4DH
4th Generation District Heating Technologies and Systems

Smart Renewable Energy Systems in the Era of Climate Neutral Societies

Professor Henrik Lund
Aalborg Universitet

INNO-CCUS Carbon capture, utilisation and storage

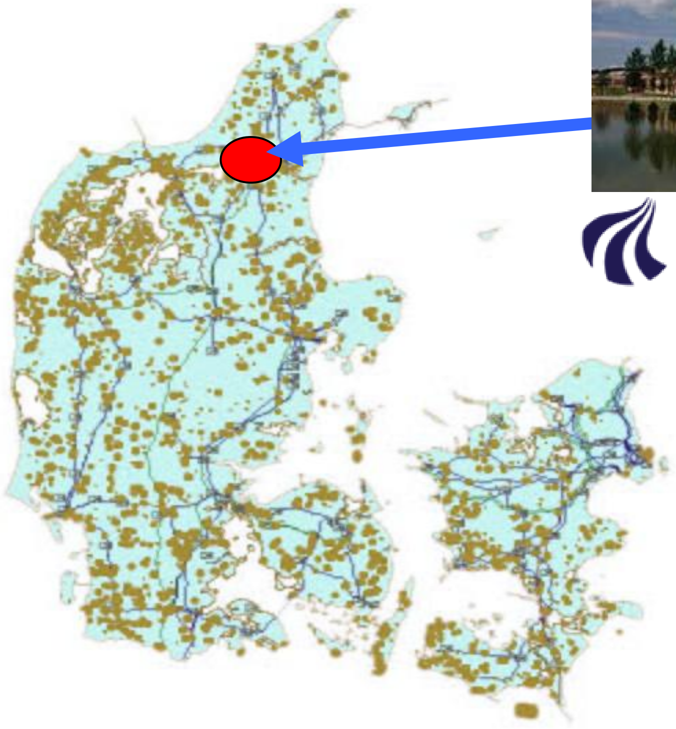
IAM COMPACT

JOINING FORCES FOR SUSTAINABLE ENERGY DENMARK

iDesignRES

MISSION GREEN FUELS

Henrik Lund, Aalborg University, Denmark

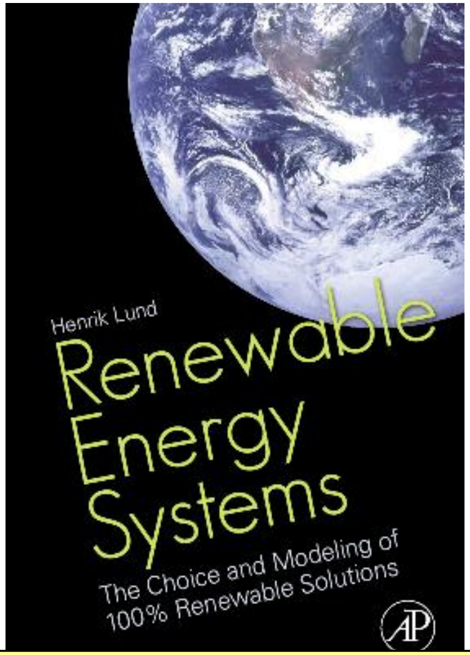


Jutland/Denmark:

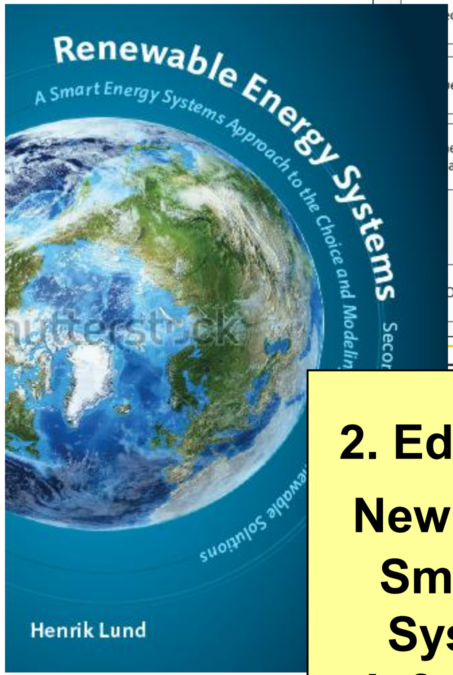
- Approx. 50% wind power
- High share of the world's offshore power
- 30-50% of electricity supplied by CHP
- >50% District Heating
- > 40% Biogas in the natural gas supply

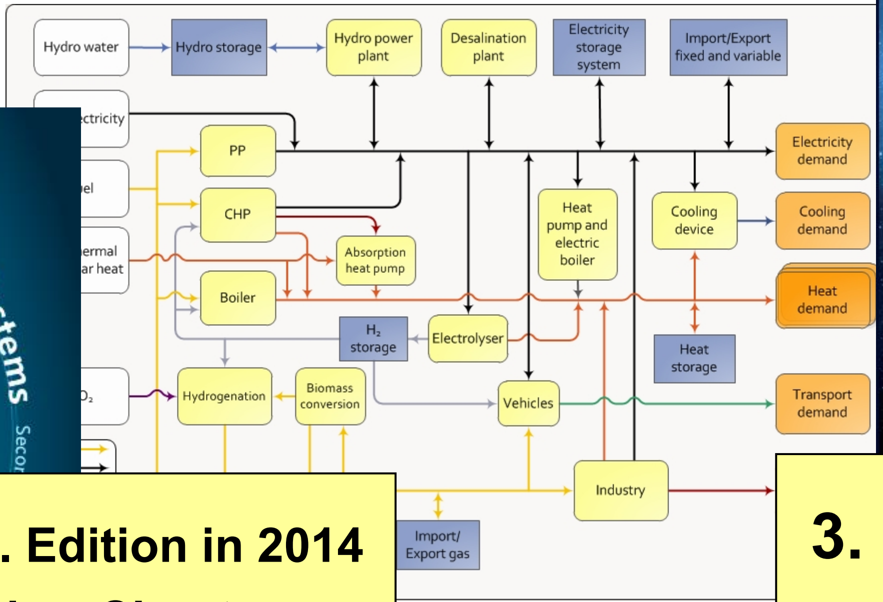
Renewable Energy Systems

A Smart Energy Systems Approach to the Choice and Modeling of Fully Decarbonized Societies



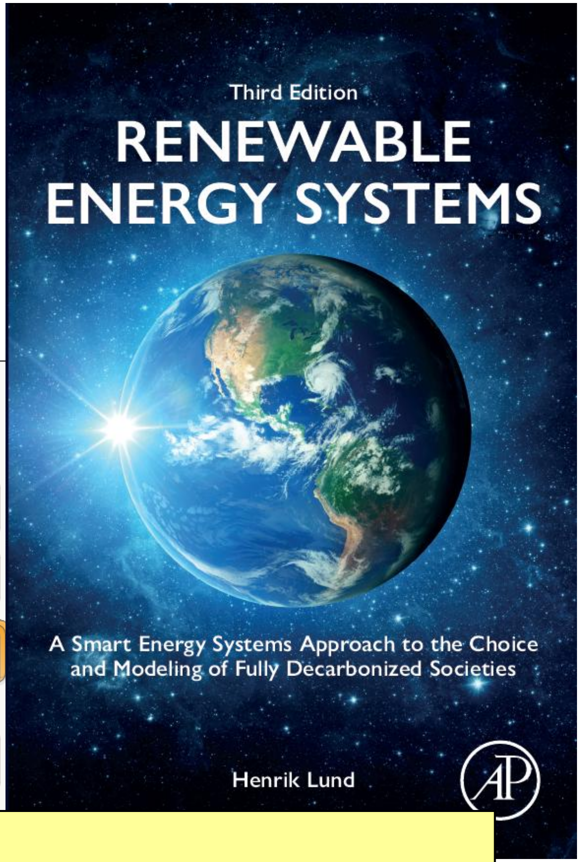
1. Edition in 2010





2. Edition in 2014

New Chapter on Smart Energy Systems and Infrastructures



3. Edition in 2024

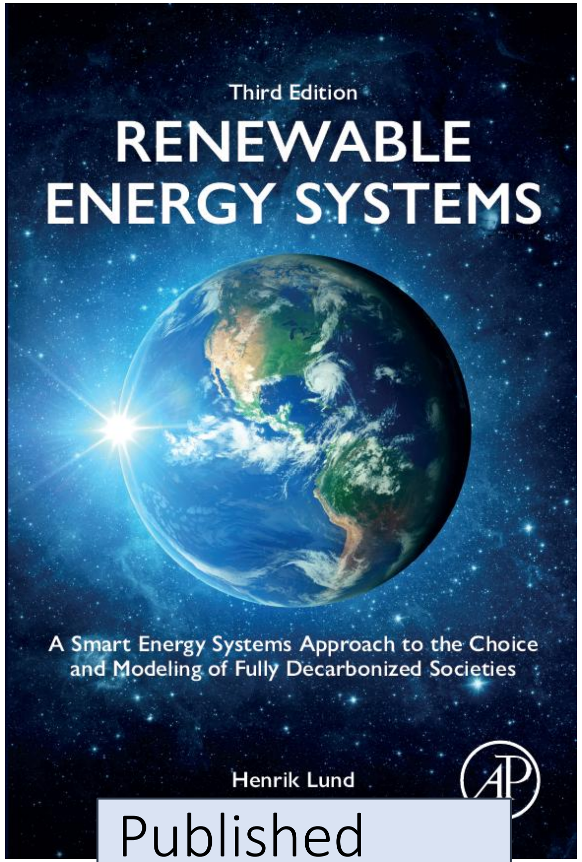
New Chapter on Carbon Neutral Societies

New insights:

1. Explicit formulation of a Smart Energy Systems **theory** (2 thesis)

2. Next step from 100% Renewable Energy to **Climate Neutral Societies**

3. Application: Smart Energy System Integration Levels to illustrate the **importance of smart energy system sector integration**

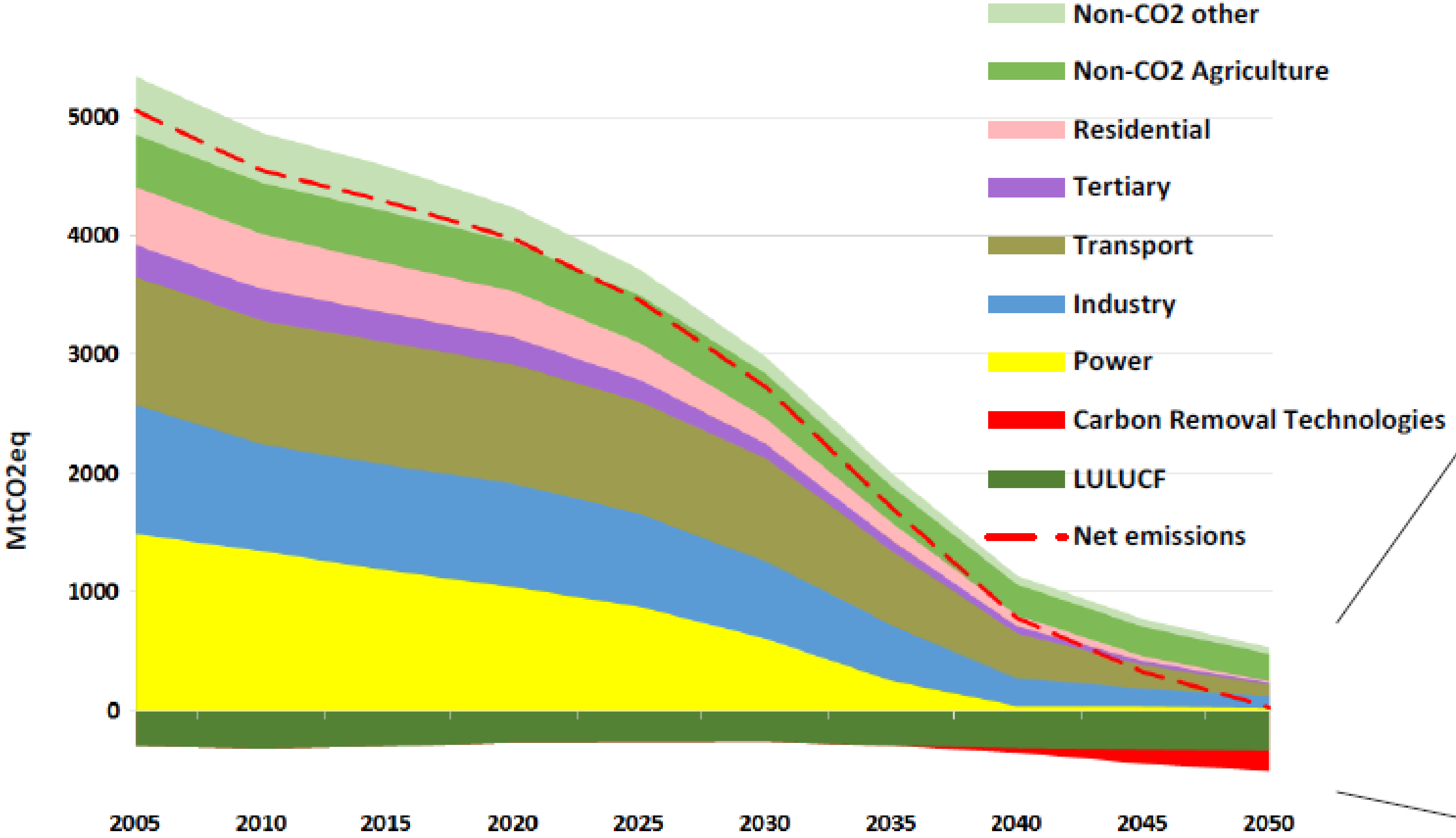


Published March 2024

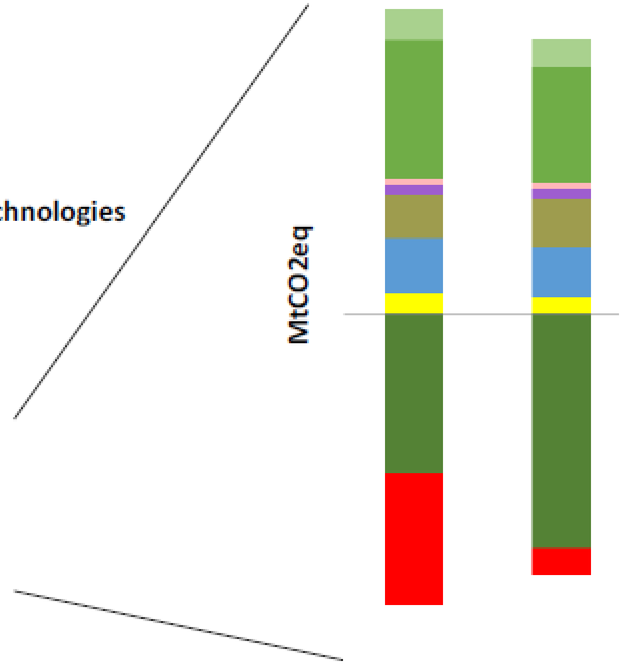
A Clean Planet for all

A European long-term strategic vision
for a prosperous, modern, competitive and climate neutral economy

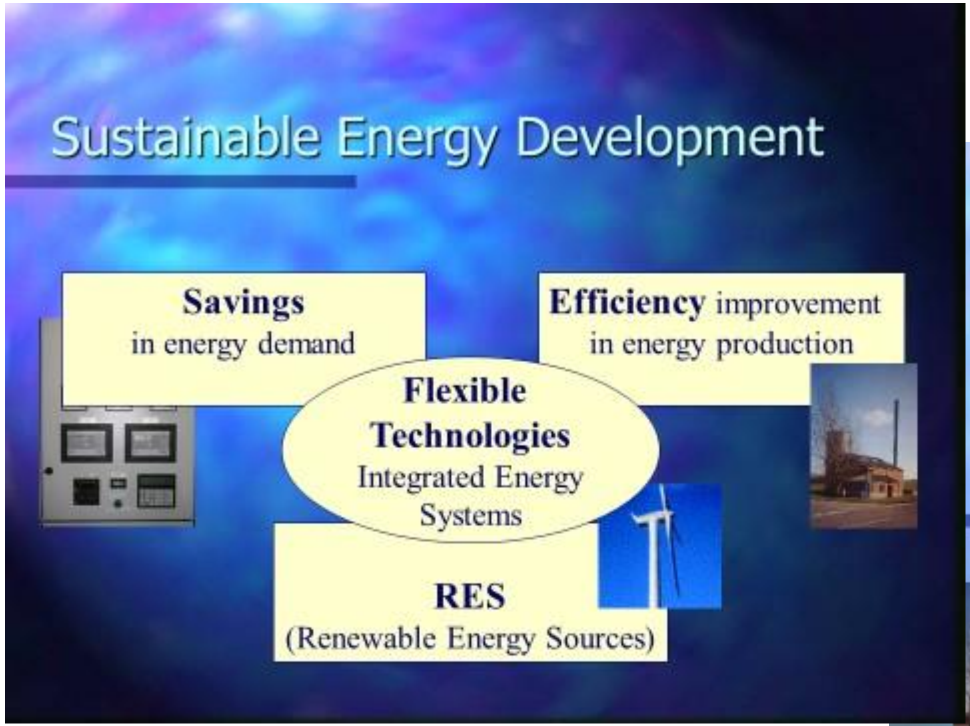
Climate Neutral

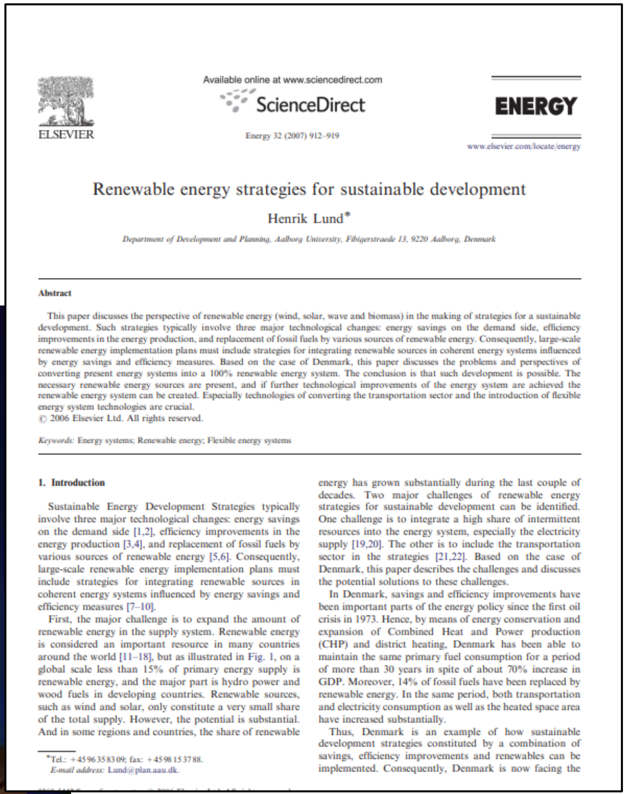


Different zero GHG pathways lead to different levels of remaining emissions and absorption of GHG emissions



Renewable Energy Strategies for Sustainable Development (2005)




Available online at www.sciencedirect.com
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ELSEVIER
ENERGY
Energy 32 (2007) 912–919
www.elsevier.com/locate/energy

Renewable energy strategies for sustainable development

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Abstract

This paper discusses the perspective of renewable energy (wind, solar, wave and biomass) in the making of strategies for a sustainable development. Such strategies typically involve three major technological changes: energy savings on the demand side, efficiency improvements in the energy production, and replacement of fossil fuels by various sources of renewable energy. Consequently, large-scale renewable energy implementation plans must include strategies for integrating renewable sources in coherent energy systems influenced by energy savings and efficiency measures. Based on the case of Denmark, this paper discusses the problems and perspectives of converting present energy systems into a 100% renewable energy system. The conclusion is that such development is possible. The necessary renewable energy sources are present, and if further technological improvements of the energy system are achieved the renewable energy system can be created. Especially technologies of converting the transportation sector and the introduction of flexible energy system technologies are crucial.

