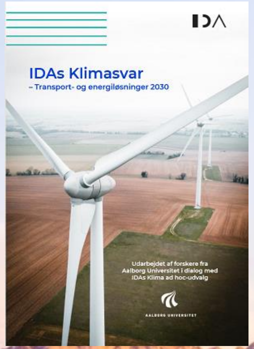
17TH CONFERENCE ON SUSTAINABLE DEVELOPMENT OF ENERGY, WATER AND ENVIRONMENT SYSTEMS

6-10 NOVEMBER, 2022
PAPHOS, CYPRUS



Smart Renewable Energy Systems and a fully decarbonized society

Professor Henrik Lund
Aalborg Universitet

SENTINEL
SUSTAINABLE ENERGY TRANSITIONS

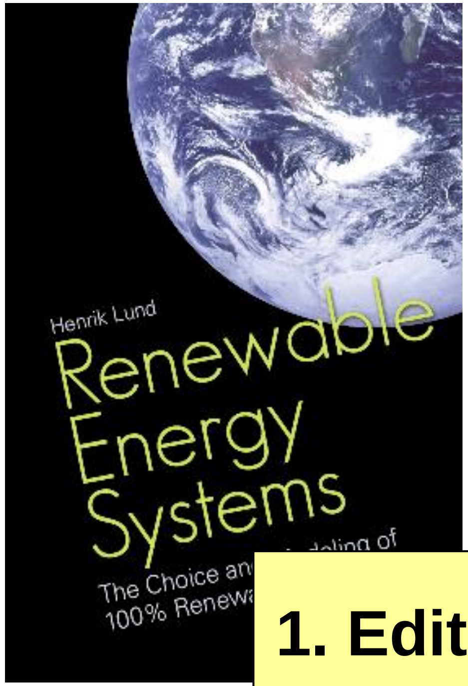
sEEnergies

AALBORG UNIVERSITY
