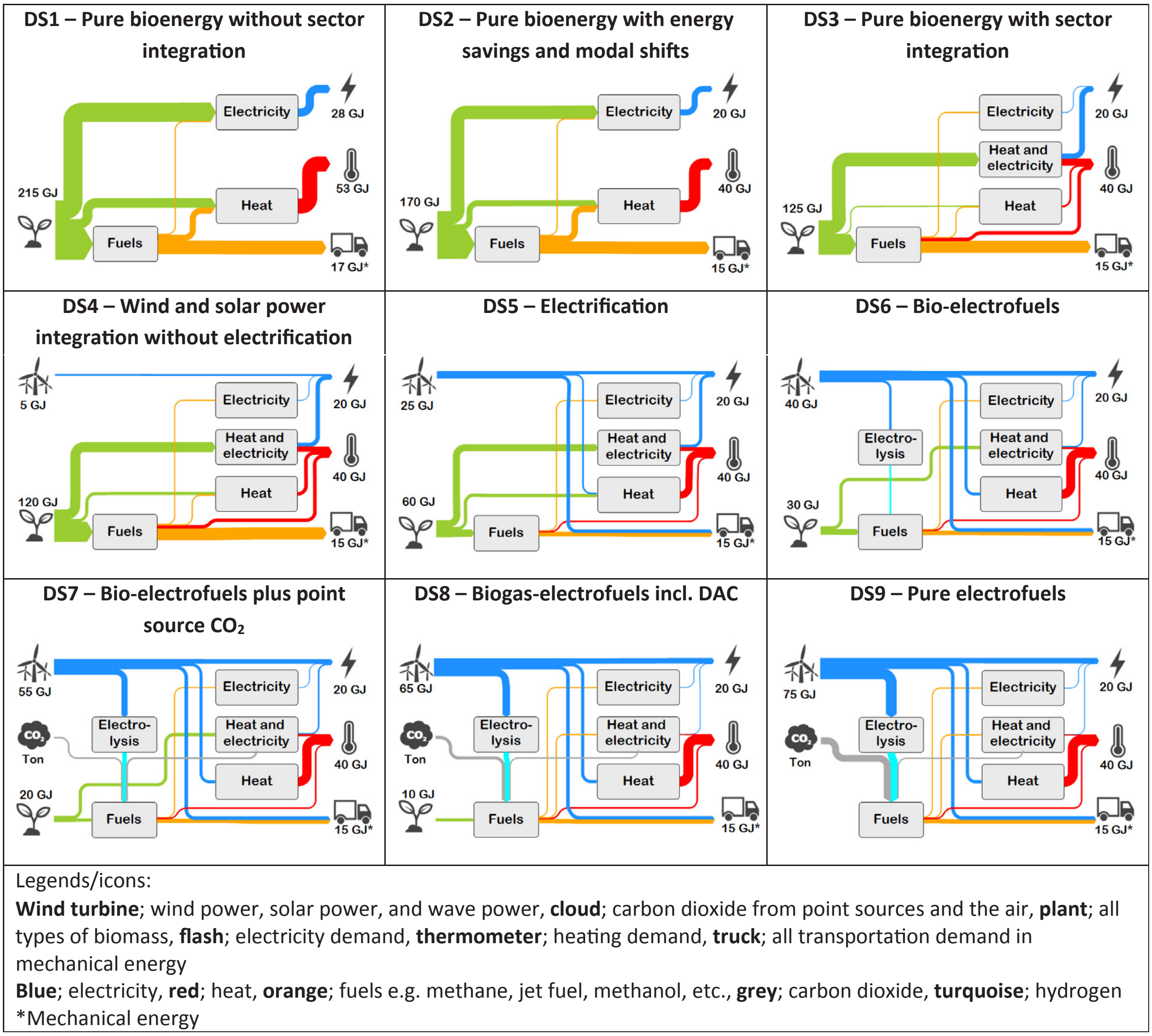

Fig. 2. Generic design strategies. The amounts are expressed in GJ per person per year. Only GJ is shown to improve the readability of the Sankey diagrams. For an explanation of each generic design strategy, see text below.

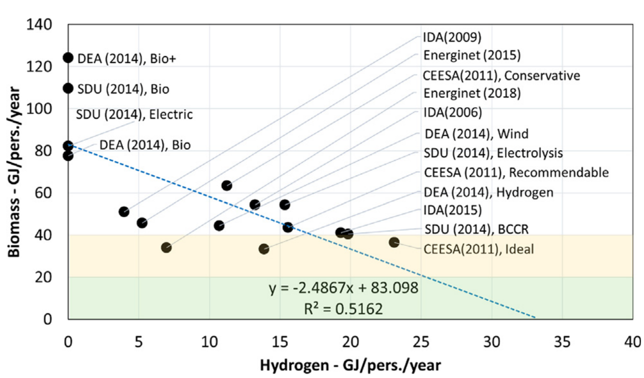

Fig. 3. The relation between biomass and hydrogen integration for all the 16 scenarios after normalization of the end-services provided. The green area indicates the sustainable technical potential of biomass on a global scale, and the yellow area indicates the Danish biomass potential. The trend line is shown as a blue line with the equation and R^2 below.

production, and 5) heat production, cf. Fig. 2 for an illustration of the model setup and Section 2.4.1 for a description of each strategy. For some strategies, not all energy inputs or production units are used. Each of the five production units have different conversion efficiencies depending on the input to the process. The production of mechanical energy also depends on the input, see Table 2 for the full overview of conversion efficiency assumptions used in the simplistic model. The conversion efficiencies are based on medians from the reviewed scenarios.

The model was configurated to supply approximately the same end-demands as the 16 normalized scenarios. The first generic design strategy is an exception of this, see Section 2.4.1. All other design strategies, thus, deliver 20 GJ of electricity per person per year, 40 GJ of heat per person per year, and 15 GJ of mechanical energy per person per year for transportation. It is important to note that mechanical energy is used, since the conversion rate from propellants to mechanical energy differs for each individual type of propellant as seen in Table 2.

With the end-demands fixed and the assumptions on conversion efficiencies, it is now possible to calculate the impact of each generic design strategy. A stylistic presentation of the generic design strategies is found in Fig. 2, where each strategy is represented by a Sankey diagram. Each generic design strategy represents a full implementation of a given technical potential considering the economic limitations outlined in the scenarios matching a given generic design strategy. It has not been feasible to conduct an economic optimization for each generic design strategy, therefore scenarios matching a given generic design strategy have been used to give an indication of the economic potential. This is discussed further for the relevant generic design strategies in Section 3.2 which also contains an explanation of each generic design strategy.