Keywords: Energy systems; Renewable energy; Flexible energy systems

1. Introduction

Sustainable Energy Development Strategies typically involve three major technological changes: energy savings on the demand side [1,2], efficiency improvements in the energy production [3,4], and replacement of fossil fuels by various sources of renewable energy [5,6]. Consequently, large-scale renewable energy implementation plans must include strategies for integrating renewable sources in coherent energy systems influenced by energy savings and efficiency measures [7–10].

First, the major challenge is to expand the amount of renewable energy in the supply system. Renewable energy is considered an important resource in many countries around the world [11–18], but as illustrated in Fig. 1, on a global scale less than 15% of primary energy supply is renewable energy, and the major part is hydro power and wood fuels in developing countries. Renewable sources, such as wind and solar, only constitute a very small share of the total supply. However, the potential is substantial. And in some regions and countries, the share of renewable energy has grown substantially during the last couple of decades. Two major challenges of renewable energy strategies for sustainable development can be identified. One challenge is to integrate a high share of intermittent resources into the energy system, especially the electricity supply [19,20]. The other is to include the transportation sector in the strategies [21,22]. Based on the case of Denmark, this paper describes the challenges and discusses the potential solutions to these challenges.

In Denmark, savings and efficiency improvements have been important parts of the energy policy since the first oil crisis in 1973. Hence, by means of energy conservation and expansion of Combined Heat and Power production (CHP) and district heating, Denmark has been able to maintain the same primary fuel consumption for a period of more than 30 years in spite of about 70% increase in GDP. Moreover, 14% of fossil fuels have been replaced by renewable energy. In the same period, both transportation and electricity consumption as well as the heated space area have increased substantially.

Thus, Denmark is an example of how sustainable development strategies constituted by a combination of savings, efficiency improvements and renewables can be implemented. Consequently, Denmark is now facing the

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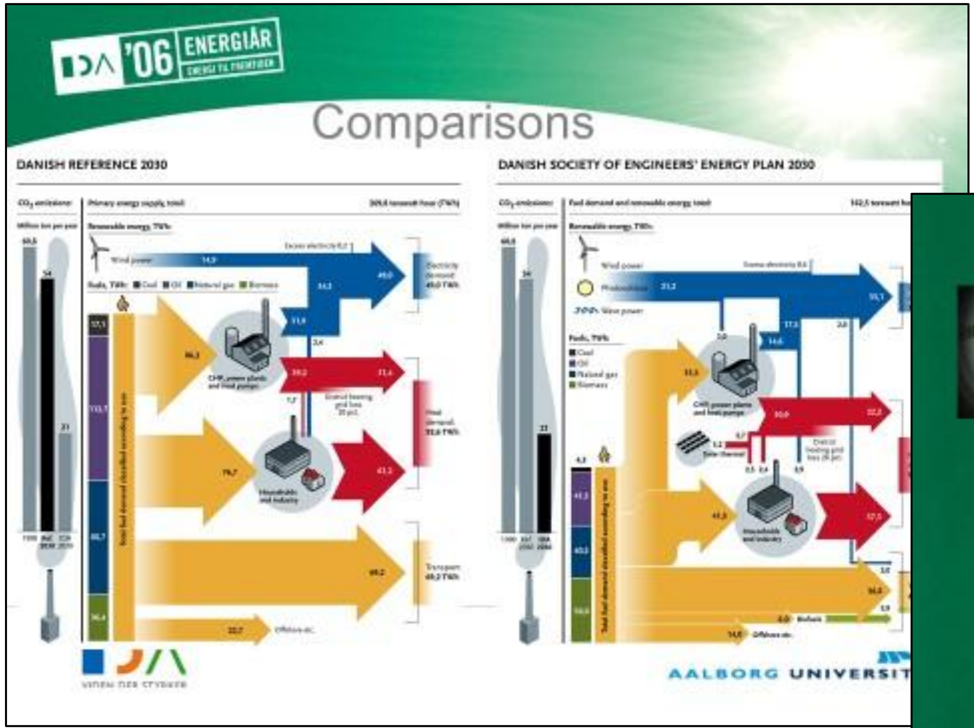
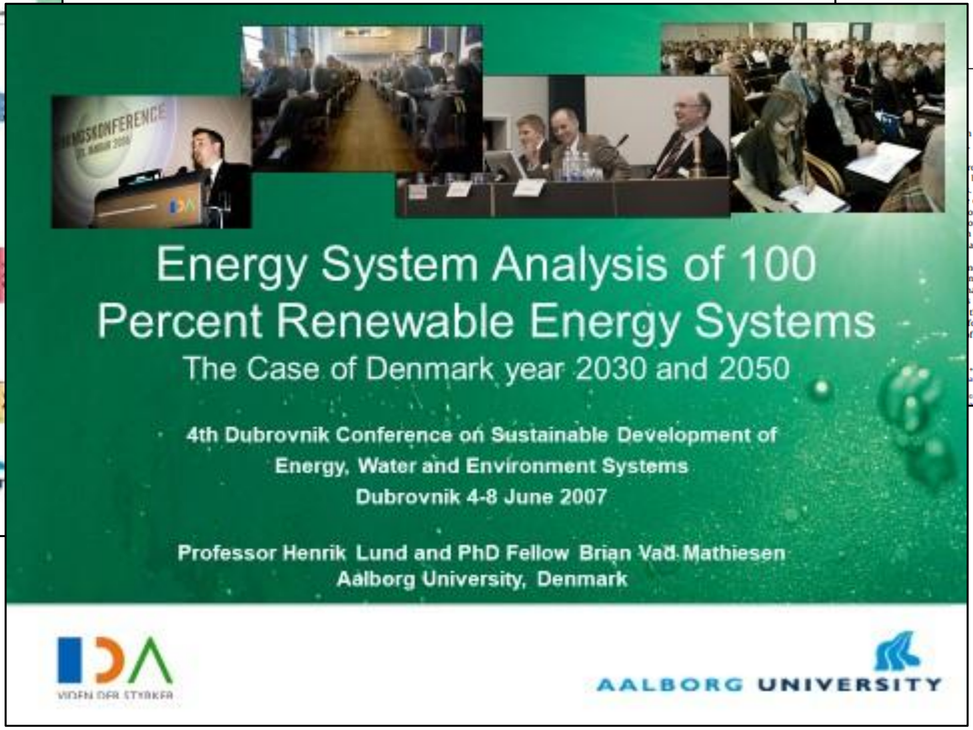
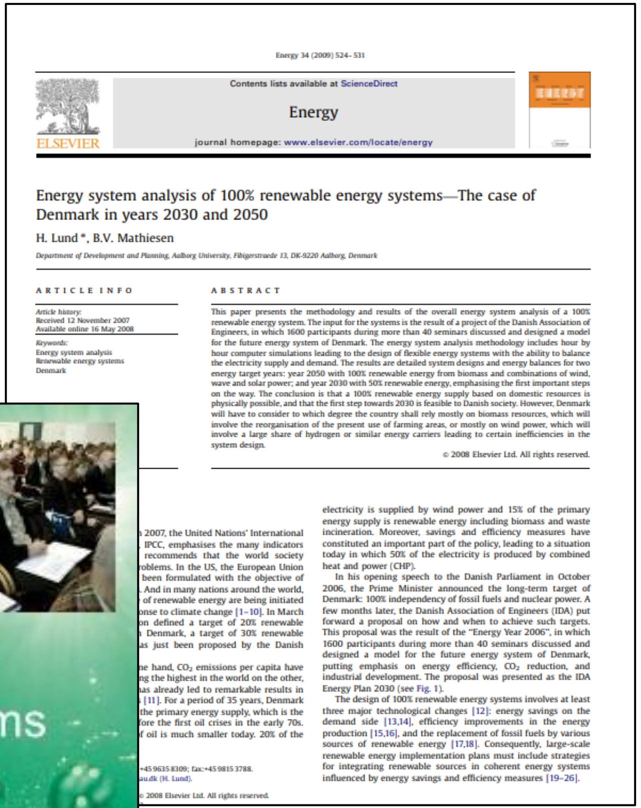
100% Renewable Energy Systems (2007)







Energy 34 (2009) 524–531

Contents lists available at ScienceDirect

Energy

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

Energy system analysis of 100% renewable energy systems—The case of Denmark in years 2030 and 2050

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ARTICLE INFO

Article history:
Received 12 November 2007
Available online 16 May 2008

Keywords:
Energy system analysis
Renewable energy systems
Denmark

ABSTRACT

This paper presents the methodology and results of the overall energy system analysis of a 100% renewable energy system. The input for the systems is the result of a project of the Danish Association of Engineers, in which 1600 participants during more than 40 seminars discussed and designed a model for the future energy system of Denmark. The energy system analysis methodology includes hour by hour computer simulations leading to the design of flexible energy systems with the ability to balance the electricity supply and demand. The results are detailed system designs and energy balances for two energy target years: year 2050 with 100% renewable energy from biomass and combinations of wind, wave and solar power; and year 2030 with 50% renewable energy, emphasising the first important steps on the way. The conclusion is that a 100% renewable energy supply based on domestic resources is physically possible, and that the first step towards 2030 is feasible to Danish society. However, Denmark will have to consider to which degree the country shall rely mostly on biomass resources, which will involve the reorganisation of the present use of farming areas, or mostly on wind power, which will involve a large share of hydrogen or similar energy carriers leading to certain inefficiencies in the system design.

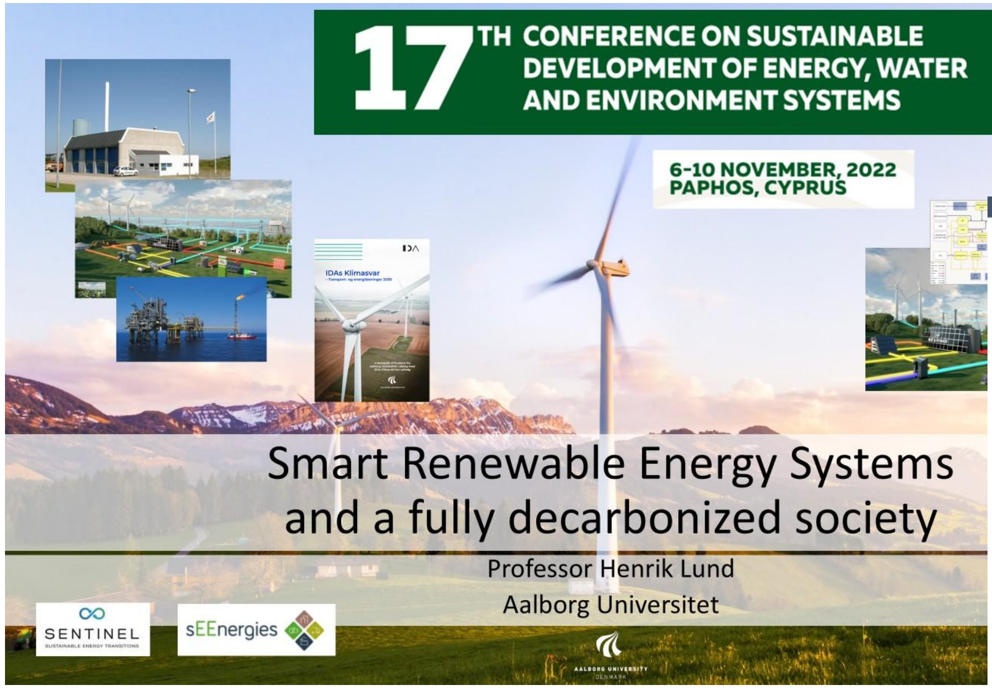
electricity is supplied by wind power and 15% of the primary energy supply is renewable energy including biomass and waste incineration. Moreover, savings and efficiency measures have constituted an important part of the policy, leading to a situation today in which 50% of the electricity is produced by combined heat and power (CHP).

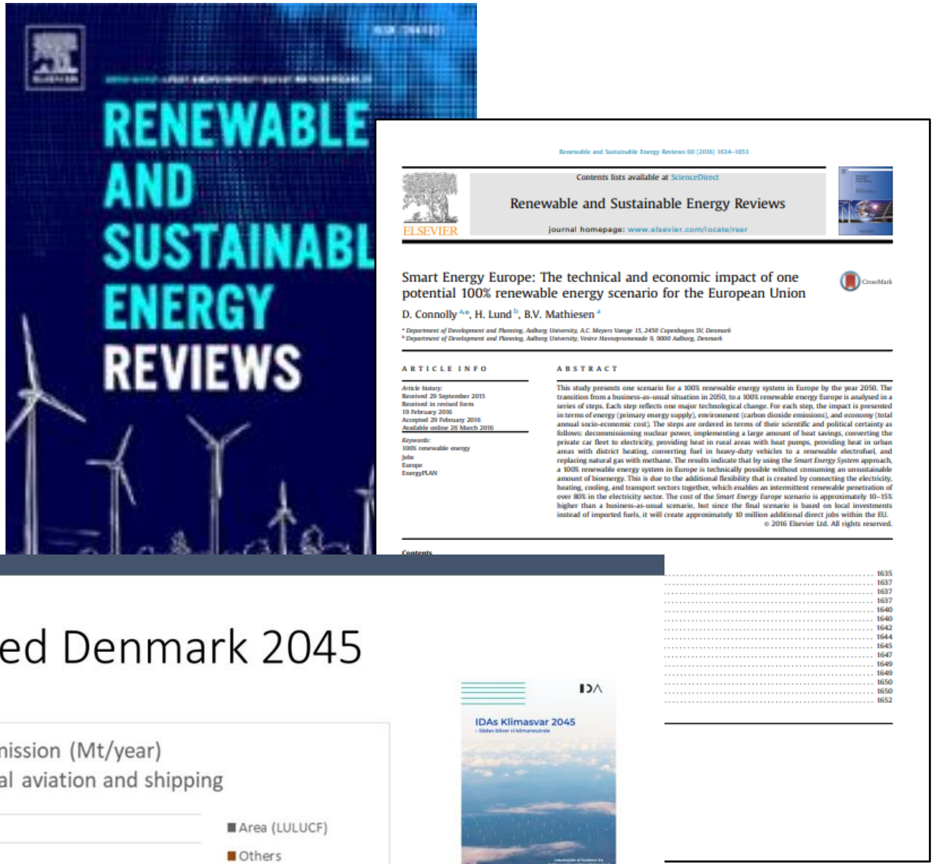
In his opening speech to the Danish Parliament in October 2006, the Prime Minister announced the long-term target of Denmark: 100% independency of fossil fuels and nuclear power. A few months later, the Danish Association of Engineers (IDA) put forward a proposal on how and when to achieve such targets. This proposal was the result of the "Energy Year 2006", in which 1600 participants during more than 40 seminars discussed and designed a model for the future energy system of Denmark, putting emphasis on energy efficiency, CO_2 reduction, and industrial development. The proposal was presented as the IDA Energy Plan 2030 (see Fig. 1).

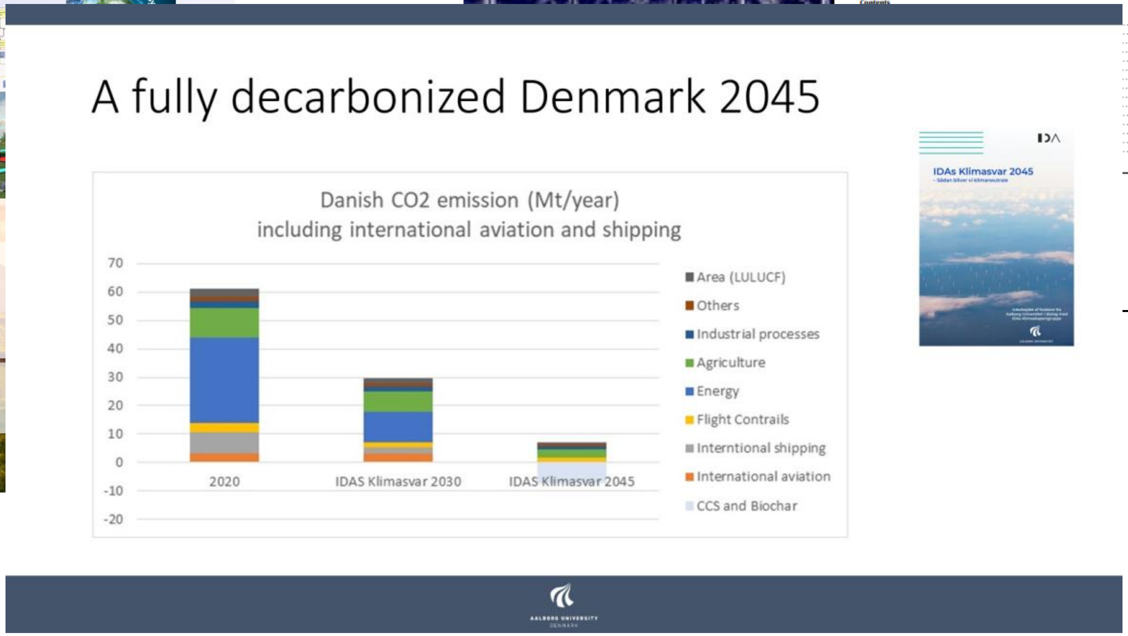
The design of 100% renewable energy systems involves at least three major technological changes [12]: energy savings on the demand side [13,14], efficiency improvements in the energy production [15,16], and the replacement of fossil fuels by various sources of renewable energy [17,18]. Consequently, large-scale renewable energy implementation plans must include strategies for integrating renewable sources in coherent energy systems influenced by energy savings and efficiency measures [19–26].

100% Renewable Energy and Decarbonized Societies (2021)

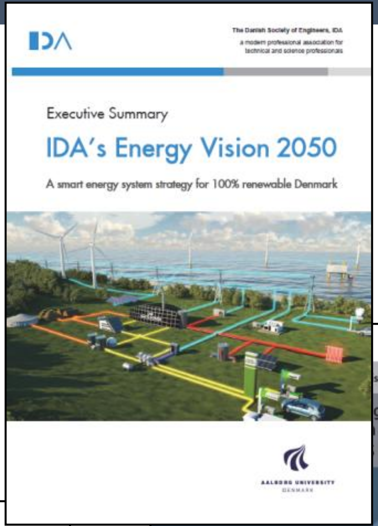
Smart Energy and decarbonized societies (2022)



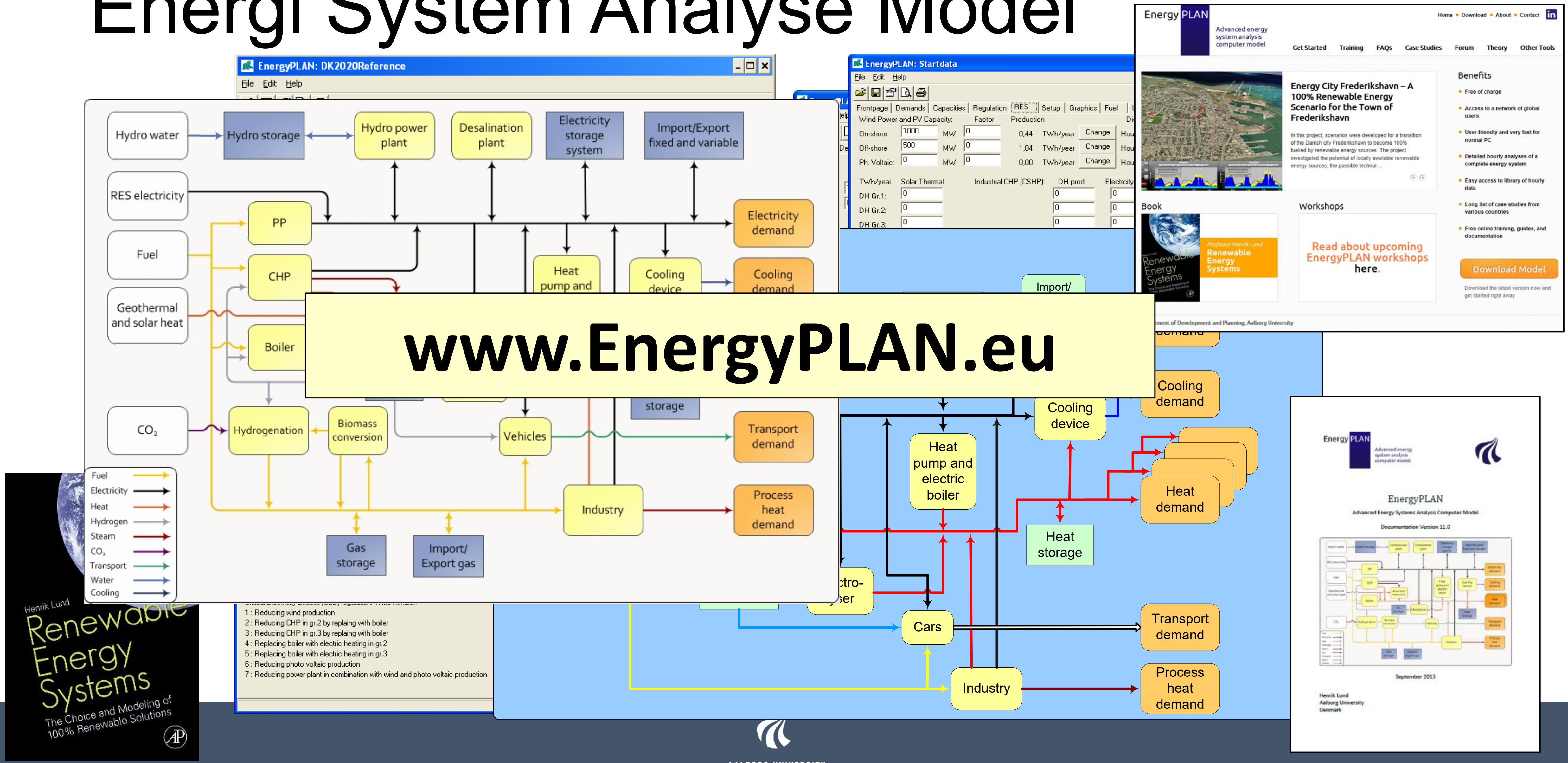




100% Renewable Energy 2050
Or a Climate Neutral Economy
…… but how…???!!



Energi System Analyse Model



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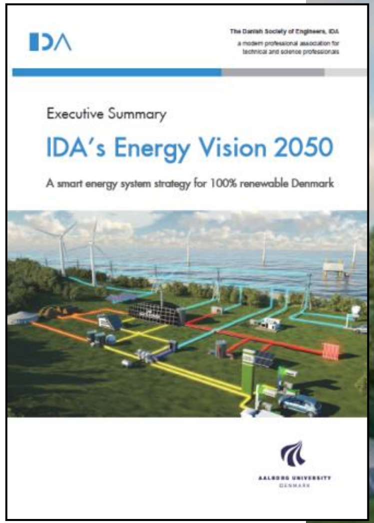
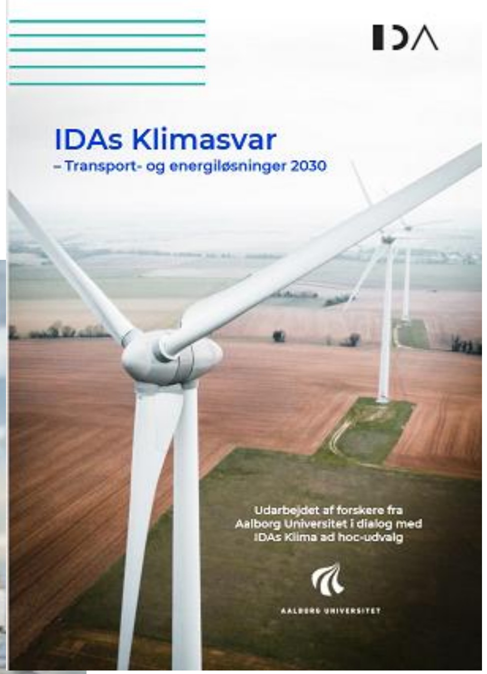
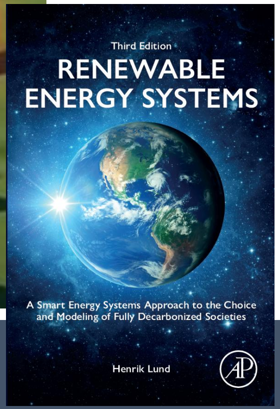
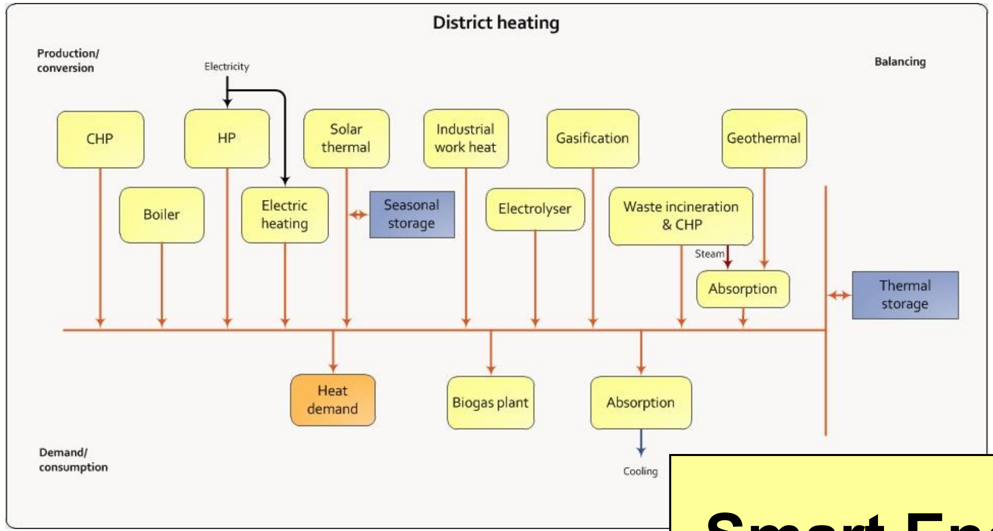
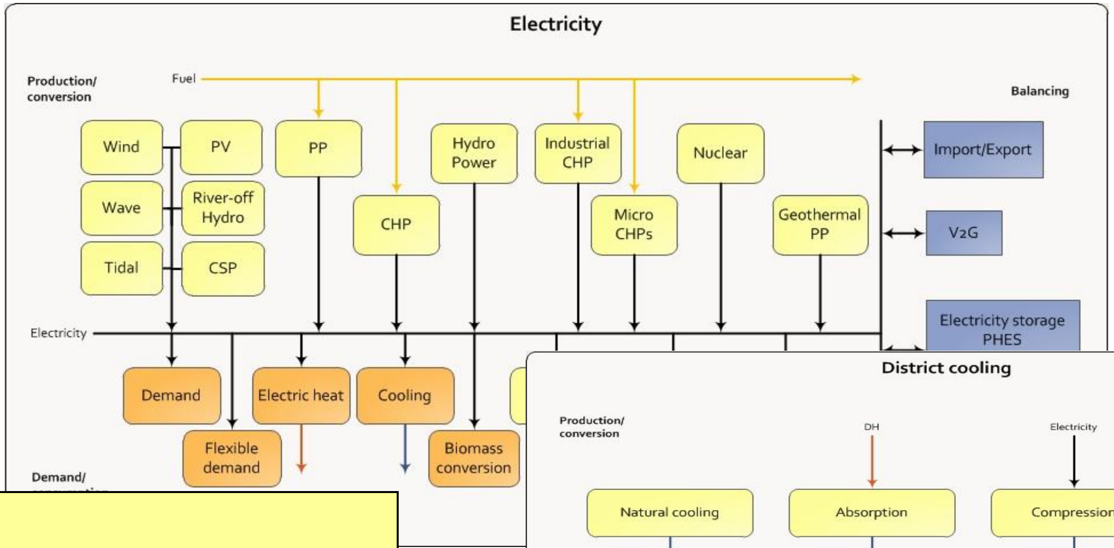
A Holistic Smart Energy Systems Approach

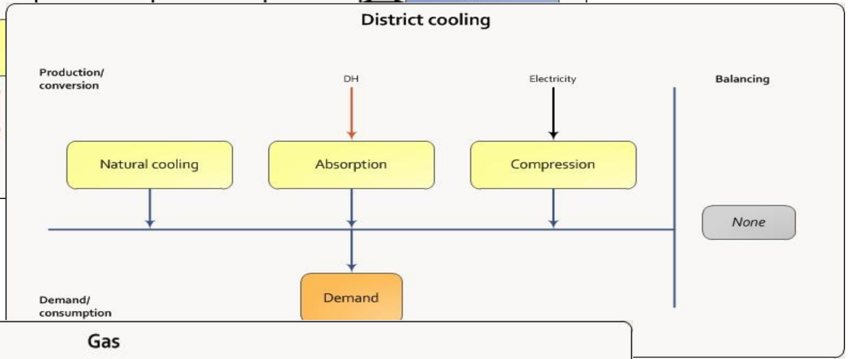






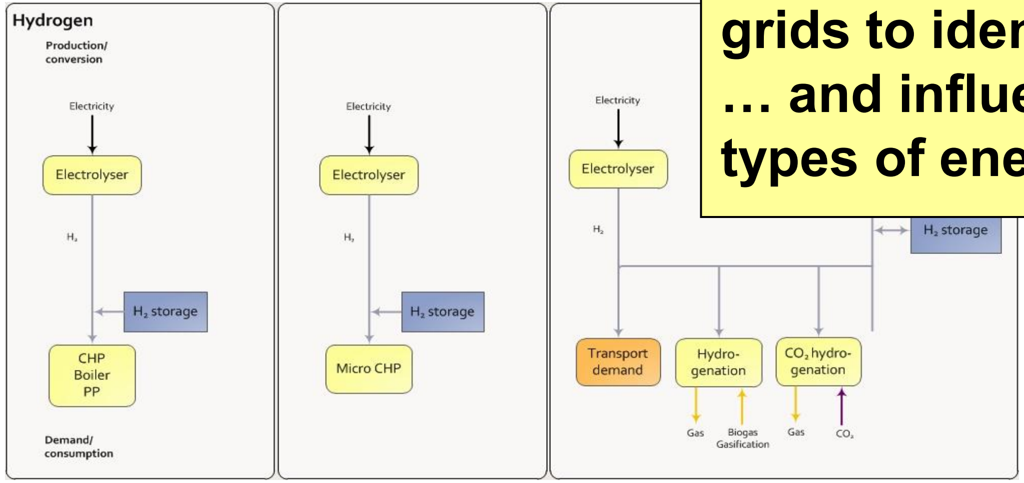


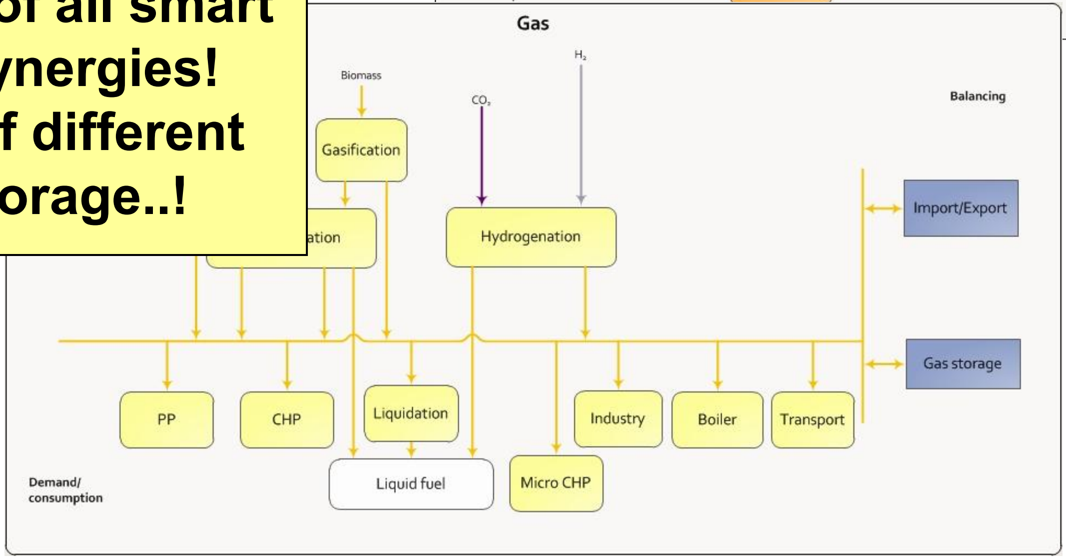




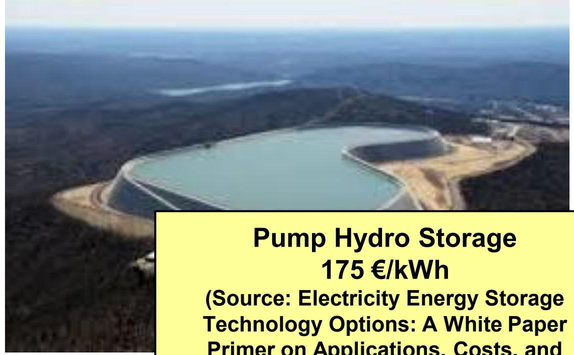
Smart Energy Systems:

Hourly modelling of all smart grids to identify synergies!
… and influence of different types of energy storage..!

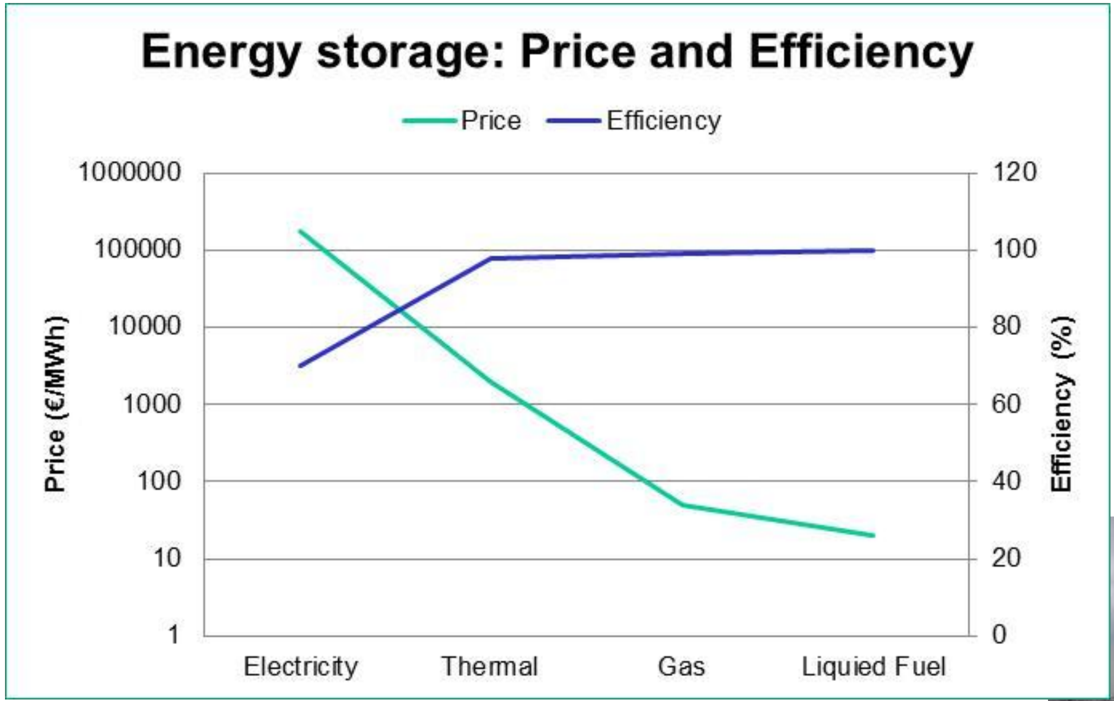




Energy Storage



Pump Hydro Storage
175 €/kWh
(Source: Electricity Energy Storage Technology Options: A White Paper Primer on Applications, Costs, and Benefits. Electric Power Research Institute, 2010)



Thermal Storage
1-4 €/kWh
(Source: Danish Technology Catalogue, 2012)

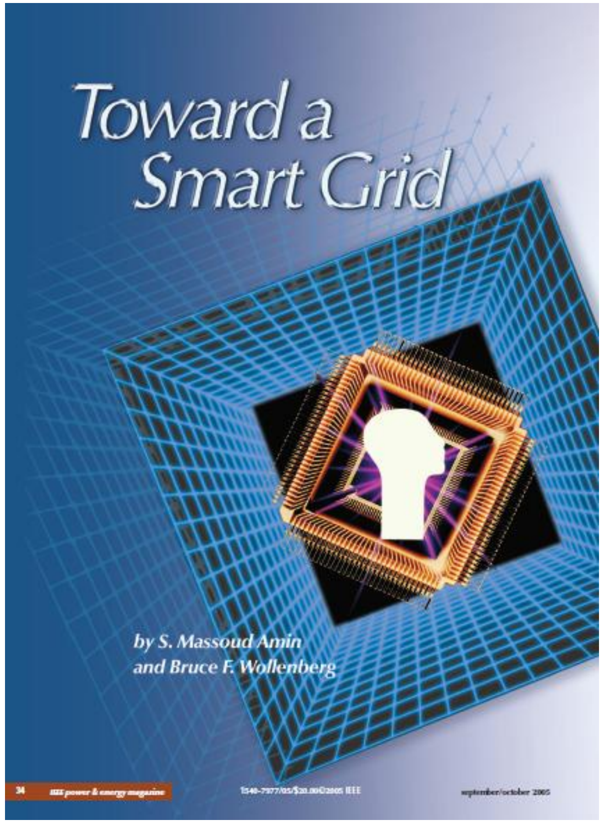
Natural Gas Underground Storage
0.05 €/kWh
(Source: Current State Of and Issues Concerning Underground Natural Gas Storage. Federal Energy Regulatory Commission, 2004)

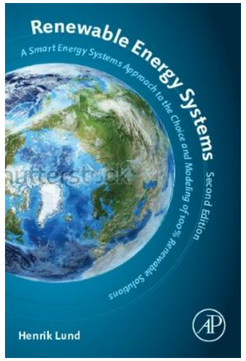
Oil Tank
0.02 €/kWh
(Source: Dahl KH, Oil tanking Copenhagen A/S, 2013: Oil Storage Tank. 2013)

Smart Grid (2005)

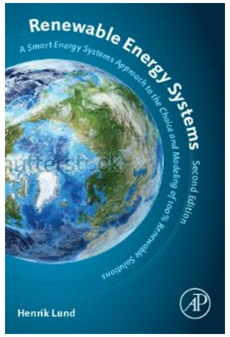
No definition.