2.4.1. Generic design strategies

In this section, a brief explanation of each generic design strategy is found together with the resulting energy flows. The design strategies are referred to both with a name and with an abbreviation e.g. DS1, meaning Design Strategy 1. To improve the readability of Fig. 2 the values have generally been rounded to the nearest multiple of five i.e. 0, 5, 10, 15, etc. and only the unit 'GJ' is shown even though the unit is 'GJ/person/year'.

DS1: Pure bioenergy without sector integration. This generic design strategy represents a non-integrated energy system where electricity, heat, and transportation fuels are produced fully separately, and where the end-consumption of energy per person is high. Biomass has replaced all fossil fuels in this system. None of the reviewed scenarios resembles this generic design strategy, since the Danish energy system has a high sector integration already today. The biomass demand under this generic design strategy ends up at 215 GJ/pers./year, which is 195 GJ/pers./year more or around 10 times more than what is globally available. Refer to Table 2 for conversion efficiencies of each production unit. All reviewed scenarios assume some degree of energy savings in the end-demands, roughly equivalent to 10% savings in transport, 25% savings in heat, and 30% savings in conventional electricity demand. Under this generic design strategy, these savings have been assumed not to take place, therefore the higher end-service demand of 28 GJ/pers./year for electricity, 53 GJ/pers./year for heat, and 17 GJ/pers./year for mechanical energy for transportation.

DS2: Pure bioenergy with energy savings and modal shifts. Lowering the demand for end-services in the energy system through energy savings for electricity, heat, and transportation, but also through modal shifts in the transportation sector, is the first step that could be taken to lower the biomass consumption in an energy system. Through energy savings and modal shifts, the same core services are still provided e.g. light, heating, or moving goods and people from A to B, but less primary energy input is used to provide these services. This can be done e.g. by insulating buildings, changing inefficient electric appliances to new efficient appliances, or by moving more goods by rail than by trucks or airplanes. The potential for energy savings highly depends on economy especially on expected return on investment. High energy costs would result in more energy savings than low energy costs, since at higher energy costs, more energy savings would become economically feasible. The real amount of saved energy is often overestimated, since some of the energy saving often rebounds into a higher consumption, e.g. if you insulate your house, you are more likely to accept or choose a higher indoor temperature than before the insulation was installed, because you can have a higher comfort level at a lower cost [39]. After energy savings and modal shifts, the biomass needed to supply this generic design strategy is 170 GJ/pers./year which according to the best expert consensus estimate [2] is 150 GJ/pers./year more or 7,5 times higher than what is globally available.

DS3: Pure bioenergy with sector integration. This generic design strategy focuses on integrating the energy system more. This involves utilizing excess heat from electricity production through CHP production and integrating process heat/waste heat from fuel production. This can be done through district heating networks, which also reduce the demand for gas or liquid fuels solely for heating purposes. Producing low temperature heat as the only product of biomass conversion inherently leads to a high biomass demand that could easily be avoided as heat supply based on wind or solar power using heat pumps is a feasible alternative. By integrating the heat, electricity, and transport sector, the biomass demand in the systems drops to 125 GJ/pers./year, which according to the best expert consensus estimate [2] is still 105 GJ/pers./year higher or more than 5 times higher than what is globally available. Now the energy system is better integrated, and the feasible energy savings have been implemented.

DS4: Wind and solar power integration without electrification. This generic design strategy shows how installing renewable energy sources such as wind, solar, and wave power can lower the biomass dependency of a system by using these sources of power directly to provide the end-demand for electricity. To supply the rather inflexible conventional end-demand for electricity in periods with low wind, one could in theory build a huge overcapacity of wind power which even at low wind speeds would produce enough electricity to satisfy the inflexible demand. When the production is too high the wind turbines can in theory then pitch their wings to lower the production. Only days or periods with absolutely no wind or no solar at all would require dispatchable back-up capacity or electricity import. Thus, technically there are few limitations in supplying most of the electricity end-demand by wind and/or solar power. The limitation is mainly economic as it is costly to install such a huge overcapacity in order to cover the demand in low wind or low sun periods. The fluctuating renewable energy penetration for electricity has been found to have a limit of around 25%, before the peak production will be curtailed [21]. This translates to 5 GJ/pers./year of fluctuating renewable energy in a system like the Danish. Therefore, the wind and solar power integration has been set to 5 GJ/pers./year in this generic system design, and the biomass demand for this design is, thus, 120 GJ/pers./year, which according to the best expert consensus estimate [2] is still 100 GJ/pers./year or 5 times higher than the global sustainable technical potential. The two scenarios, *DEA (2014), Bio +* and *SDU (2014), Bio*, both follow approximately this type of generic design strategy with a very low degree of electrification in heat and transport. In a Danish context, this is the *least* ambitious design strategy, when it comes to saving biomass, because the designs with district heating grids and a high degree of combined heat and power production are already well established in Denmark.

DS5: Electrification. Under this generic design strategy, a massive electrification of the energy system takes place to lower the biomass demanded in the energy system. In this generic design strategy, a higher fraction of the fluctuating renewable electricity goes directly for end-demand electricity consumption, which is explained by the presence of a large-scale flexible consumption of especially heat pumps and electric vehicles. Electric vehicles, for example, has previously been reported to increase the wind power integration by 8% for the case of Inner Mongolia [40]. This flexible consumption allows for a much higher installed wind/solar power capacity and simultaneously a higher share going for direct electricity end-use, because the flexible consumption in heat pumps and battery electric vehicles ensures the balancing of supply–demand and allows full use of supply at much higher installed capacity. For the transportation sector, a full technical potential for electrification is assumed in this generic design strategy and the following strategies DS6, DS7, DS8, and DS9. The technical potential for electrification of the transportation sector keeps increasing, as battery technology and other electrification technologies develop and mature. The number used to illustrate the maximum potential for electrification of the transportation sector in the generic design strategies is taken the most recent study i.e. *Energinet (2018)*. In this scenario, a total of 11 GJ/pers./year of electricity goes into the transportation sector leaving 14.5 GJ/pers./year to be supplied by fuels. Both numbers include conversion losses, thus they do not add up to the 15 GJ/pers./year shown in the illustrations, since the later number is expressed in terms of mechanical energy. Under this strategy, the amount of biomass demanded by the system ends up at approximately 60 GJ/pers./year – still 40 GJ/pers./year or 3 times higher than the available global average according to the best expert consensus estimate [2]. The fluctuating renewable electricity production adds up to 25 GJ/pers./year. The scenarios named *SDU (2014), electrification* and *DEA (2014), bio* are both examples of an *electrification* design strategy like this.