However it can be understood from the context 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.





4DH
4th Generation District Heating Technologies and Systems



Smart Grid - definitions

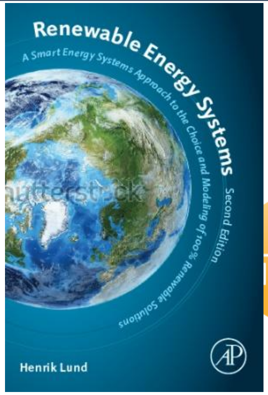
"A *smart grid* is an electricity grid that uses information and communications technology to gather and act on information, such as information about the behaviors of suppliers and consumers, in an automated fashion to improve the efficiency, reliability, economics, and sustainability of the production and distribution of electricity." (U.S. Department of Energy)

"*Smart Grids* … concerns an electricity network that can intelligently integrate the actions of all users connected to it - generators, consumers and those that do both - in order to efficiently deliver sustainable, economic and secure electricity supplies." (SmartGrids European Technology Platform, 2006).

"A *Smart Grid* is an electricity network that can cost efficiently integrate the behaviour and actions of all users connected to it – generators, consumers and those that do both – in order to ensure economically efficient, sustainable power system with low losses and high levels of quality and security of supply and safety." (European Commission, 2011)

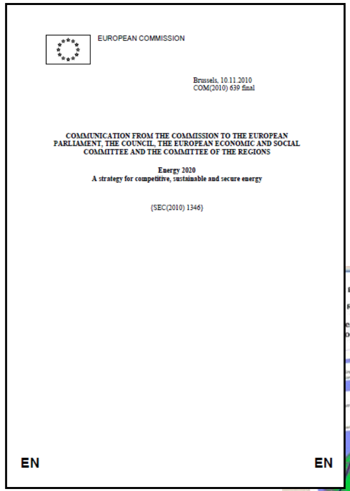
"*Smart grids* are networks that monitor and manage the transport of electricity from all generation sources to meet the varying electricity demands of end users" …. "The widespread deployment of smart grids is crucial to achieving a more secure and sustainable energy future." (International Energy Agency 2013).

Smart heating and cooling grids - 2010



4DH
4th Generation District Heating Technologies and Systems

- In the European Commission’s strategy [7] for a competitive, sustainable and secure “Energy 2020“, the need for *“high efficiency cogeneration, district heating and cooling*” is highlighted (page 8). The paper launches projects to promote, among others, *“smart electricity grids*” along with *“smart heating and cooling grids*” (page 16).


EUROPEAN COMMISSION

Brussels, 10.11.2010
COM(2010) 639 final

COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS

Energy 2020
A strategy for competitive, sustainable and secure energy

{SEC(2010) 1346}

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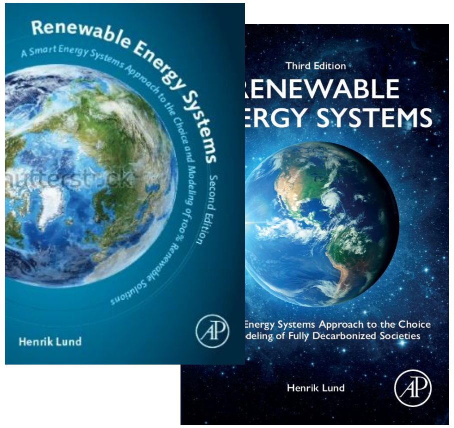
Smart Energy Systems

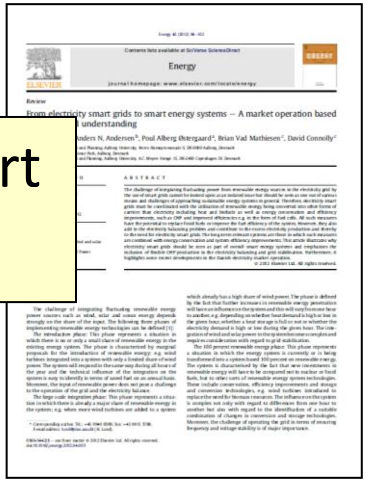


- **Smart Electricity Grids** are electricity infrastructures that can intelligently integrate the actions of all users connected to it - generators, consumers and those that do both - in order to efficiently deliver sustainable, economic and secure electricity supplies.

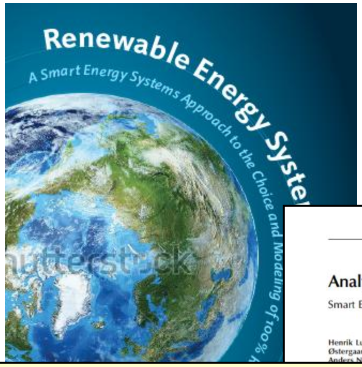
Smart Energy System is defined as an approach in which smart Electricity, Thermal and Gas Grids are combined and coordinated to identify synergies between them in order to achieve an optimal solution for each individual sector as well as for the overall energy system.

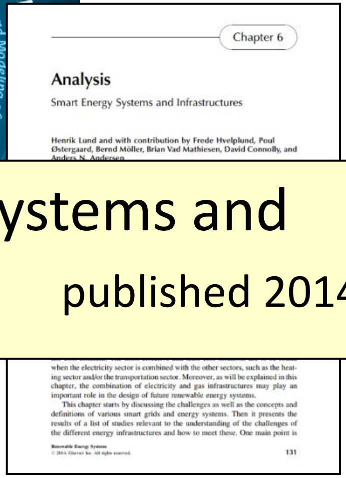
- **Smart Thermal** ... town centre or ... number of distri... from the connec...

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

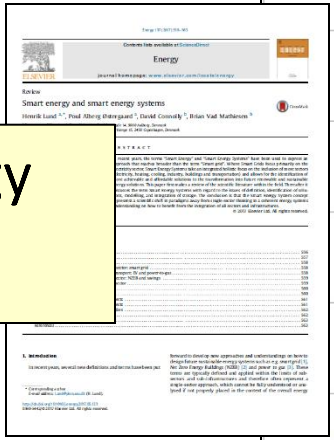


From electricity smart grids to smart energy systems published 2012

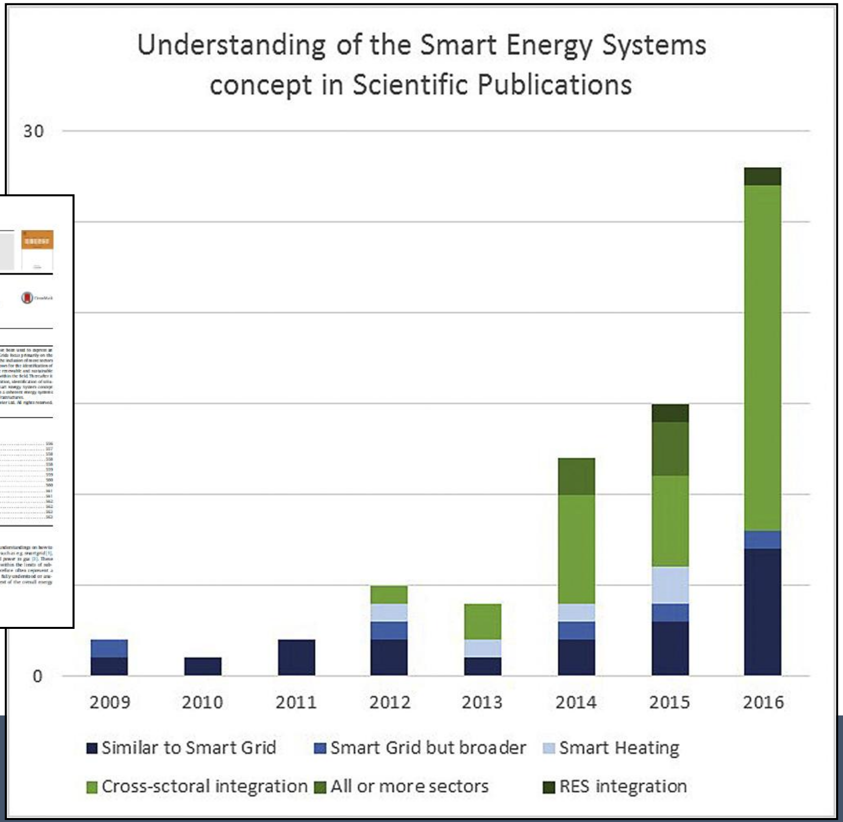


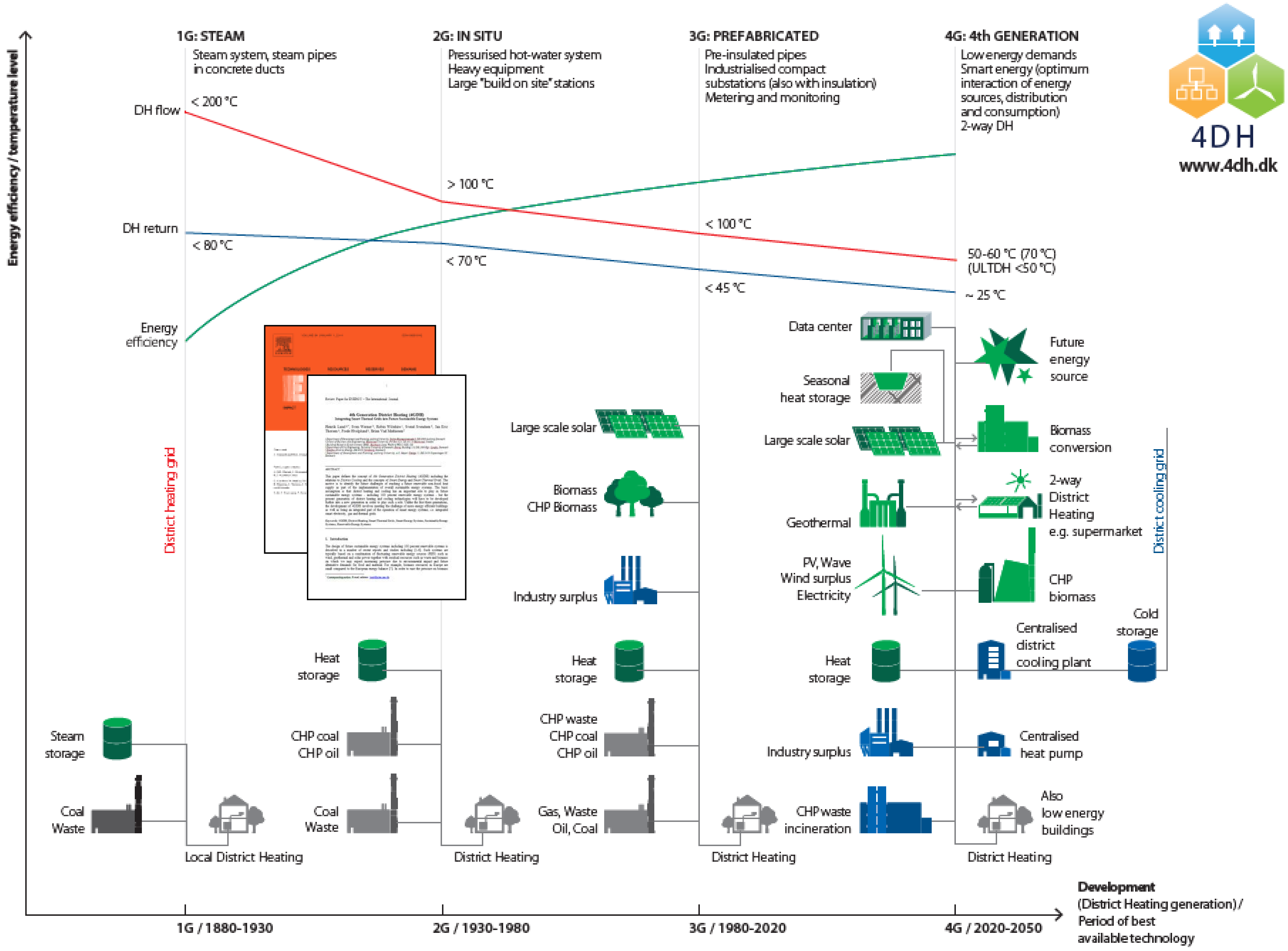


Smart Energy Systems and Infrastructures published 2014



Smart Energy and Smart Energy Systems published 2017




1G: STEAM
Steam system, steam pipes in concrete ducts
2G: IN SITU
Pressurised hot-water system
Heavy equipment
Large "build on site" stations
3G: PREFABRICATED
Pre-insulated pipes
Industrialised compact substations (also with insulation)
Metering and monitoring
4G: 4th GENERATION
Low energy demands
Smart energy (optimum interaction of energy sources, distribution and consumption)
2-way DH
4DH
www.4dh.dk
Energy efficiency / temperature level
DH flow
< 200 °C
> 100 °C
< 100 °C
50-60 °C (70 °C)
(ULTDH <50 °C)
DH return
< 80 °C
< 70 °C
< 45 °C
~ 25 °C
Energy efficiency
District heating grid
District cooling grid
Data center
Future energy source
Seasonal heat storage
Large scale solar
Biomass conversion
Biomass CHP Biomass
Geothermal
2-way District Heating e.g. supermarket
Industry surplus
PV, Wave Wind surplus Electricity
CHP biomass
Heat storage
Centralised district cooling plant
Cold storage
Steam storage
CHP coal CHP oil
CHP waste CHP coal CHP oil
Industry surplus
Centralised heat pump
Coal Waste
Gas, Waste Oil, Coal
CHP waste incineration
Also low energy buildings
Local District Heating
District Heating
1G / 1880-1930
2G / 1930-1980
3G / 1980-2020
4G / 2020-2050
Development (District Heating generation) / Period of best available technology

4GDC: 4th Generation District Cooling

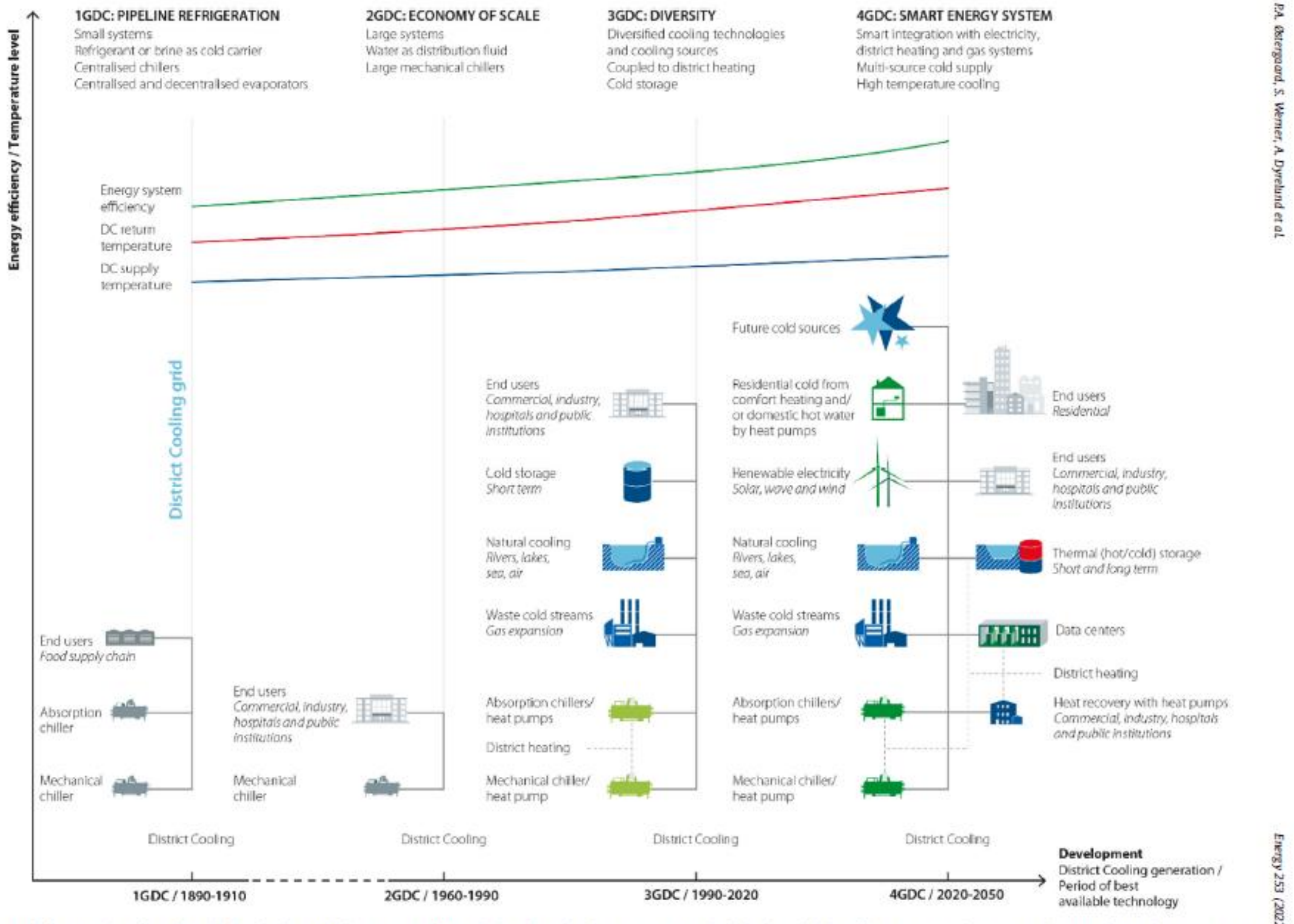


Fig. 1. *The four generations of DC. The major driver for the 4GDC is the cross-sectoral integration into the RES-based smart energy system including the exploitation of the CHC synergy wherever appropriate. Depending on the context, a 4GDC system may not include all the shown components. E.g. in climatic zones with no heat demand, current 2GDC systems may upgrade to 4GDC systems simply by integrating with other sectors and providing flexibility to the smart energy systems using solar, wind, and wave power* [79].

Energy 253 (2022) 124098

Contents lists available at ScienceDirect

Energy

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

The four generations of district cooling - A categorization of the development in district cooling from origin to future prospect

Poul Alberg Østergaard [a,*], Sven Werner [b], Anders Dyrelund [c], Henrik Lund [a], Ahmad Arabkoohsar [d], Peter Sorknæs [a], Oddgeir Gudmundsson [e], Jan Eric Thorsen [e], Brian Vad Mathiesen [f]

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A R T I C L E I N F O

Article history:
Received 19 January 2022
Received in revised form
21 April 2022
Accepted 23 April 2022
Available online 28 April 2022

Keywords:
District cooling generations
District cooling approaches
District cooling case review
Energy system integration

A B S T R A C T

Research into new advanced district heating concepts has increased since the first four generations of district heating were defined in 2014. This definition created a common framework for research and industry alike, and pointed to potential futures for district heating which could benefit from low-temperature heating in buildings. The fully developed fourth-generation district heating includes the cross-sectoral integration into the smart energy system. This paper defines four generations of district cooling to make a similar useful framework for district cooling. The first generation being pipeline refrigeration systems that were first introduced in the late 19th century, the second generation being mainly based on large compression chillers and cold water as distribution fluid, the third generation having a more diversified cold supply such as natural cooling, and the fourth generation combining cooling with other energy sectors sometimes into a renewable energy-based smart energy systems context, including combined heating and cooling.