DS6: Bio-electrofuels. In this generic design strategy, all carbon from biomass is upgraded with hydrogen. This also includes the carbon dioxide fraction of biogas. Biomass-carbon is still the only carbon source in the energy system, and the total biomass demand ends up at 30 GJ/pers./year which is almost within the globally available quantity. This is not only due to the integration of hydrogen, but also because the flexible electricity demand from electric vehicles, heat pumps, and electrolyzers allows a higher share of fluctuating electricity production to penetrate the end-demand of electricity for two reasons, first the peaks from a higher installed production capacity can now be utilized instead of being curtailed and second because the demands from the flexible electricity demands can be moved away from low wind periods. Due to the electrolysis and the higher degree of electrification, the fluctuating renewable electricity production ends up at 40 GJ/pers./year. Upgrading the carbon dioxide with hydrogen requires approximately 5 GJ/pers./year of electricity, depending on the final product of these reactions. This number is inspired by the scenarios *DEA (2014), wind*, and *DEA (2014), hydrogen*, since these scenarios deal thoroughly with fuel production.

DS7: Bio-electrofuels plus point source CO_2. Within this generic design strategy, the economically most feasible point source emissions of carbon dioxide are upgraded to electrofuels with hydrogen until the point where the biomass demand reaches the sustainable technical potential. The three major streams of point source CO_2 in this generic design strategy are found in biogas, cement production, and biomass fed CHP's. Since all CO_2 from biogas was already assumed upgraded in the previous generic design strategy (DS6), only additional CO_2 from cement production and biomass fed CHP's are considered in DS7. In 2015, cement production emitted slightly more than 2 $GtCO_2$ globally, and reacting this amount of CO_2 with hydrogen into a liquid hydrocarbon gives around 30 EJ of fuel equivalent to 3 GJ/pers./year. Capturing all the CO_2 from biomass fed CHP's under this generic design strategy and reacting this CO_2 with hydrogen gives another 10 GJ/pers./year of fuel, which is more than enough to reduce the total biomass use of the energy system to the sustainable level. The biomass demand is thus 20 GJ/pers./year which is in line with the global sustainable biomass potential according to the best expert consensus estimate [2]. The renewable electricity production ends up at 55 GJ/pers./year. The resulting hydrogen is around 15 GJ/pers./year. None of the reviewed scenarios directly applies this generic design strategy.

DS8: Biogas-electrofuels plus DAC. In this generic design strategy, no land is used directly to produce fuels for the energy system and all useful minerals and nutrients and non-degraded biomass carbon from the input biomass are re-circulated to agricultural soils. This is done by only using biomass residues suitable for biogas, thus both animal manure and agricultural crop residues like straw, beet tops and other are assumed used in biogas. This approach frees up land while treating residual biomasses that if left untreated could lead to methane emissions. The residual demand for fuels is covered by electrofuels based on unavoidable point sources or direct air capture (DAC). The carbon dioxide from the biogas process is still upgraded with hydrogen. Gas is now the input for the CHP plants and due to the cost, all efforts are made to lower the consumption of gas, thus more electricity goes directly from the fluctuating sources to the end-demand supported by more flexible electrolyzer capacity. The biomass demand in this generic design strategy ends up being lower than the sustainable technical potential for bioenergy. The global potential for residues suitable for biogas in 2050 has been estimated by IPPC's expert panel to range from 25 to 170 EJ/year [2] equivalent to 2.5 to 17 GJ/pers./year . The technical primary energy potential in 2050 of crop residues, municipal solid waste and animal manures has in another study been estimated to 100 EJ/year [8] equivalent to 10 GJ/pers./year. The more specific value of 10 GJ/pers./year is here used to illustrate this specific design strategy. The total demand for hydrogen in the generic design strategy is approximately 17 GJ/pers./year. The amount of fluctuating renewable electricity production ends up at 65 GJ/pers./year.

DS9: Pure electrofuels. Under this generic design strategy, no biomass is used in the system – not even residues from agriculture. The carbon source for electrofuels is based on direct air capture or unavoidable exhaust streams of carbon dioxide, like the ones from cement production. The biomass demand ends up at 0 GJ/pers./year and the fluctuating renewable electricity production ends up at 75 GJ/pers./year. The total hydrogen demand ends up at slightly more than 25 GJ/pers./year based on the same assumptions as in the *DS8 - Biogas-electrofuels plus DAC* strategy. To produce this quantity of hydrogen, a bit less than 700 L of water is needed per person per year. This amount of water is less than 7 days of the average water consumption for a Dane. Around 2000 kg of CO_2 per person per year would be needed to convert the abovementioned quantity of hydrogen into hydrocarbon fuels. This system is not pure fiction, it is technically possible to create such a system with the technology we have available today [41,42], and it is once again mainly an economic question. CO_2 from DAC could in 2050 under the right conditions reach prices of 32 to 54 EUR/ton [43]. Methanol produced from wind power electricity, water electrolysis and DAC is today being estimated to cost around 750–800 EUR/ton [44].

2.5. The impact of electrification on the biomass-hydrogen correlation

The simplistic energy system model developed to synthesize the generic design strategies has also been used to study the effect of electrification on the relation between biomass and hydrogen, where all other parameters are fixed. To conduct this analysis two technically realistic degrees of electrification has been determined i.e. a low and a high degree of electrification. The low degree of electrification has been inspired by the scenarios *DEA(2014), Bio +* and *SDU (2014), Bio* and the high degree of electrification was inspired by *Energinet (2018)*, see Table 3 for specific values. Along these fixed degrees of electrification, it is now possible to determine how much hydrogen will be needed to bring the biomass demand to a sustainable level.

3. Results and discussion

This section consists of four parts: 1) the immediate relationship between biomass and hydrogen integration, 2) a comparison of the generic design strategies and the reviewed scenarios, 3) an analysis of how the degree of electrification influence the biomass and hydrogen relationship, and 4) a perspectivation part.

3.1. The relationship between biomass and hydrogen integration

Fig. 3 depicts the relationship between energy system biomass demands and hydrogen integration for all 16 scenarios scrutinized in this paper. The data presented in Fig. 3 is the normalized data from Table 1 for all of the studies, where each scenario supplies the same scale of end energy services. From Fig. 3, a negative correlation between biomass demands and hydrogen integration is seen, as suggested by the hypothesis. From the slope of the trend line, it appears that 1 GJ of hydrogen can replace almost 2.5 GJ of biomass in the energy system, but this is not the entire story. Many parameters differ from scenario to

Table 3
The low and the high degree of electrification used to determine the impact of electrification on the biomass-hydrogen relationship. The 'Coverage of end-service demand" refers respectively to electricity, heat, and mechanical energy for transport.