1. Introduction

Studies show that district energy systems, such as district heating (DH) and district cooling (DC), allow for a low cost and energy-efficient transition towards renewable energy (RE)-based energy systems [1], enabling, for example, increased flexibility in the operation of energy conversion technologies [2], low-costs storage solutions [3], and the utilisation of otherwise non-utilised energy sources such as excess heat from industries and natural cooling from natural cold sources [4,5].

Globally, modern commercial DH has been utilised since the 1870s, and has since then expanded to around 80,000 systems delivering a total of around 11.5 EJ of heat in 2014 [6]. DH has especially seen a wide implementation in Russia, China, and the European Union (EU), accounting for around 85% of the globally delivered DH [4]. It is estimated that DH supplies 8% of the global end-user heating demand [4]. Due to the relatively high utilisation and potential for allowing a more fuel- and cost-efficient transition to RE-based energy systems, DH has been the subject of extensive focus within research [7] and is playing an important role in the EU and national energy policies.

Currently, it is estimated that nearly 20% of the total global electricity demand is used for cooling purposes, via air conditioners and electric fans in buildings. Furthermore, the electricity consumption due to cooling is expected to increase due to urbanisation, industrialisation, climate change, and as the standard of living increases globally, with some projecting a tripling of the current electricity demand for cooling [5]. Moreover, uncontrolled use of chillers creates a cooling peak and risk of brown-out. Where DH has seen a relatively wide global utilisation, DC is less utilised for covering cooling demands, only delivering around 300 PJ/year globally [4]. However, DC could provide a more efficient and low-cost option for covering cooling demands, as it allows for, e.g.,

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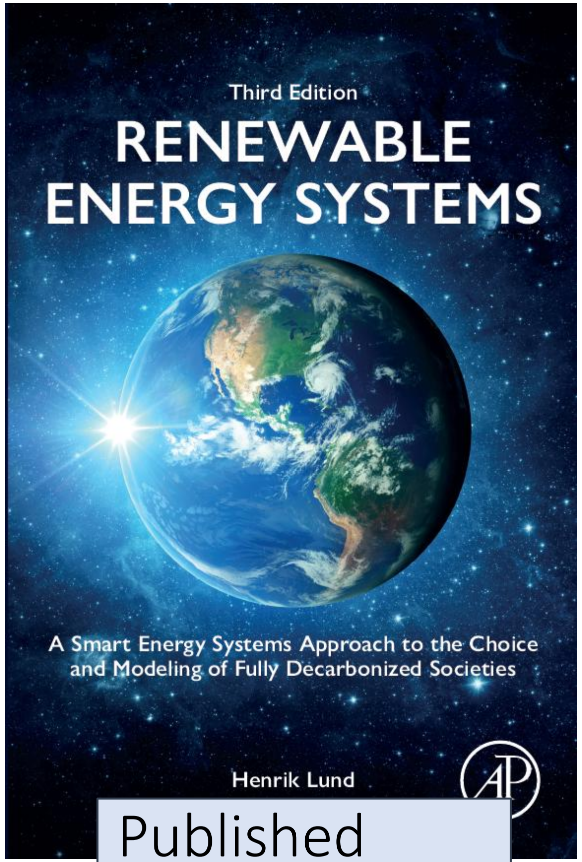
https://doi.org/10.1016/j.energy.2022.124098

New insights:

1. Explicit formulation of a Smart Energy Systems **theory** (2 thesis)

2. Next step from 100% Renewable Energy to **Climate Neutral Societies**

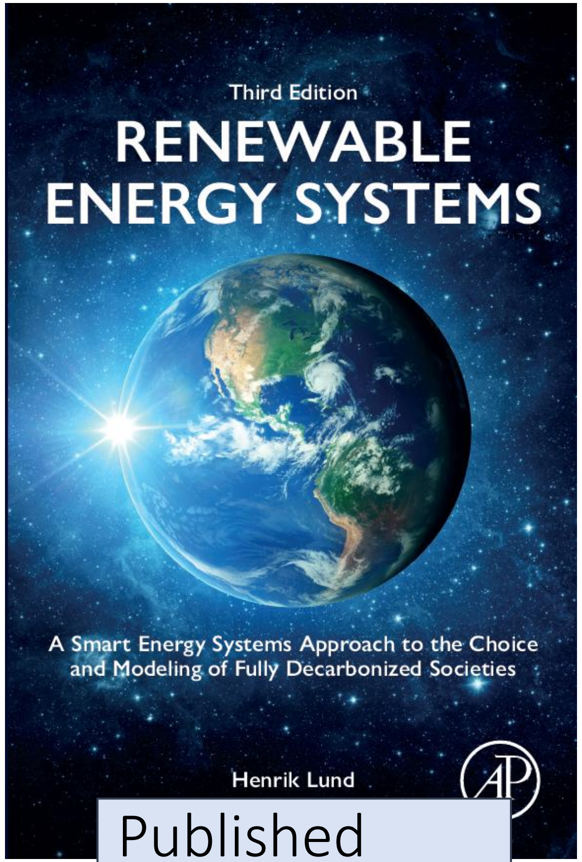
3. Application: Smart Energy System Integration Levels to illustrate the **importance of smart energy system sector integration**



Published March 2024

Two Smart Energy Systems Theses:

1. One cannot find the best solutions for affordable and reliable transitions of the energy system into a carbon neutral society solely within each subsector of the energy system. One must approach the transition in a holistic and cross-sectoral smart energy system perspective in order to be able to identify the best solution for the overall energy system and for society as a whole.
2. Subsector studies (no matter if they concern the role of a specific technology or the role of a region or country) should aim at identifying the role to play in an overall transition of the whole system, rather than aim at decarbonizing the sub-sector on its own



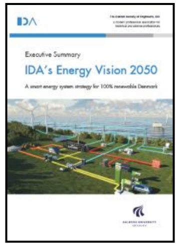
Published March 2024

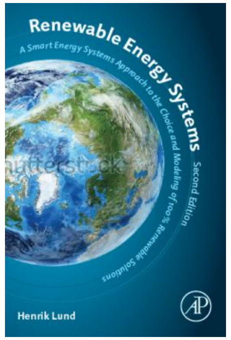
IDAs Climate Response: In a European context

Denmark should fulfill its objective of renewable energy and CO2-reductions in a way, so it fits well into a context in which the rest of Europe - and the world - will do the same.

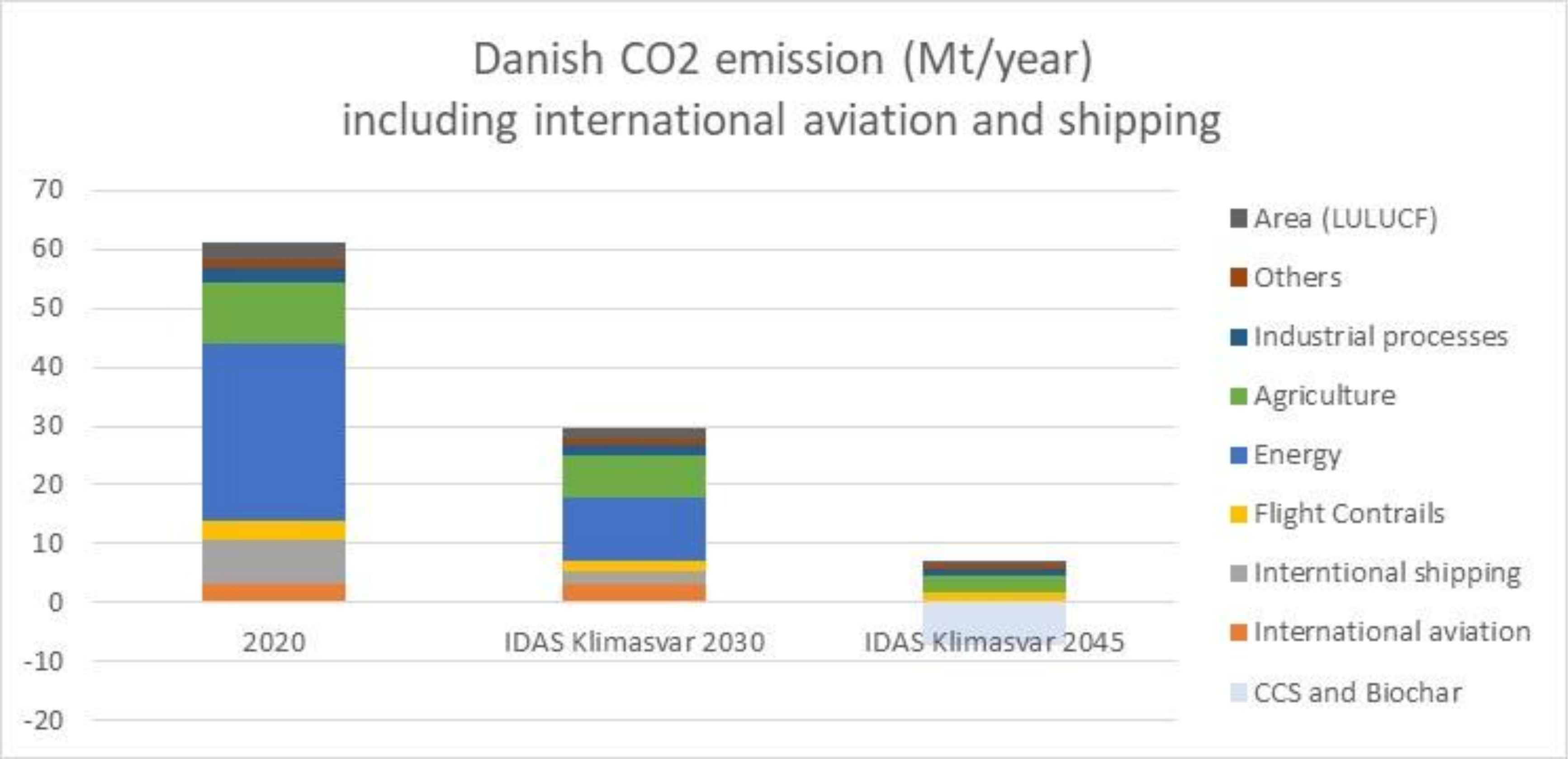
Therefore:

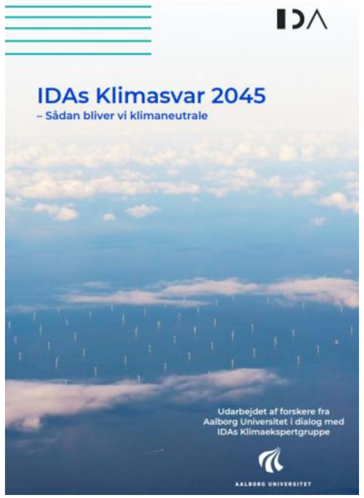
- Denmark should include the Danish share of ***international aviation and shipping*** even though it is not included yet in the UN way of calculating the Danish CO2 emissions.
- Denmark should not exceed our share of ***sustainable use of biomass*** in the world.
- Denmark should make our contribution in terms of ***flexibility and reserve capacity*** to integrate wind and solar into the ***European electricity supply***.





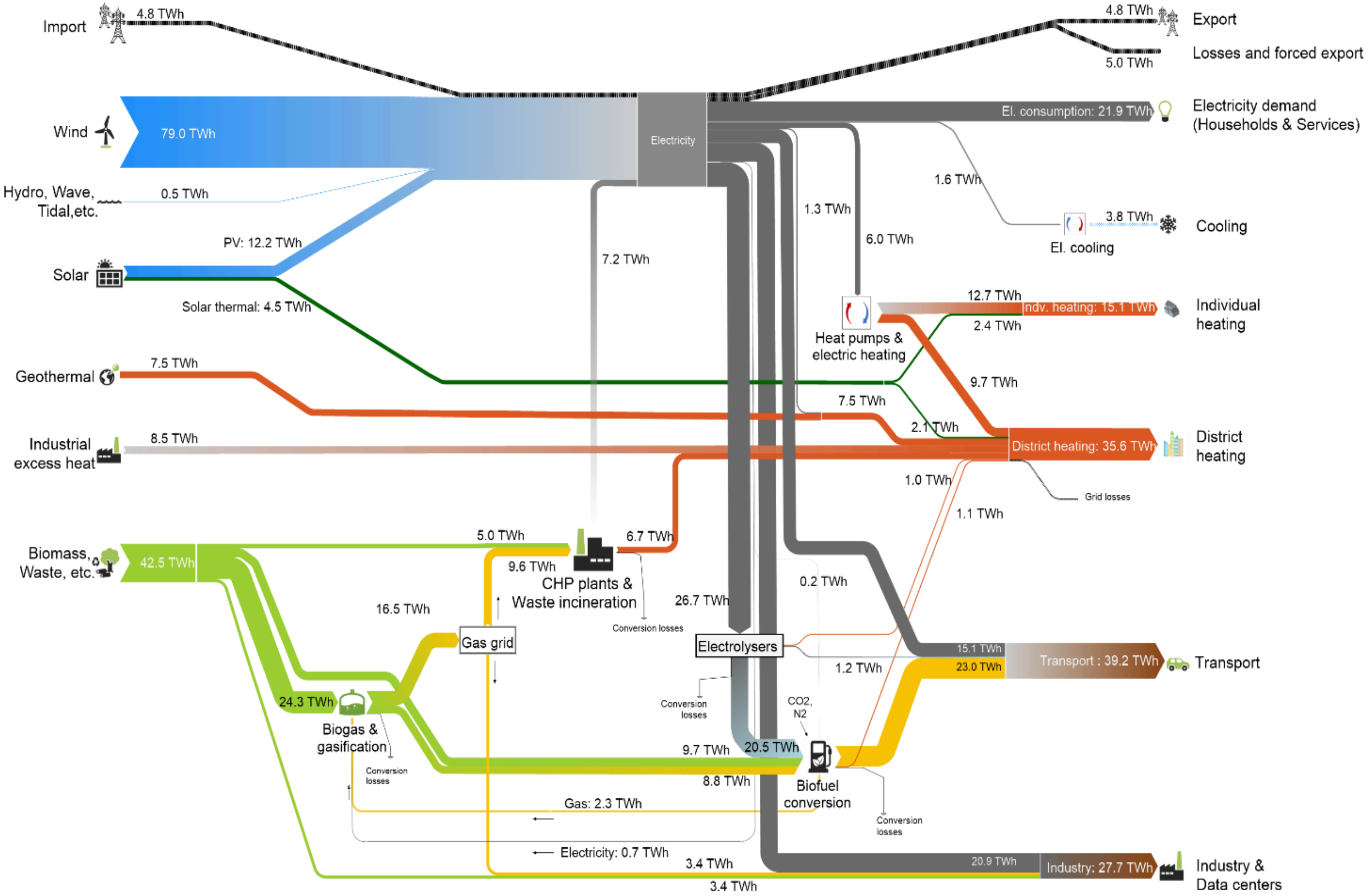
A fully decarbonized Denmark 2045





2045

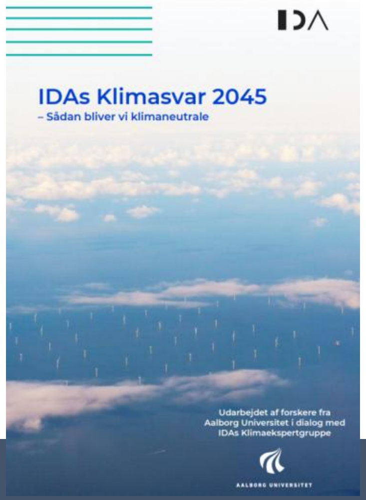

IDAs Klimasvar
– Transport- og energiløsninger 2030
IDAs Klimasvar 2045
– Sådan bliver vi klimaneutrale

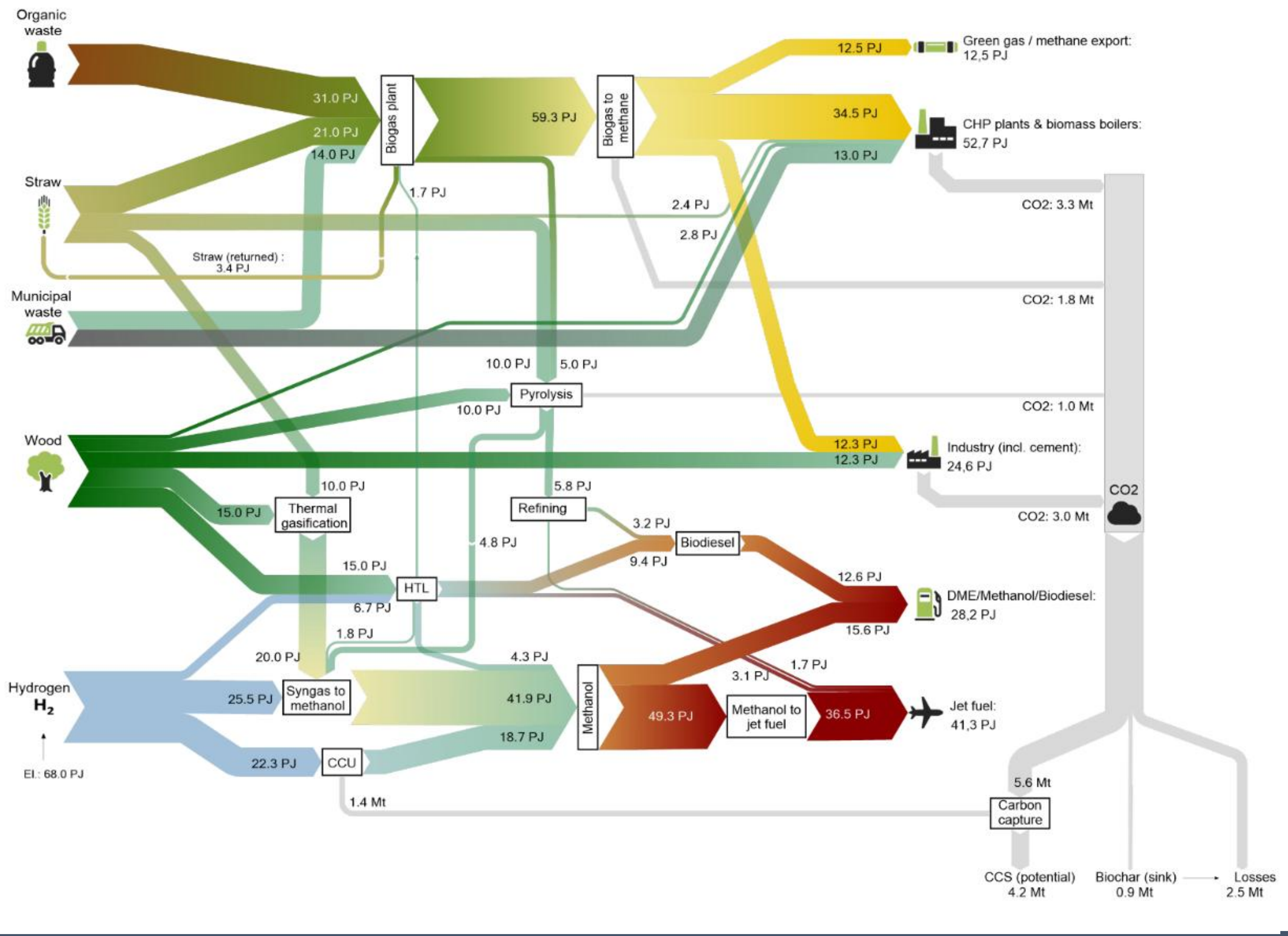

Import
4.8 TWh
Wind
79.0 TWh
Hydro, Wave, Tidal,etc.
0.5 TWh
PV: 12.2 TWh
Solar
Solar thermal: 4.5 TWh
Geothermal
7.5 TWh
Industrial excess heat
8.5 TWh
Biomass, Waste, etc.
42.5 TWh
Electricity
7.2 TWh
5.0 TWh
6.7 TWh
9.6 TWh
CHP plants & Waste incineration
Conversion losses
16.5 TWh
Gas grid
26.7 TWh
Electrolysers
24.3 TWh
Biogas & gasification
Conversion losses
9.7 TWh
20.5 TWh
8.8 TWh
CO2, N2
Biofuel conversion
Conversion losses
Gas: 2.3 TWh
Electricity: 0.7 TWh
3.4 TWh
3.4 TWh
4.8 TWh
Export
5.0 TWh
Losses and forced export
El. consumption: 21.9 TWh
Electricity demand (Households & Services)
1.6 TWh
1.3 TWh
6.0 TWh
3.8 TWh
Cooling
El. cooling
12.7 TWh
Indv. heating: 15.1 TWh
Individual heating
2.4 TWh
Heat pumps & electric heating
9.7 TWh
7.5 TWh
2.1 TWh
District heating: 35.6 TWh
District heating
1.0 TWh
Grid losses
1.1 TWh
0.2 TWh
15.1 TWh
Transport : 39.2 TWh
Transport
1.2 TWh
23.0 TWh
20.9 TWh
Industry: 27.7 TWh
Industry & Data centers