	Low degree of electricity		High degree of electricity	
	Electricity used: [GJ/pers./year]	Coverage of end-service demand	Electricity used: [GJ/pers./year]	Coverage of end-service demand
Directly for electricity	7	35%	15	75%
To produce heat	0	0%	9	66%
For transportation	1	6%	11	75%

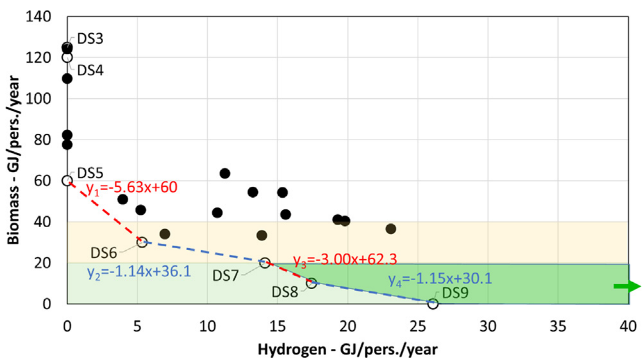

Fig. 4. The 9 generic design strategies represented by open white dots compared to the 16 scenarios represented by black dots. Equations for the red trend lines are shown in red and the equations for the blue trend lines are shown in blue. The red lines include a change in the degree of electrification, whereas the blue lines represent a fixed degree of electrification. Note that the exact numbers for the generic design strategies are plotted, not the rounded numbers from the illustrations. The light green area indicates the sustainable technical potential of biomass on a global scale, the yellow area indicates the Danish biomass potential, and the more intense green area and the arrow indicates the feasible and sustainable operating point for an energy system. The more intense green area stretching to the right as indicated by the arrow thus represents the technically feasible and environmentally sustainable 'solution space' for the transition to a fully renewable energy system.

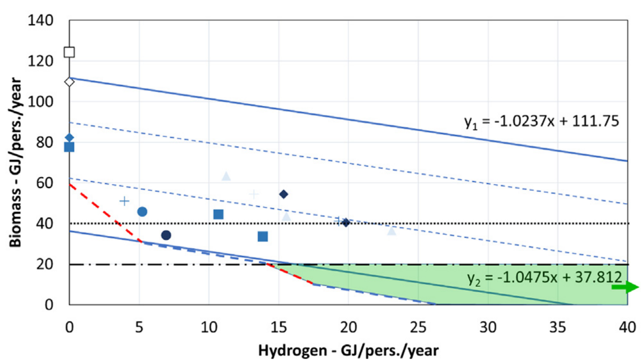

Fig. 5. The relation between biomass and hydrogen for all 16 scenarios and their degree of electrification. The thick blue lines, y_1 and y_2, are based on the simplistic system model where the degree of electrification is completely fixed. The correlation equations related to each line respectively is placed just above the line. New on this Figure is also the two thin blue punctured lines indicating not further specified degrees of electrification between y_1 and y_2. The Danish and global biomass potential is now shown respectively as a horizontal black dotted line and a horizontal black dash-dot-dash line. The DEA scenarios are represented by squares, the SDU scenarios by diamonds, the CEESA scenarios by triangles, the Energinet scenarios by dots, and the IDA scenarios by plusses. The shading of the scenarios represents the degree of electrification i.e. no shade (white) is an electrification of less than 5 GJ/pers./year of electricity for heat and transport, light shade between 5 and 10 GJ/pers./year of electricity for heat and transport, medium shade between 10 and 15 GJ/pers./year of electricity for heat and transport, and dark shade more than 15 GJ/pers./year of electricity for heat and transport.

scenario e.g. conversion efficiencies, degrees of electrification, amount of fluctuating electricity going directly to satisfy end-demands, import and export of electricity and more. The specific framework conditions for each scenario on these aspects thus influence the biomass-hydrogen relation. Due to these differences, especially on the degree of electrification of the heat and transport sectors, the correlation is not high. For example, the two scenarios by Energinet (2015 and 2018) assume a high degree of electrification, making these scenarios fall significantly under the correlation line.

Furthermore, almost none of the scenarios follow the same design principles. It is, thus, not straight forward to isolate the relation between biomass and hydrogen integration from the influence of other framework conditions on biomass demand, even when normalized to the same end-services. Fig. 3 of course, gives the logical indication that integrating more electrolysis and hydrogen into the system allows for a lower biomass demand. But the influence of other framework conditions cannot be seen from the Figure, nor from the data in the uniform template because too many parameters change from scenario to scenario. Thus, the real correlation cannot be identified between biomass demand and hydrogen integration from Fig. 3 alone.

3.2. Comparing the generic design strategies to the reviewed scenarios

A comparison of the generic design strategies and the scenarios investigated in this paper can be found in Fig. 4. The scenarios are represented by black dots, while the generic design strategies (DS) are marked by open white dots. After improving the system integration to the Danish level, both the generic design strategies and the reviewed scenarios to a wide extend follow the same progression of first electrifying the systems and then integrating hydrogen to limit the overall biomass consumption in the energy system.

The red lines in Fig. 4 indicate a change both in electrification and in hydrogen integration and the blue lines indicate a change only in the hydrogen integration i.e. the degree of electrification is fixed. From the blue lines, the relation between biomass and hydrogen integration seems to be almost 1 to 1, not 2.5 to 1 as Fig. 3 indicates. The higher 'red-line' ratios in Fig. 4 and the correlation line ratio in Fig. 3 are due to electrification and hydrogen integration changing at the same time. The equations shown in Fig. 4 are only based on the generic design strategies. The reviewed scenarios all lie above the generic design strategies in Fig. 4, since the design principles are not implemented in as radical and complete a fashion as under the generic design strategies i.e. electrification is not implemented to its full potential in the scenarios and some special design features in the scenarios also have an influence of the biomass-hydrogen relationship in Fig. 4. Still, Fig. 4 does not fully explain or show why the scenarios differ from the generic design strategies, but it starts to give an indication.

From Fig. 4, it is now also possible to find the technically feasible and sustainable solutions space for a fully renewable energy system, sustainable here defined as staying within the limits of a sustainable biomass demand. This solutions space is marked by the more intense green area and continues in the direction of the arrow on Fig. 4. The identified solution space is technically feasible since the degree of electrification is not unrealistic, and the solution space is sustainable in the sense that not too much biomass is used i.e. 10 billion people could have the same energy demands as a Dane without the global energy systems exceeding the global biomass potential – if staying within this system design space. Practically speaking, it means that using the Danish energy system as a model, it will *not* be possible to stay below 20 GJ biomass/pers./year unless at least 15 GJ hydrogen/pers./year is integrated into the energy system, even with the highest possible degree of electrification, energy storage, dispatchable loads, demands response, and transmission infrastructure. Further, it *is* possible to fully avoid the use of biomass, with maximum electrification and the integration of around 25 GJ hydrogen/pers./year or more. The key reasons behind this conclusion are further discussed in the perspectivation section.

3.3. The impact of electrification on the biomass-hydrogen correlation

As earlier stated, the relation between hydrogen and biomass is dependent on other aspects of the system design and especially the degree of electrification, i.e. 1) how much of the final end-demand for electricity that is supplied directly from fluctuating energy sources, 2) how much of the heating sector that is electrified, and 3) how much of the transportation sector that is electrified. These three electrification areas seem to be able to explain a lot of the differences between each of the reviewed scenarios and the variations from the correlation line in Fig. 3. Data suggest that the higher the degree of electrification, the lower the need for hydrogen to reduce biomass demand. This is not surprising, as it is generally the demand for hydrocarbons, i.e. liquid and gaseous fuels, that determines how much biomass or hydrogen that is needed. This is because renewable hydrocarbons can be supplied either as biomass/biofuels or as electrofuels produced from hydrogen and carbon sources.

Fig. 5 is an extension of Fig. 4, but on Fig. 5 the black dots representing the reviewed scenarios has been substituted with different shapes representing each study, i.e. the scenarios from DEA are shown as squares, the scenarios from SDU as diamonds, the scenarios from IDA as plusses, the scenarios from CEESA as triangles, and the scenarios from Energinet as dots. The different shades of blue indicate the amount of electricity used for heat and transport based on the data from Table 1, the darker blue the more electricity is used. Two thick blue lines are added in Fig. 5 where the line, y_1, indicates a system with a low and fixed degree of electrification and the line, y_2, indicates a system with a high and fixed degree of electrification, cf. the Methodology for details. The two thin punctured lines running in parallel with the two thick blue lines have been added to illustrate further non-specified degrees of electrification in between y_1 and y_2.

The darker shaded scenarios are expected to lie closer to the line, y_2, than the lighter shaded points. Furthermore, scenarios with the same shade of blue are expected to lie along the same electrification line for example one of the two thin blue punctured lines. At least this is the theory, but there are two problems with this theory 1) the assumptions on conversion efficiencies in the systems are not consistent the studies in between, and 2) some use hydrogen directly for transportation or electricity production, which has not been added to the simplistic model. For studies containing several scenarios, the first problem is not an issue since the efficiency assumptions are the same, however, the second problem could still be an issue. The theory about predictability of the placements of the points according to their degree of electrification is tested by comparing the data from Table 1 for each study with the placements of the scenarios in Fig. 5. Overall the degree of electrification seems to explain the location of the scenario in the graph relative to scenarios from the same studies. Here follows a short comment on all the scenarios divided on the responsible entity.

The scenarios from DEA are all from the same study and the degree of electrification seems to explain the placement in Fig. 5 well (cf. Table 1 for details on the degree of electrification). The Bio + -scenario comprise almost no electrification, whereas the Bio-scenario is on a line with higher electrification but no electrolysis, and the wind-scenario with even higher electrification and significant electrolysis (greater than10 GJ hydrogen/pers./year), followed by the hydrogen-scenario with the highest electrification and even more electrolysis (greater than13 GJ hydrogen/pers./year). The scenarios from CEESA show that the conservative-scenario assumes a lower degree of electrification, while the recommendable- and the ideal-scenario assume the same, higher degree of electrification. The scenarios from SDU also follow the theory well, but not when comparing to the other studies, the reason being that the conversion efficiency from electricity to heat is substantially lower for the SDU scenarios than for the other studies. The scenarios from IDA are not conducted the same year and the assumptions on energy conversion efficiencies within the system differ, which also results in the data not following the theory, though *IDA (2009)* and *IDA (2015)* are almost on the same line, but according to the theory the *IDA (2015)* should be in a line with a higher, not lower, degree of electrification. The scenarios from Energinet once again follow the theory; they are also conducted in two different years but have more or less the same assumptions on conversion efficiencies.

Comparing the scenarios in between the studies shows a tendency for the theory to be correct but does not explain all scenarios since different models have been used and too many assumptions differs from one study to another. An example of this could be the Bio + -scenario from DEA and the Bio-scenario from SDU, both studies should according to the theory lie almost the same place, but since the DEA study imports a lot of fuel, a lot of the system integration benefit is lost since the conversion losses happens abroad, where only very little sector integration is assumed to be found, and thus the biomass demand goes up – as also illustrated by the generic design strategies.

Overall electrification has a big influence on the hydrogen and biomass relationship as seen from Fig. 5. In an energy system with a low degree of electrification such as the line, y_1, around 90 GJ/pers./year of hydrogen should be integrated into fuels to limit the biomass demand to 20 GJ/pers./year which according to the best expert consensus estimate [2] is the sustainable level. Under a high degree of electrification as indicated by the line, y_2, only around 17 GJ/pers./year of hydrogen should be integrated into fuels to limit the biomass demand to the sustainable level. For these two specific cases, the higher electrification reduces the need for hydrogen integration by a factor of 5 compared to the lower. If no biomass at all were to be used in the energy system, the amount of hydrogen that should be integrated would be around 35 GJ/pers./year under a high electrification framework represented by line, y_2, and around 110 GJ/pers./year under a low electrification framework represented by line, y_1. The thick blue and red punctured lines were taken from Fig. 4 to illustrate how the development of the generic design strategies compares. The lowest blue part of the line for the generic design strategies shows a higher degree of electrification than the line, y_2, the difference is the assumption about the amount of electricity going directly from the fluctuating production to supply the end-demand for electricity. The heating sector is almost fully electrified for both lines, except some backup and integration of excess heat from the fuel production.

3.4. Perspectivation – Replacing wind with solar or hydro

This study has been conducted based on 16 Danish fully renewable energy scenarios and is thus in principle only applicable in a Danish context. But the results are not that dependent on the Danish framework conditions and can also be interpreted for other countries as well. The global applicability of this study increases as the economic development moves more countries in the direction of a higher energy demand like the Danish.