Biomasse 2045

Overview:

(153 PJ minus eksport 13 PJ = 140 PJ svarende til 23 GJ/capita)

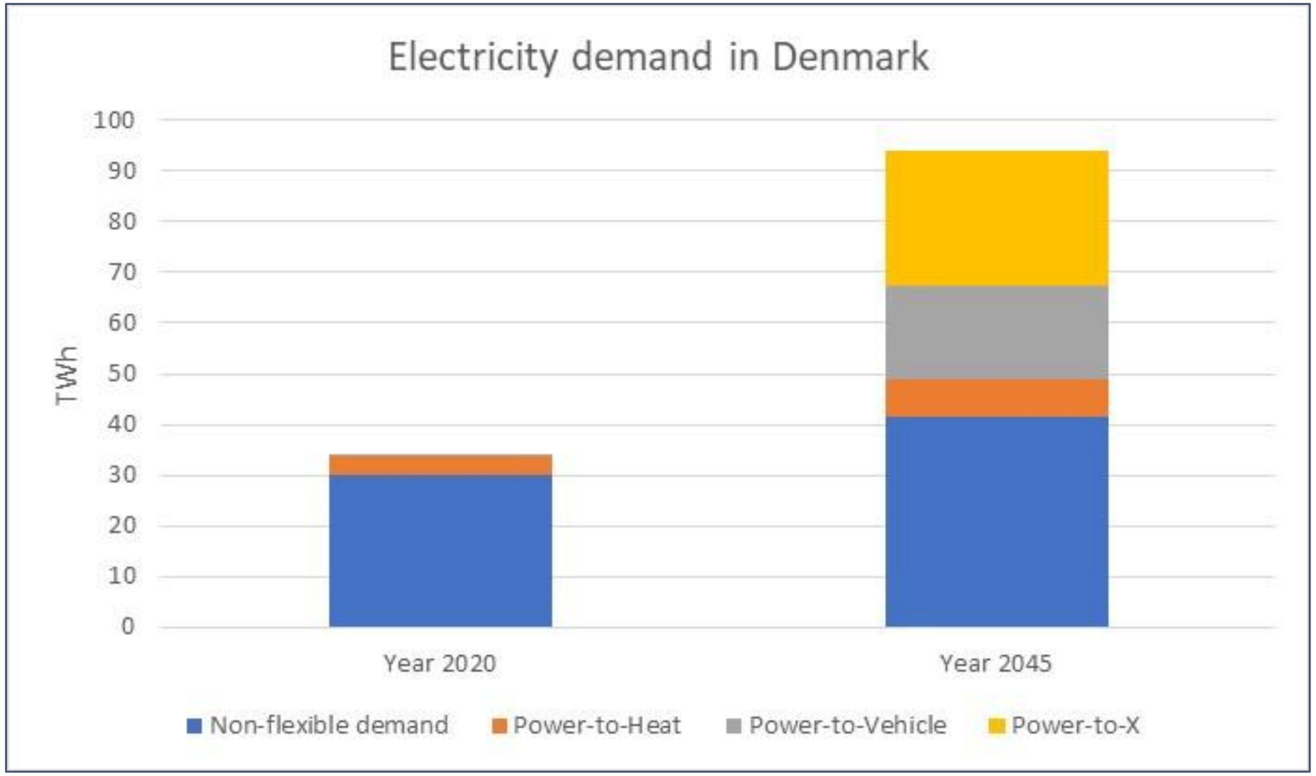




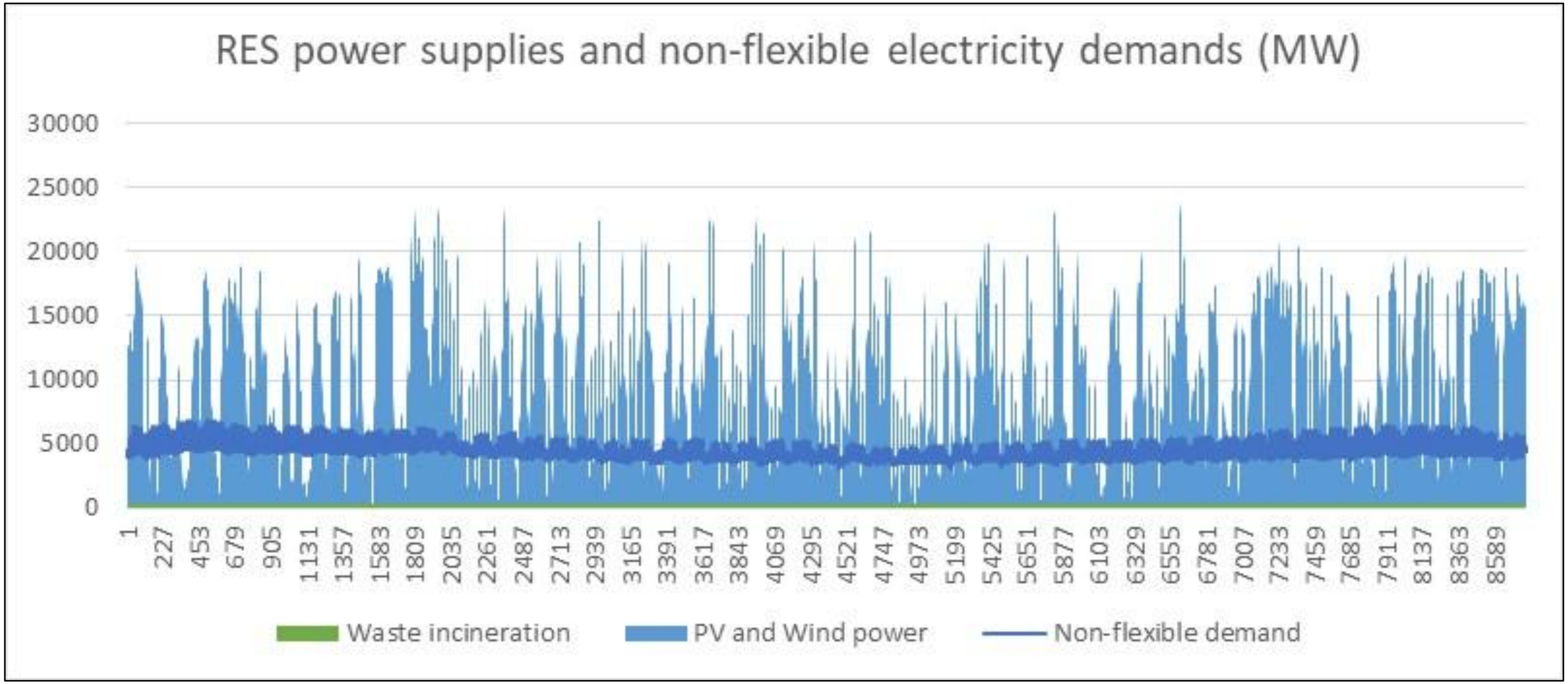
Essential changes in the future electricity demand

The ”classical” non-flexible electricity demand increases by new flexible demands for:

- Electric Vehicles
- Power-to-Heat (heat pumps and electrical boilers)
- Electrolysis and Power-to-X



PV and wind will cover the ”classical” non-flexible electricity demand in the hour except for only 7%



Literature:

Renewable and Sustainable Energy Reviews 60 (2016) 1634–1653

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

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

Smart Energy Europe: The technical and economic impact of one potential 100% renewable energy scenario for the European Union

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ARTICLE INFO

Article history:
Received 29 September 2015
Received in revised form
19 February 2016
Accepted 29 February 2016
Available online 26 March 2016

Keywords:
100% renewable energy
Jobs
Europe
EnergyPLAN

ABSTRACT

This study presents one scenario for a 100% renewable energy system in Europe by the year 2050. The transition from a business-as-usual situation in 2050, to a 100% renewable energy Europe is analysed in a series of steps. Each step reflects one major technological change. For each step, the impact is presented in terms of energy (primary energy supply), environment (carbon dioxide emissions), and economy (total annual socio-economic cost). The steps are ordered in terms of their scientific and political certainty as follows: decommissioning nuclear power, implementing a large amount of heat savings, converting the private car fleet to electricity, providing heat in rural areas with heat pumps, providing heat in urban areas with district heating, converting fuel in heavy-duty vehicles to a renewable electrofuel, and replacing natural gas with methane. The results indicate that by using the *Smart Energy System* approach, a 100% renewable energy system in Europe is technically possible without consuming an unsustainable amount of bioenergy. This is due to the additional flexibility that is created by connecting the electricity, heating, cooling, and transport sectors together, which enables an intermittent renewable penetration of over 80% in the electricity sector. The cost of the *Smart Energy Europe* scenario is approximately 10–15% higher than a business-as-usual scenario, but since the final scenario is based on local investments instead of imported fuels, it will create approximately 10 million additional direct jobs within the EU.

Contents

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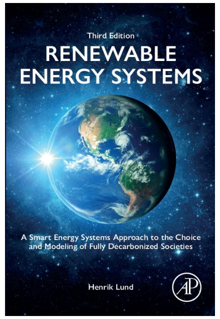
http://dx.doi.org/10.1016/j.rser.2016.02.025

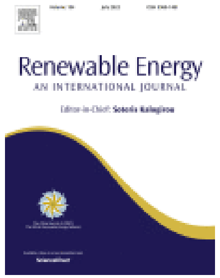
- Smart Energy Denmark. A consistent and detailed strategy for a fully decarbonized society. **Renewable and Sustainable Energy Reviews**

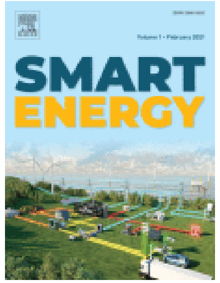
- Smart Energy Europe: **The technical and economic impact of one potential 100% renewable energy scenario for the European Union**. **Renewable and Sustainable Energy Reviews**, **Vol 60**, pp. 1634–1653, July 2016.

- **The role of sustainable bioenergy in a fully decarbonised society**, **Renewable Energy**, August 2022, https://doi.org/10.1016/j.renene.2022.06.026

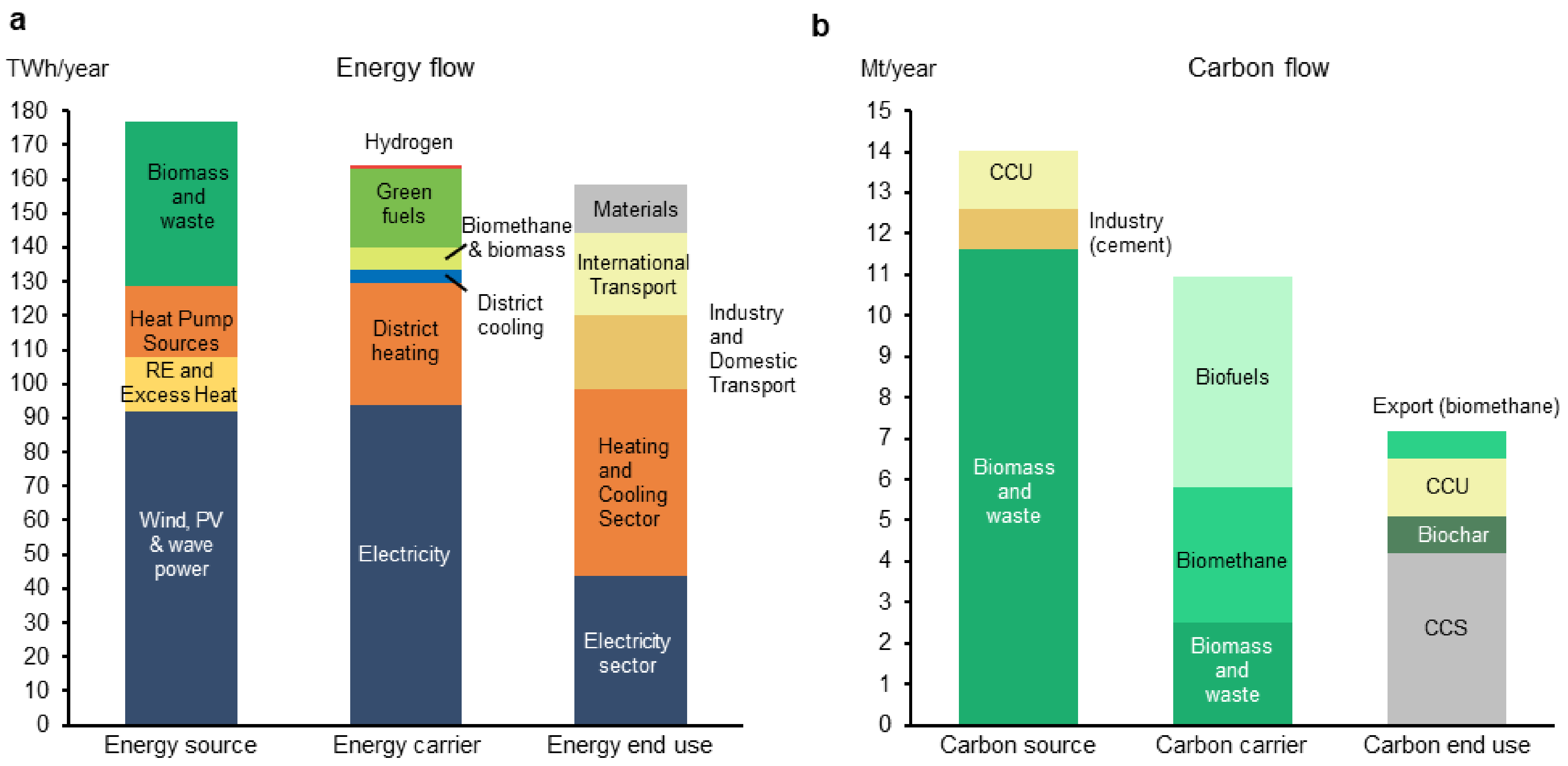
- **Energy efficient decarbonisation strategy for the Danish transport sector by 2045**, Smart Energy, February 2022. https://doi.org/10.1016/j.segy.2022.100063



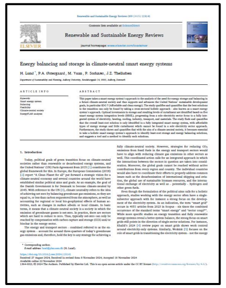


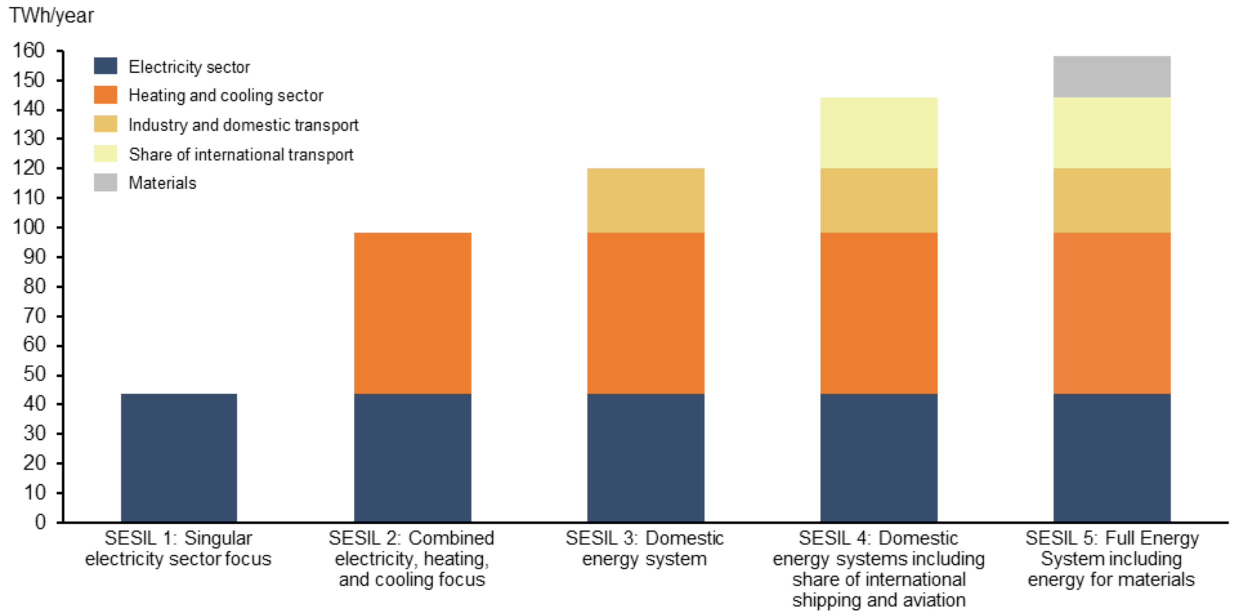


Energy and Carbon Flows of the "Smart Energy Denmark 2045" scenario



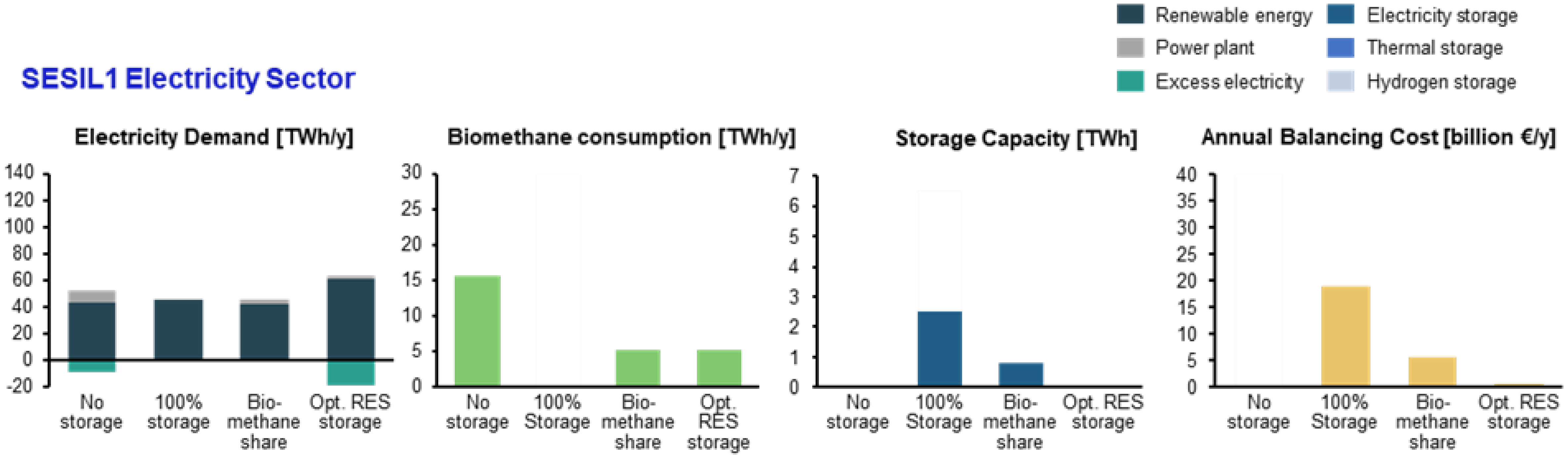
System Integration levels (SESIL)