Importantly, the demand for transportation fuels is the most decisive framework condition in determining the hydrocarbon demand and thus the biomass or hydrogen demand of the system. Other demands for hydrocarbons, or other carbon containing fuels, are much less significant, i.e. for electricity balancing, for industry or for domestic heating. In the high electrification scenarios, these demands are found to be well below 20% of total carbon containing fuel demands. It is, thus, the carbon demand of the non-electrifiable transport fuels for heavy transport that predominantly determines the need for either biofuels or electrofuels quite independent of the rest of the system. As biofuels and electrofuels mutually substitute each other, and as no other substitutes are available for this dimensioning demand from the heavy transport, the relation between biomass and hydrogen (for electrofuels) is rather unaffected by the rest of the system.

In locations with predominantly solar power, power supply fluctuations are different from wind power supply, but still any fuel demand for electricity balancing is small compared to transport sector demand. The same holds true for locations with plenty of hydropower.

The demand for biomass in the fully renewable energy system with a high degree of sector integration is, thus, mainly driven by the hydrocarbon demand of the transport sector, but the production of plastics, iron and steel, and cement could also become big consumers of carbon-containing fuels. The production of plastic is estimated to 1.2 Gt in 2050 [45] which will take around 120 EJ/year of biomass to produce taking into account the feedstock and the process energy at a 50/50 split, the energy demand for iron and steel from coal and gas was around 30 EJ in 2017 [46] and the energy demand for cement production was around 15 EJ in 2017 [47]. If the fossil energy used for iron, steel, and cement production were to be replaced by biomass, then the total demand for biomass could easily end up around 165 EJ/year in 2050 for plastic, iron and steel, and cement alone. If these sectors are not electrified or supplied by other sustainable feedstocks and fuels, they will take up almost the entire sustainable technical potential of biomass in 2050. Adding this to the conclusions drawn from Fig. 5, the role and scale of hydrogen needed for breaking the biomass bottleneck is, thus, significant and greatly influenced by the degree of electrification in all sectors. More electrification means less hydrogen, but even with the highest degree of electrification, significant quantities of hydrogen is still needed to stay below the globally available biomass potential. Therefore, if we wish to stay within the sustainable technical potential for global bioenergy, then hydrogen should be an integrated part of the energy system targeted to displace biomass also considering the production of plastics, iron and steel, and cement.

It should be mentioned that electrofuels can in principle also be produced without using hydrogen as the energy carrier for converting CO_2 to fuels, e.g. in a co-electrolysis type of conversion, in which CO_2 and water vapor is converted to CO and further to higher carbon molecules directly on the catalyst without hydrogen carrying the electrons to CO_2. Throughout this article, such a pathway is meant as being included as part of the electrolytic hydrogen demand of the scenarios.

3.4.1. The cost of transforming the energy system

Many examples of fully renewable energy system designs have been scrutinized in this article. None of them has a biomass demand in compliance with the global average potential. One of the scenarios that comes closest, or at least stays within the Danish biomass potential, is the *wind-scenario* from DEA (2014). The extra cost of realizing this system in Denmark by 2050, compared to continuing with a fossil based system, has been estimated at around 0.5% of the Danish GDP [34]. This cost implication differs slightly depending on the chosen design strategy, but not much.

Generally, reduced hydrocarbon combustion in a system leads to less air pollution. The annual cost of premature deaths and sick days related to air pollution in Denmark amounts to approximately 1.5% of GDP [48]. By cutting down heavily on biomass and fuel combustion in the system, the invested 0.5% of GDP in a fully renewable energy system will be recovered already by the potential savings on health expenditure and reduced loss of working ability due to air pollution. It also underlines that the electrification of the heating sector and the transportation sector should have a high political focus. Another Danish study found that the health costs could be more than halved [49], by transitioning the energy system including transport to 100% renewable energy. On top of this potential saving comes all the other benefits of avoiding severe climate change [50,51]. Thus, an investment in a fully renewable energy system is not perceived at a net cost on a longer-term basis, but as an investment with a high rate of return. Similar findings are also being reported for countries with continental climate conditions such as Kazakhstan [52].

4. Conclusions

The study has succeeded in meeting the aims and in verifying the hypothesis.

We found that the best consensus estimate of the future global sustainable biomass potential seems to be around 100–200 EJ per year in 2050. The upper limit is equivalent to 20 GJ/person/year, if the 10 billion people expected to live on planet Earth by 2050 were to have their equal share of the potential.

We found that following a pure bioenergy strategy for renewable energy system designs without any electrification or hydrogen will lead to a biomass demand from above 200 GJ/person/year to around 120 GJ/person/year in respectively poorly integrated energy systems with low energy efficiencies and in highly integrated and energy efficient systems with a degree of wind and solar power that would not need significant curtailing.

We found that electrification of the transport and heating sectors allows a biomass demand below this point, from a very low degree of electrification leading to a biomass demand of around 110 GJ/person/year to a very high degree of electrification leading to around 40 GJ/person/year. Further, that a supply of electrofuels through hydrogen integration is called for in order to reach the biomass limit of 20 GJ/person/year, i.e. a hydrogen integration of at least 15 GJ/person/year in the highest electrification scenarios to 90 GJ/person/year in the low electrification scenario. These parameters also identify the sustainable solution space for renewable energy system designs.

The vital role of hydrogen for electrofuel production in our energy systems might be reduced, if the demand for hydrocarbons fell, but the demand should fall below the 20 GJ/pers./year that can sustainably be supplied from biomass if there should be no role for hydrogen.

The demand for carbon containing, high density fuels is the main driver of the carbon demand for a fully renewable energy system, and since this demand only can be satisfied by either biomass/biofuels or electrofuels there is an almost 1:1 replacement ratio of biomass and hydrogen (transformed into electrofuels with carbon). This verifies our hypothesis of a significant negative correlation between biomass demands and hydrogen integration. For systems with higher degrees of electrification, fewer hydrocarbons are demanded and thus less hydrogen is needed to lower the biomass demand to a sustainable level. The technical limitations of electrifying the transportation sector are what most significantly determines the hydrocarbon demand for a highly advanced energy system.