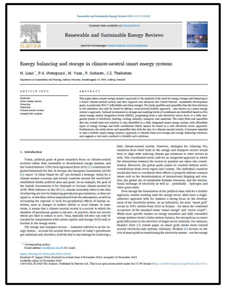


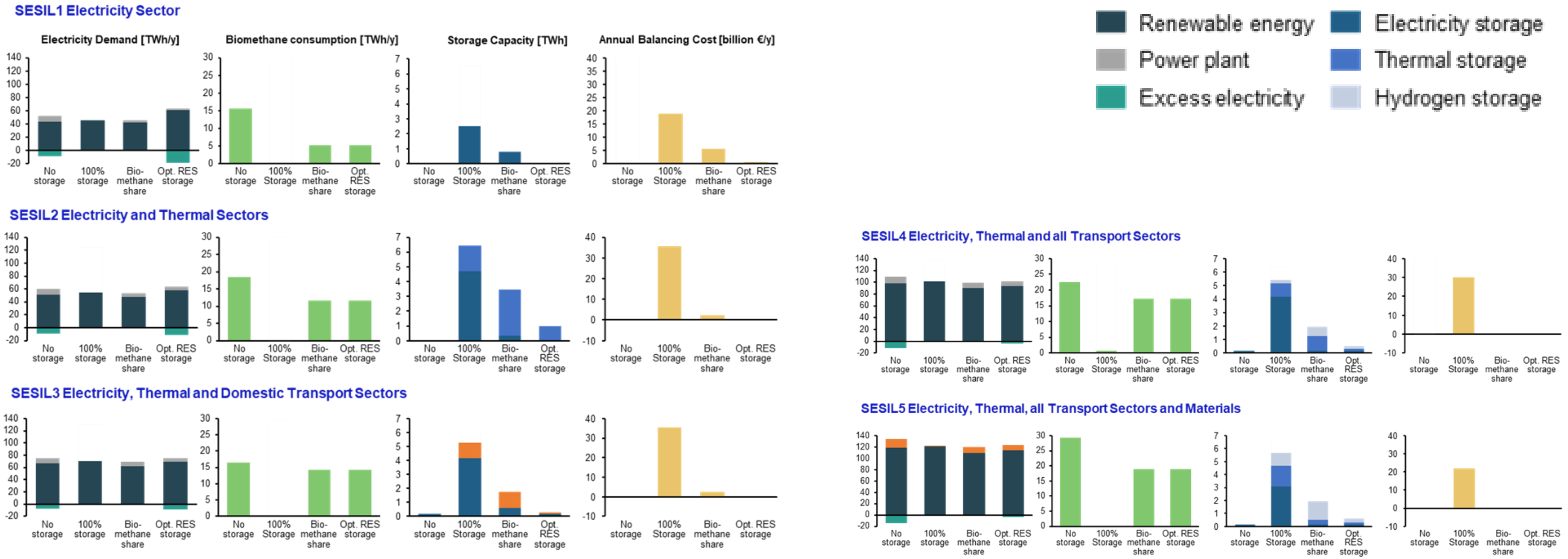
- *SESIL 1: Singular electricity sector focus.* The classical electricity demand with electricity storage as the only option.
- *SESIL 2: Combined electricity, heating, and cooling focus.* Thermal storage as an additional option.
- *SESIL 3: Domestic energy system*. Industrial and domestic transport demands. Smart charging or even V2G.
- *SESIL 4: Domestic energy systems including the share of international shipping and aviation.* Significant increase in Power-to-X technologies to provide liquid green fuels. Gaseous and liquid green fuel storage.
- *SESIL 5: Full Energy System including energy for materials.*

Electricity balancing and least-cost storage solutions in SESIL1

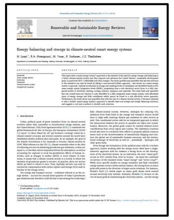


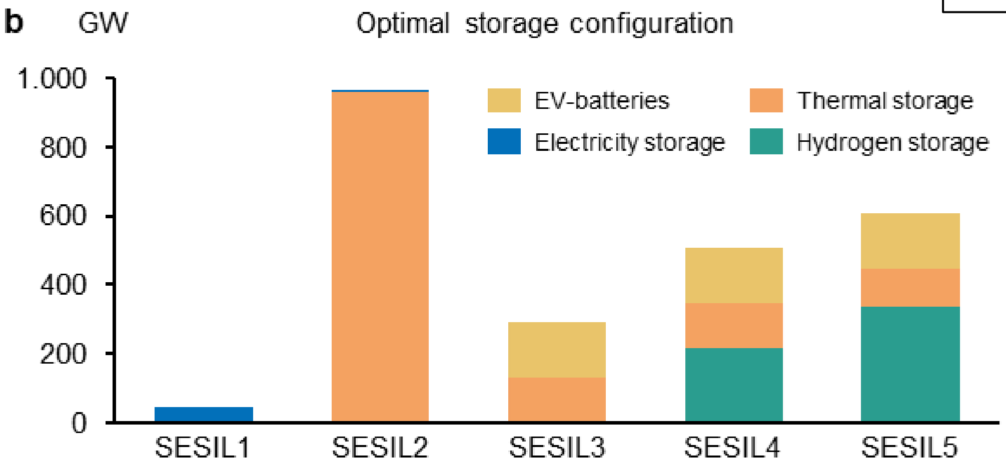
Electricity balancing and least-cost storage solutions in each of the five SESILs

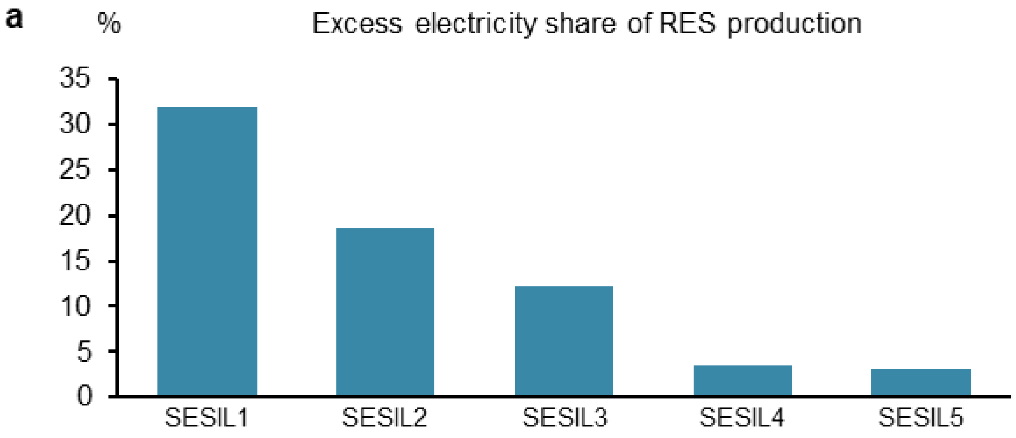


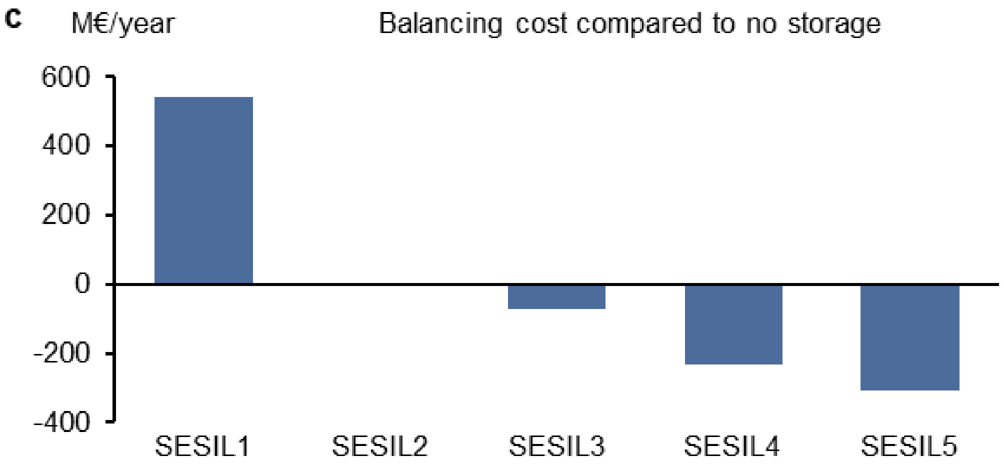


Comparison of least-cost balancing and storage solutions

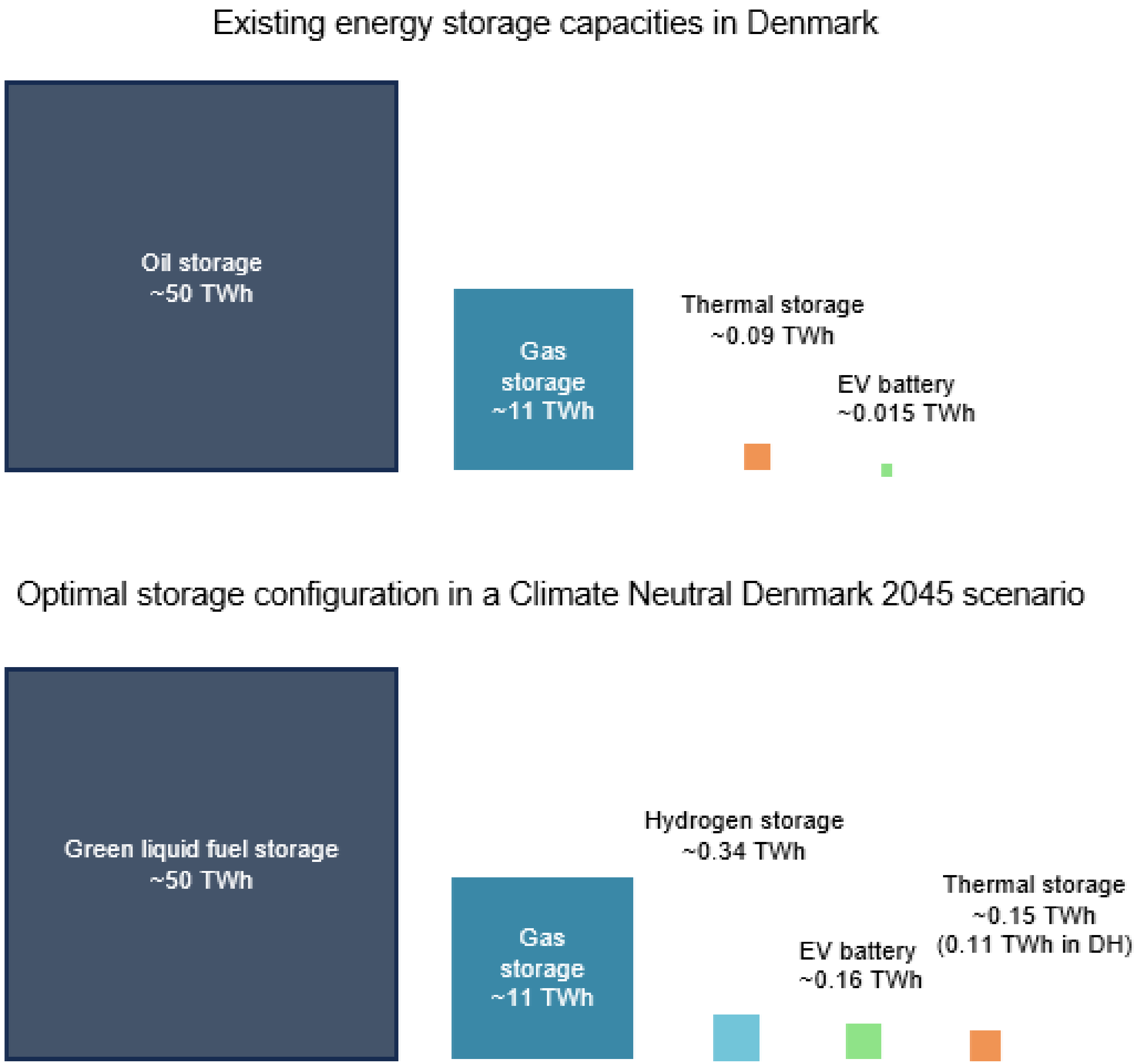








The need for storage in a climate-neutral Denmark




Renewable and Sustainable Energy Reviews 209 (2025) 115141

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

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

Energy balancing and storage in climate-neutral smart energy systems

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ARTICLE INFO

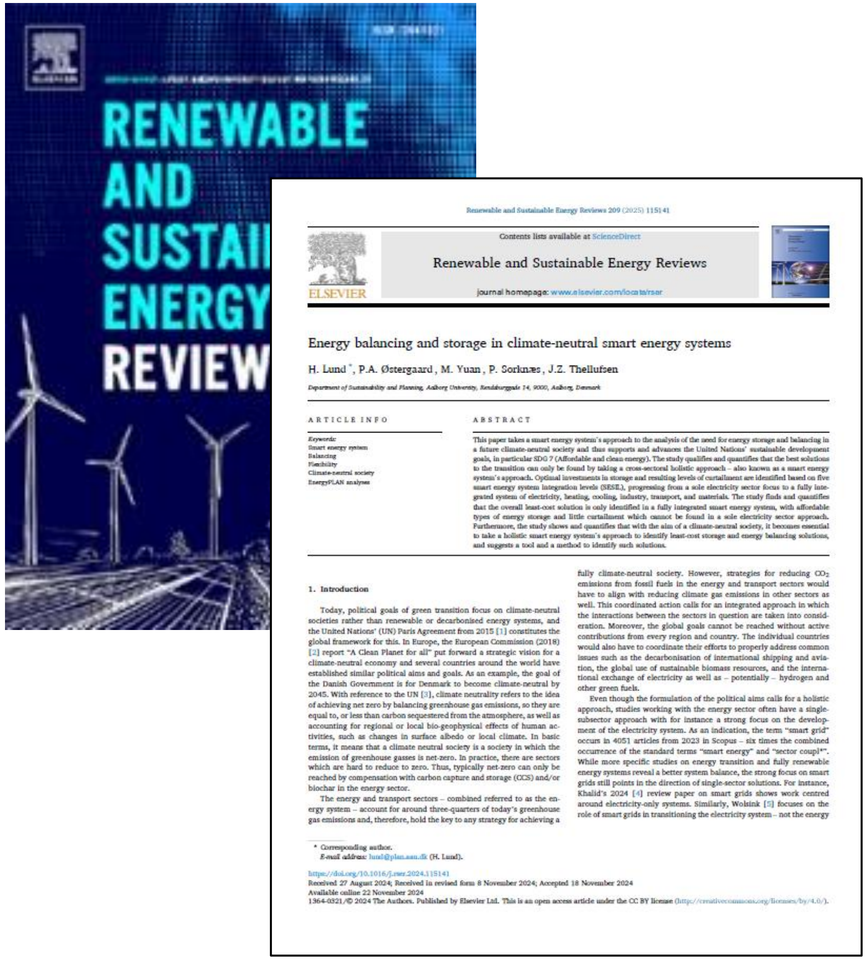
Keywords:
Smart energy system
Balancing
Flexibility
Climate-neutral society
EnergyPLAN analyses

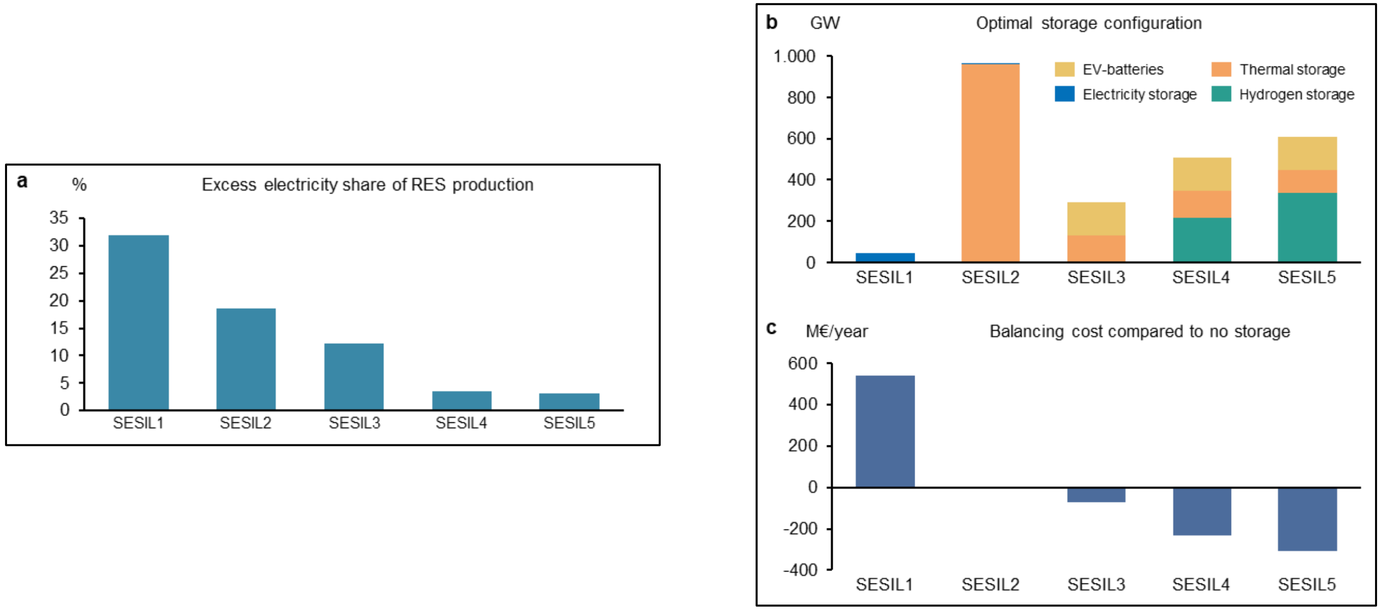
ABSTRACT

This paper takes a smart energy system's approach to the analysis of the need for energy storage and balancing in a future climate-neutral society and thus supports and advances the United Nations' sustainable development goals, in particular SDG 7 (Affordable and clean energy). The study qualifies and quantifies that the best solutions to the transition can only be found by taking a cross-sectoral holistic approach – also known as a smart energy system's approach. Optimal investments in storage and resulting levels of curtailment are identified based on five smart energy system integration levels (SESIL), progressing from a sole electricity sector focus to a fully integrated system of electricity, heating, cooling, industry, transport, and materials. The study finds and quantifies that the overall least-cost solution is only identified in a fully integrated smart energy system, with affordable types of energy storage and little curtailment which cannot be found in a sole electricity sector approach. Furthermore, the study shows and quantifies that with the aim of a climate-neutral society, it becomes essential to take a holistic smart energy system's approach to identify least-cost storage and energy balancing solutions, and suggests a tool and a method to identify such solutions.