The findings are based on an analytical review of Danish energy system design scenarios on the one side, and on our own synthesis of generic principles and system designs for a gradual advancing of the system towards lower biomass demands. Our results and conclusions are, thus, directly interpretable under the framework conditions prevailing for Denmark. Importantly, however, we conclude that in systems with significant electrification of heat and transport, the main driver of biomass demands is the scale of high energy dense transport fuels. In such systems, only very little carbon containing fuels were found to be required for heat and electricity. Even systems without district heating and very low integration of heat and power can transition the electrical heating through e.g. heat pumps, and the degree of integration is, thus, not dimensioning for the need for hydrogen. Further, the fluctuation pattern of wind power versus solar or hydro power does not significantly change the need for carbon and thereby the relation between biomass and hydrogen. We do, thus, believe our findings to have general value for renewable energy system design globally.

The identification of the sustainable solution space is significant for researchers and decision makers in the green transition towards renewable energy. Decisions towards pure bioenergy may be a problematic technological lock-in that is binding biomass resources to non-sustainable long-term investments.

Broader context

This article contributes to the field of energy system analysis and design, and to studies of the challenge of transitioning to renewable energy. Additionally, it contributes to studies of global biomass supply and to the understanding of the sustainability of bioenergy. The study is an in-depth analytical review of detailed energy system design solutions for fully renewable energy systems and a synthesis of system design principles and their implications for the biomass dependency of the renewable energy system. The study advances the understanding of biomass dependency of renewable energy systems, and it shows the requirements for the system design in order to stay within a sustainable level of biomass demand. In particular, the study reveals the possibility and necessity of electrification of the heat and transport sectors, as well as the integration of electrolysis and hydrogen into the system to reduce biomass dependency to a sustainable level.

CRediT authorship contribution statement

Anders Winther Mortensen: Conceptualization, Methodology, Validation, Formal analysis, Writing - original draft, Visualization. **Brian Vad Mathiesen:** Methodology, Investigation, Resources, Data curation, Writing - review & editing. **Anders Bavnhøj Hansen:** Methodology, Investigation, Resources, Data curation, Writing - review & editing. **Sigurd Lauge Pedersen:** Methodology, Investigation, Resources, Data curation, Writing - review & editing. **Rune Duban Grandal:** Methodology, Investigation, Resources, Data curation, Writing - review & editing. **Henrik Wenzel:** Conceptualization, Writing - review & editing, Supervision, Project administration, Funding acquisition.

Declaration of Competing Interest

There are no conflicts to declare.

Acknowledgements

The authors wish to thank the Villum Foundation and the V-SUSTAIN project (1346548-9), as well as the Innovation Fund Denmark and the SYMBIO (12-132654) and HiGradeGas (5157-00008B) projects for their economic support.