Literature:

- Energy balancing and storage in climate-neutral smart energy systems, [Renewable and Sustainable Energy Reviews](#), [Volume 209](#), March 2025, 11514. https://doi.org/10.1016/j.rser.2024.115141



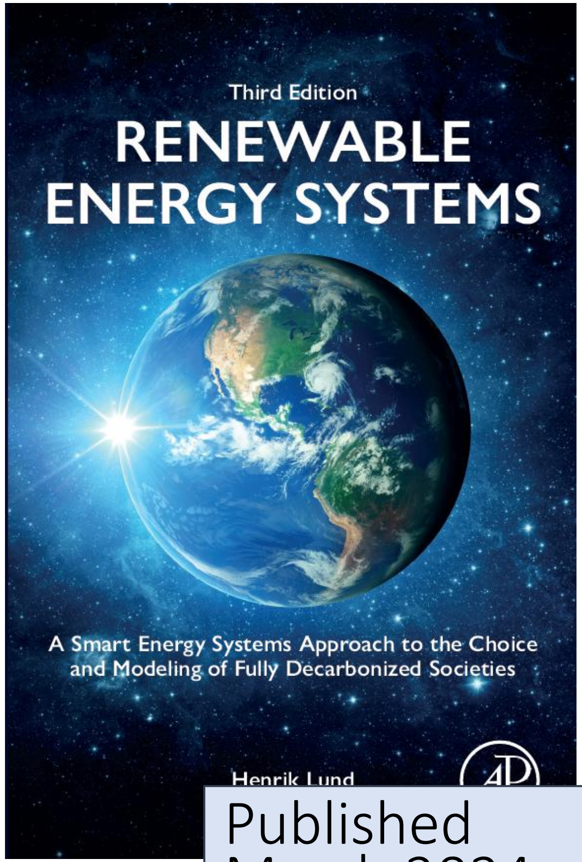


Some important news:

1. A **Smart Energy Systems approach** allows for finding a better solution to the green transition.

2. The context of **Climate Neutral Societies** defines a new paradigm for the design of solutions

3. Future Smart Energy System allows for **affordable storage solutions**



Published March 2024

New study (not published yet)

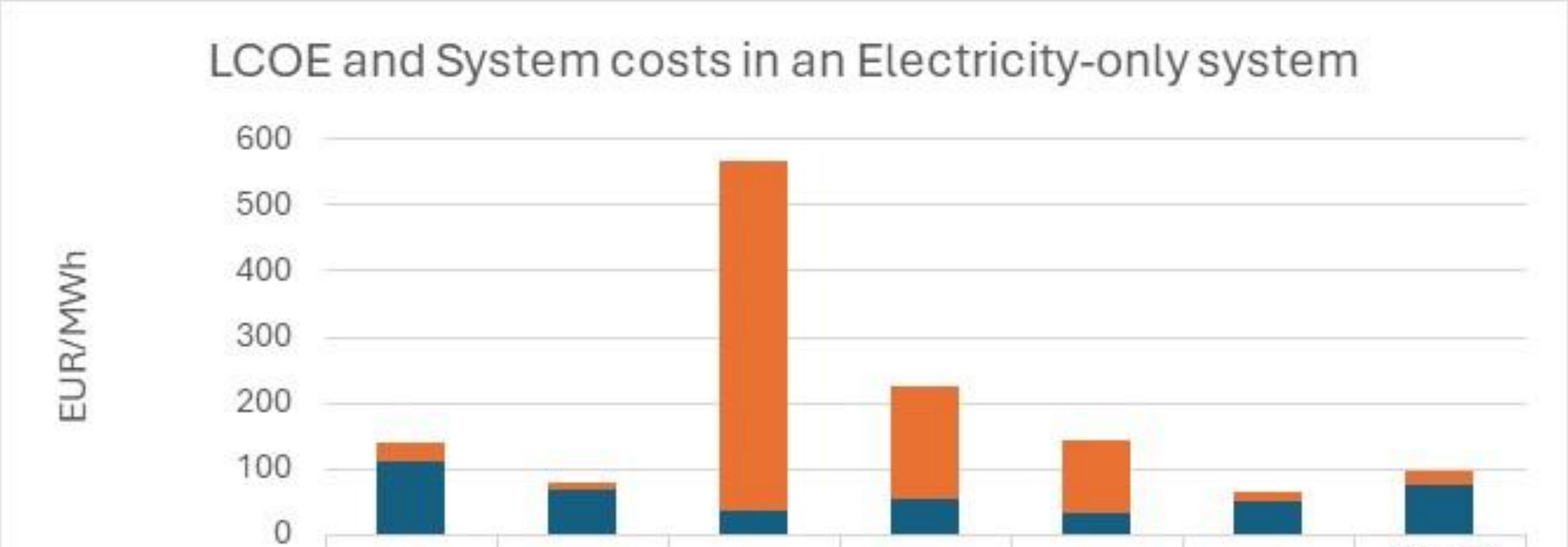
LCOE (Levelized Cost of Energy) vs SLCOE (System Levelized Cost of Energy)

LCOE = f (technology)

SLCOE = f (technology, energy system)

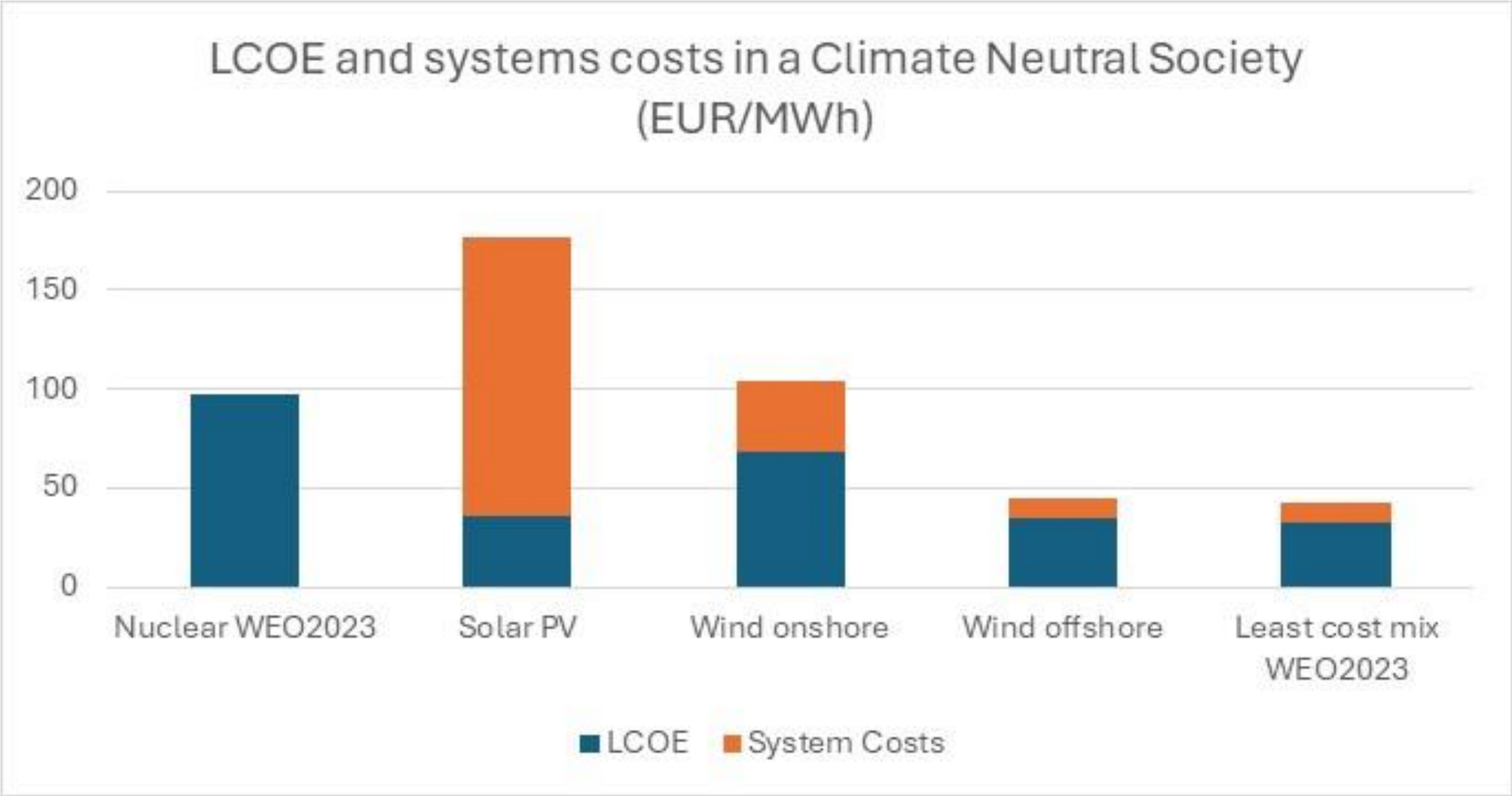
Moreover, the identification of least cost solutions imply combination of technologies and cannot be found only by comparing each of the individual technologies.

Results: (S)LCOE in an Electricity-only system

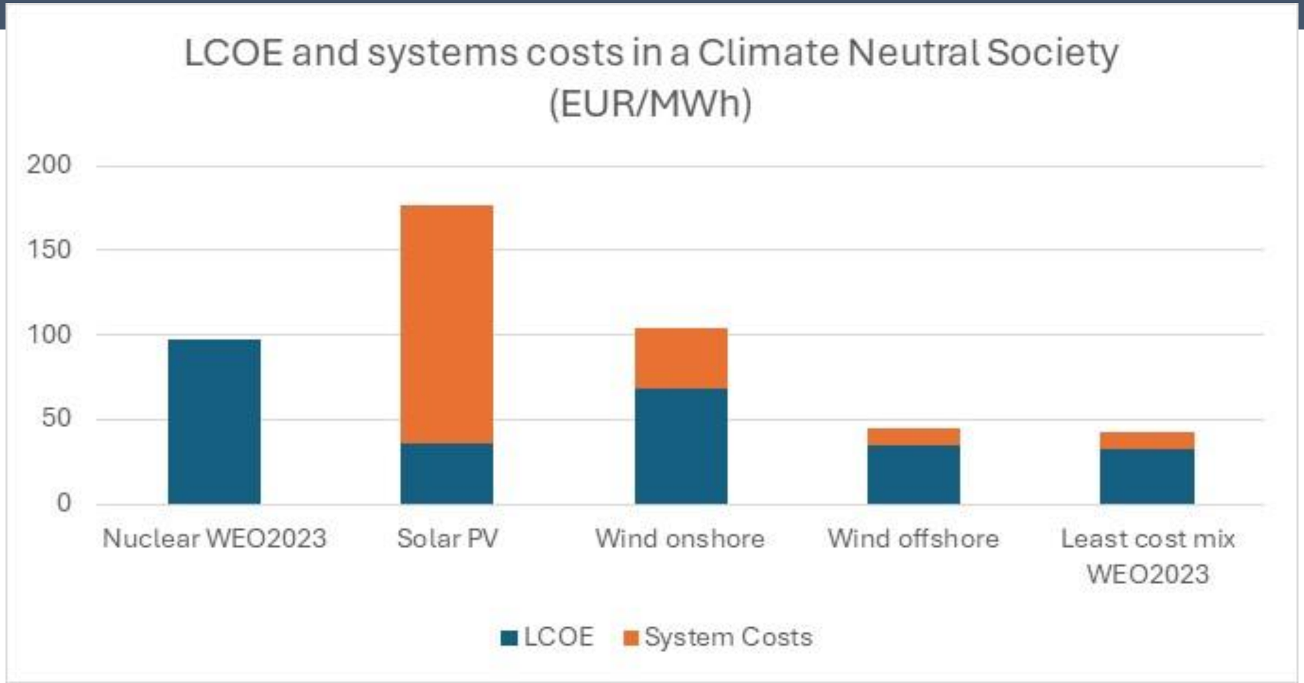


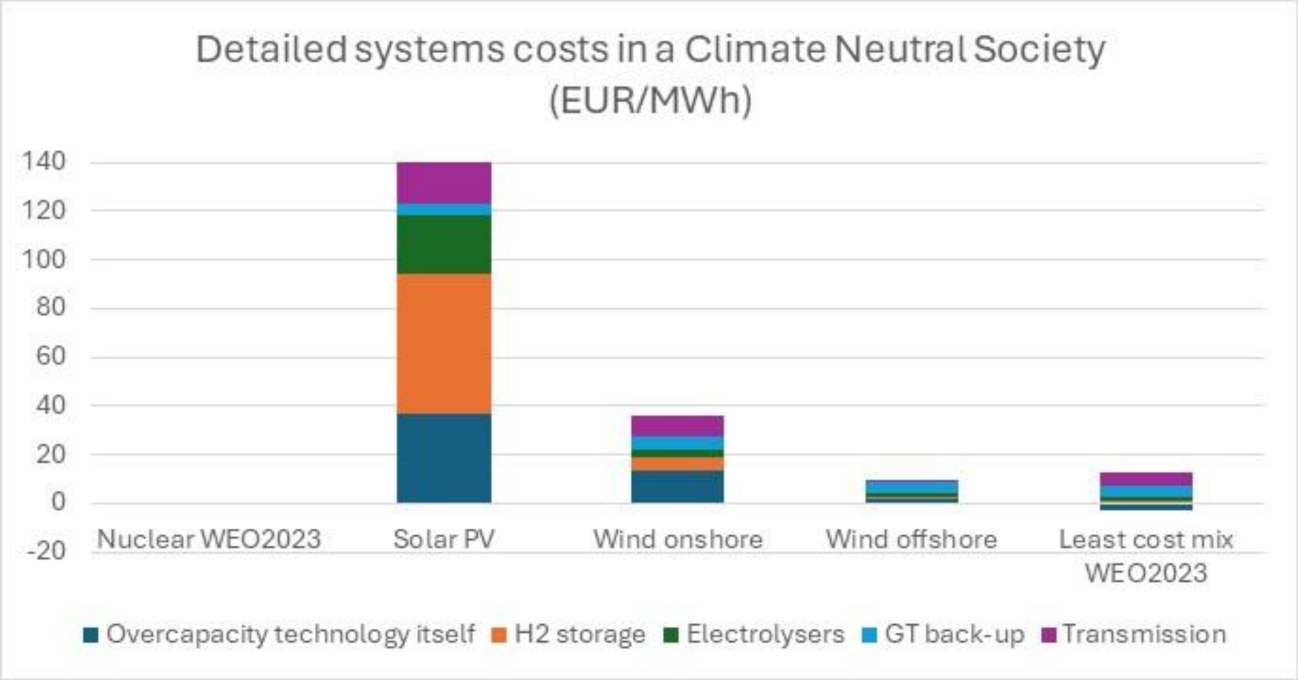
	Nuclear NOAK	Gas CCGT	Solar PV	Wind onshore	Wind offshore	Least cost mix	LC mix Biomass restricte d
System Costs	31	8	530	172	109	15	22
LCOE	110	70	35	55	35	51	77

Results: (S)LCOE in a Climate Neutral Society



Breakdown of system cost





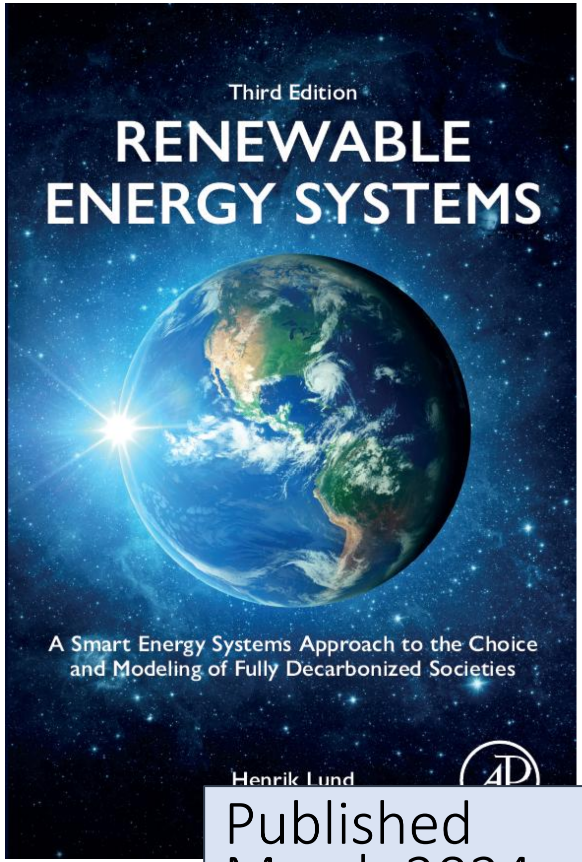
Some important news:

1. A **Smart Energy Systems approach** allows for finding a better solution to the green transition.

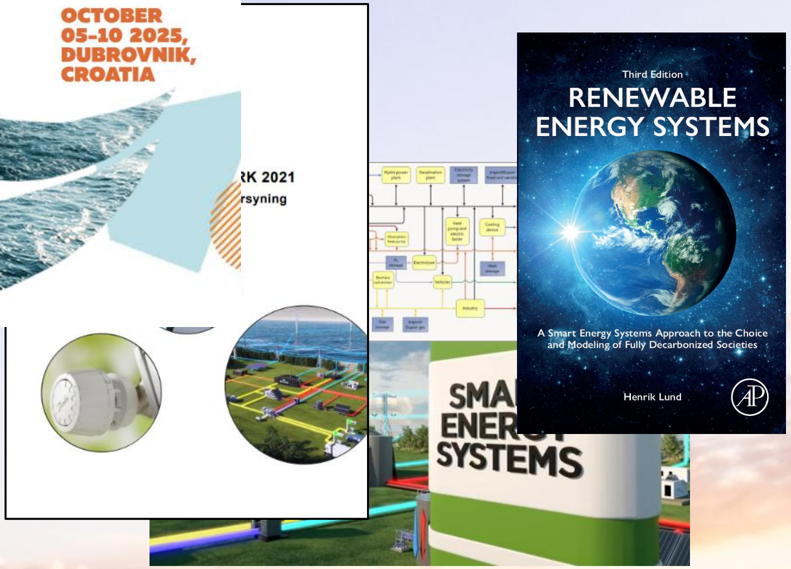
2. The context of **Climate Neutral Societies** defines a new paradigm for the design of solutions

3. Future Smart Energy System allows for **affordable storage solutions**

4. Combinations of different PV and Wind sources provide for the least cost system integration costs.



Published March 2024



4DH
4th Generation District Heating Technologies and Systems

Smart Renewable Energy Systems in the Era of Climate Neutral Societies

Professor Henrik Lund
Aalborg Universitet

INNO-CCUS Carbon capture, utilisation and storage

IAM COMPACT

JOINING FORCES FOR SUSTAINABLE ENERGY DENMARK

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MISSION GREEN FUELS