References

[1] Nations D of E and SAU. World Population Prospects: The 2010 Revision. 2011.
[2] Chum H, Faaij A, Moreira J, Berndes G, Dhamija P, Dong H, Gabrielle B, Eng AG, Lucht W, Mapako M, Cerutti OM, Mcintyre T, Minowa T, Pingoud K. Bioenergy. In IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation [O. Edenhofer, R. Pichs-Madruga, Y. Sokona, K. Seyboth, P. Matschoss, S. Kadner, T. Zwickel, P. Eickemeier, G. Hansen, S. Schlömer, C. von Stechow (eds)]. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press; 2011.
[3] Haberl H, Erb KH, Krausmann F, Gaube V, Bondeau A, Plutzar C, et al. Quantifying and mapping the human appropriation of net primary production in earth's terrestrial ecosystems. Proc Natl Acad Sci 2007;104:12942–7. https://doi.org/10.1073/pnas.0704243104.
[4] Wenzel H, Høibye L, Duban Grandal R, Hamelin L, Bird DN, Olesen A. Carbon footprint of bioenergy pathways for the future Danish energy system. 2014.
[5] Ngo HT, Guèze M, Agard Trinidad J, Arneth A, Balvanera P, Brauman K, Watson R, Baste I, Larigauderie A, Leadley P, Pascual U, Baptiste B, Demissew S, Dziba L, Erpul G, Fazel A, Fischer M, María Hernández A, Karki M, Mathur V, Pataridze T, Sousa Pinto I, Stenseke M, Török K, Vilá B, Carneiro da Cunha M, Mace G, Mooney H. Summary for policymakers of the global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. 2019.
[6] Department of Economic and Social Affairs United Nations. World Population Prospects The 2017 Revision. 2017.
[7] Alexandratos N, Bruinsma J. World agriculture towards 2030/2050: the 2012 revision. 2012.
[8] Haberl H, Beringer T, Bhattacharya SC, Erb K-H, Hoogwijk M. The global technical potential of bio-energy in 2050 considering sustainability constraints. Curr Opin Environ Sustain 2010;2:394–403. https://doi.org/10.1016/j.cosust.2010.10.007.
[9] Haberl H, Erb K-H, Krausmann F, Running S, Searchinger TD, Smith WK. Bioenergy: how much can we expect for 2050? Environ Res Lett 2013;8:31004. https://doi.org/10.1088/1748-9326/8/3/031004.
[10] International Energy Agency. Technology Roadmap: Delivering Sustainable Bioenergy. 2017. www.iea.org/reports/technology-roadmap-delivering-sustainable-bioenergy. All rights reserved.
[11] Creutzig F, Ravindranath NH, Berndes G, Bolwig S, Bright R, Cherubini F, et al. Bioenergy and climate change mitigation: An assessment. Glob Change Biol Bioenergy 2015;7:916–44. https://doi.org/10.1111/gcbb.12205.
[12] United Nations. Paris Agreement. 21st Conference of the Parties 2015;21932:3. FCCC/CP/2015/L.9.
[13] International Energy Agency. Key World Energy Statistics 2019. 2019. www.iea.org/reports/key-world-energy-statistics-2019. All rights reserved.
[14] International Energy Agency. World Energy Outlook 2018. 2018. www.iea.org/reports/world-energy-outlook-2018. All rights reserved.
[15] World Energy Council. World Energy Scenarios: Composing energy futures to 2050. 2013.
[16] Ridjan I, Mathiesen BV, Connolly D. Terminology used for renewable liquid and gaseous fuels based on the conversion of electricity: a review. J Cleaner Prod 2016;112:3709–20. https://doi.org/10.1016/j.jclepro.2015.05.117.
[17] Herz G, Reichelt E, Jahn M. Techno-economic analysis of a co-electrolysis-based synthesis process for the production of hydrocarbons. Appl Energy 2018;215:309–20. https://doi.org/10.1016/j.apenergy.2018.02.007.
[18] 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. https://doi.org/10.1016/j.energy.2012.04.003.
[19] Lund H, Østergaard PA, Connolly D, Mathiesen BV. Smart energy and smart energy systems. Energy 2017;137:556–65. https://doi.org/10.1016/j.energy.2017.05.123.
[20] Mathiesen BV, Lund H. Comparative analyses of seven technologies to facilitate the integration of fluctuating renewable energy sources. IET Renew Power Gener 2009;3:190–204. https://doi.org/10.1049/iet-rpg:20080049.
[21] Mathiesen BV, Lund H, Connolly D, Wenzel H, Ostergaard PA, Möller B, et al. Smart Energy Systems for coherent 100% renewable energy and transport solutions. Appl Energy 2015;145:139–54. https://doi.org/10.1016/j.apenergy.2015.01.075.
[22] Mathiesen BV, Lund H, Connolly D. Limiting biomass consumption for heating in 100% renewable energy systems. Energy 2012;48:160–8. https://doi.org/10.1016/j.energy.2012.07.063.
[23] Danish District Heating Association. Facts about district heating [In Danish: Fakta om fjernvarme] 2018. https://www.danskfjernvarme.dk/presse/fakta-om-fjernvarme (accessed November 14, 2018).
[24] Danish Energy Agency. Analysis of bioenergy in Denmark [In Danish: Analyse af bioenergi i Danmark]. 2014.
[25] Ea Energianalyse. Biogas and other renewable fuels for heavy duty transport - analysis of the posibilities and challenges relaed to facing out fossil fuels [In Danish: Biogas og andre VE brændstoffer til tung transport - Analyse af muligheder og udfordringer ved udfasning]. 2016.
[26] Energinet. Energinet's underlying assumptions for analyses 2017[In Danish: Energinets analyseforudsætninger 2017]. 2017.
[27] Hvelplund F, Illum K, Jensen J, Meyer NI, Nørgård JS, Sørensen B. Energy for the future - alternative energy plan 1983 [In Danish: Energi for fremtiden - alternativ Energiplan 1983]. 1983.
[28] Sørensen B, Nielsen LH, Pedersen SL, Illum K, Morthorst PE, Hye-Knudsen H, Klüver L. The future renewable energy system - a light green and a dark green scenario [In Danish: Fremtidens vedvarende energisystem - et lysegrønt og et mørkegrønt scenarie]. 1994.
[29] Lund H, Mathiesen B V. The Danish Society of Engineers Energy Plan 2030: Background report [In Danish: Ingeniørforeningens Energiplan 2030: baggrundsrapport]. Copgenhagen: 2006.
[30] Mathiesen B V., Lund H, Karlsson K. The Danish Society of Engineers Climate plan 2050: Background report [In Danish: IDA's Klimaplan 2050: Baggrundsrapport]. 2009.
[31] The Danish Commission on Climate Change Policy. Green energy - the road to a Danish energy system without fossil fuels. 2010.
[32] Energinet. Energy 2050 - development pathways for the energy system - [In Danish: Energi 2050 - udviklingsspor for energisystemet]. 2010.
[33] Lund H, Hvelplund F, Mathiesen BV, Østergaard P, Christensen P, Connolly D, et al. Coherent Energy and Environmental System Analysis. 2011.
[34] Danish Energy Agency. Energy scenarios towards 2020, 2035, and 2050 [In Danish: Energiscenarier frem mod 2020, 2035 og 2050]. 2014.
[35] Energinet. Energy concept 2030 - background report [In Danish: Energikoncept 2030 - Baggrundsrapport]. 2015.
[36] Mathiesen BV, Lund H, Hansen K, Skov IR, Djørup SR, Niselsen S, et al. IDA's Energy Vision 2050. 2015.
[37] Energinet. System perspective 2035 [In Danish: Systemperspektiv 2035]. 2018.
[38] Government D. For a more liberal, richer and more safe Denmark: Government platform, Marienborg agreement 2016 [In Danish: For et friere, rigere og mere trygt Danmark: regeringsgrundlag, Marienborgaftalen 2016]. 2016. 978-87-93422-35-3.
[39] Milne G, Boardman B. Making cold homes warmer: the effect of energy efficiency improvements in low-income homes. Energy Policy 2000;28:411–24.
[40] Liu W, Hu W, Lund H, Chen Z. Electric vehicles and large-scale integration of wind power - The case of Inner Mongolia in China. Appl Energy 2013;104:445–56. https://doi.org/10.1016/j.apenergy.2012.11.003.
[41] de Klerk A. Fischer-Tropsch Refining. 2011. 10.1002/9783527635603.
[42] Tollefson J. Sucking carbon dioxide from air is cheaper than scientists thought. Nature 2018;558:173. https://doi.org/10.1038/d41586-018-05357-w.
[43] Fasihi M, Efimova O, Breyer C. Techno-economic assessment of CO2 direct air capture plants. J Cleaner Prod 2019;224:957–80. https://doi.org/10.1016/j.jclepro.2019.03.086.
[44] Bos MJ, Kersten SRA, Brilman DWF. Wind power to methanol: Renewable methanol production using electricity, electrolysis of water and CO2 air capture. Appl Energy 2020;264:114672https://doi.org/10.1016/j.apenergy.2020.114672.
[45] World Economic Forum, Ellen MacArthur Foundation, McKinsey & Company. The New Plastics Economy - Rethinking the future of plastics. 2016.
[46] Vass T, Pales AF, Levi P. Iron and Steel - Tracking Clean Energy Progress 2019. https://www.iea.org/tcep/industry/steel/ (accessed August 13, 2019).
[47] Vass T, Pales AF, Levi P. Cement - Tracking Clean Energy Progress 2019. https://www.iea.org/tcep/industry/cement/ (accessed August 13, 2019).
[48] Brandt J, Solvang Jensen S, Andersen M, Plejdrup M, Nielsen O-K. Health effects and health costs from emission sectors in Denmark [In Danish: Helbredseffekter og helbredsomkostninger fra emissionssektorer i Danmark]. 2016.
[49] Mathiesen BV, Lund H, Karlsson K. 100% Renewable energy systems, climate mitigation and economic growth. Appl Energy 2011;88:488–501. https://doi.org/10.1016/j.apenergy.2010.03.001.

[50] Stern N. The Economics of Climate Change. Stern Rev 2006:662. https://doi.org/10.1257/aer.98.2.1.
[51] IPCC. Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. Geneva, Switzerland: 2014. 10.1017/CBO9781107415324.
[52] Bogdanov D, Toktarova A, Breyer C. Transition towards 100% renewable power and heat supply for energy intensive economies and severe continental climate conditions: Case for Kazakhstan. Appl Energy 2019;253:113606https://doi.org/10.1016/j.apenergy.2019.113606.