DENMARK

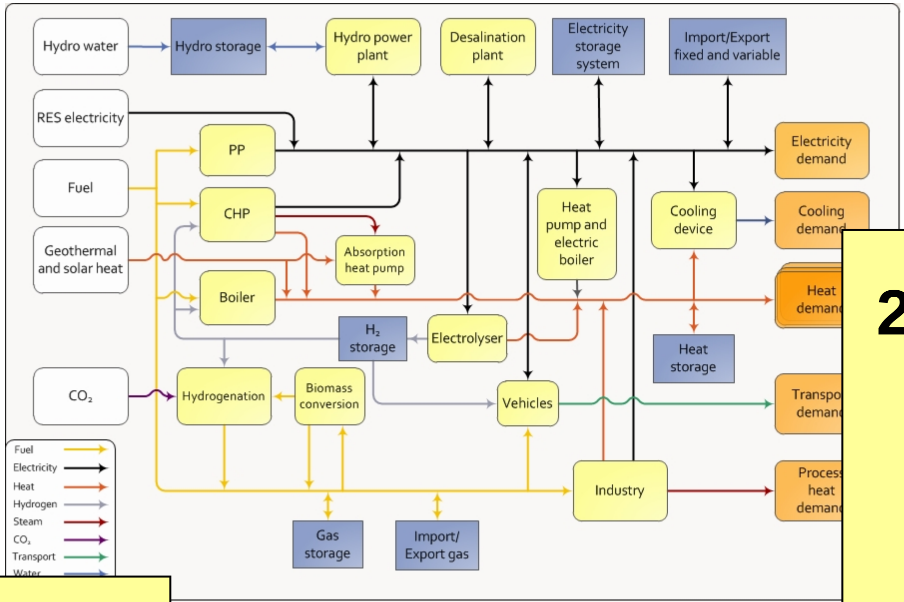
MISSION GREEN FUELS

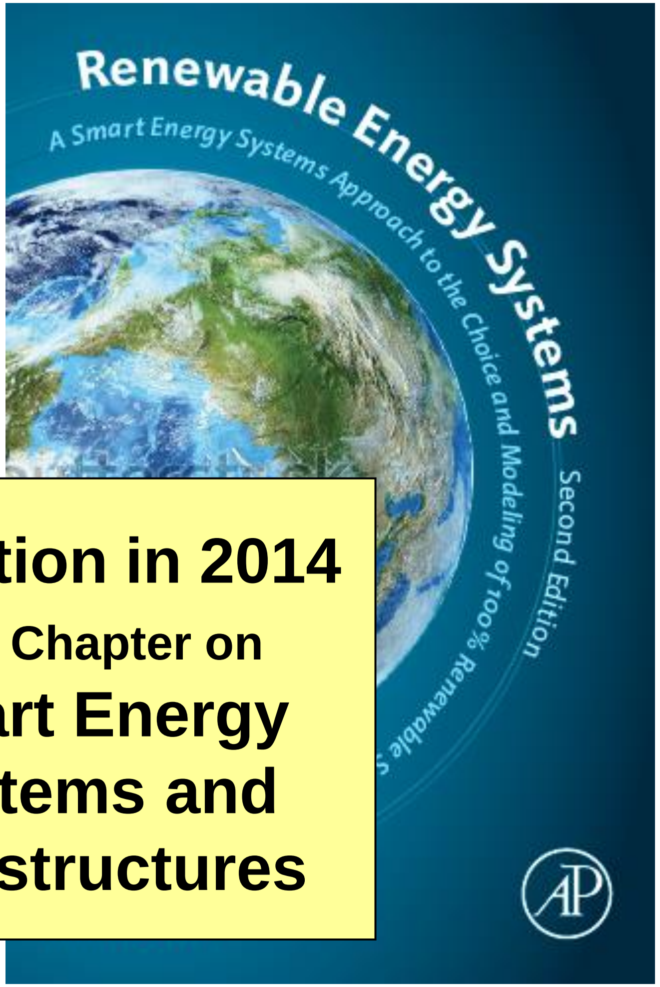
Renewable Energy Systems

A Smart Energy Systems Approach to the Choice and Modeling of 100% Renewable Solutions



1. Edition in 2010





2. Edition in 2014

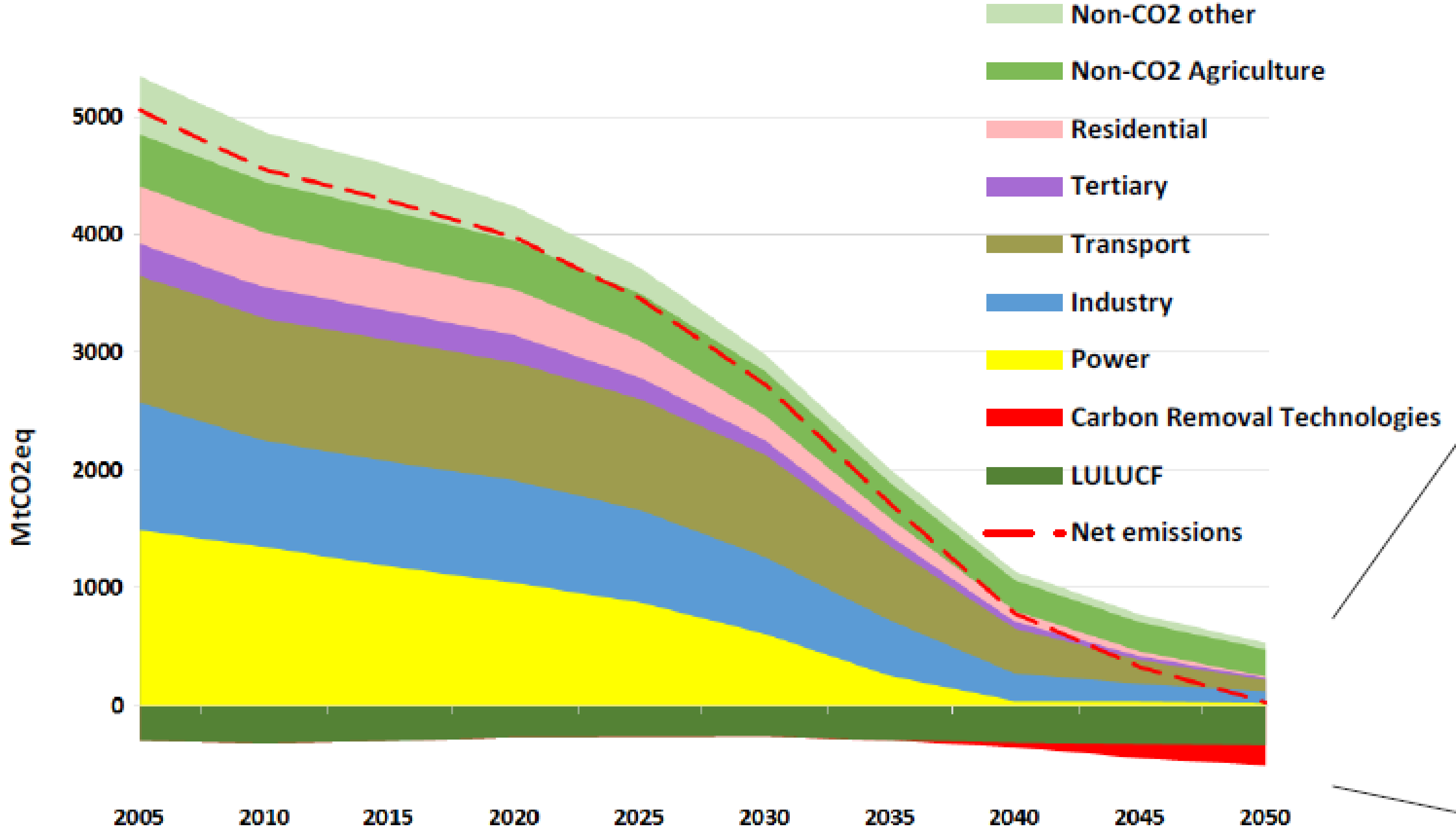
New Chapter on

Smart Energy Systems and Infrastructures

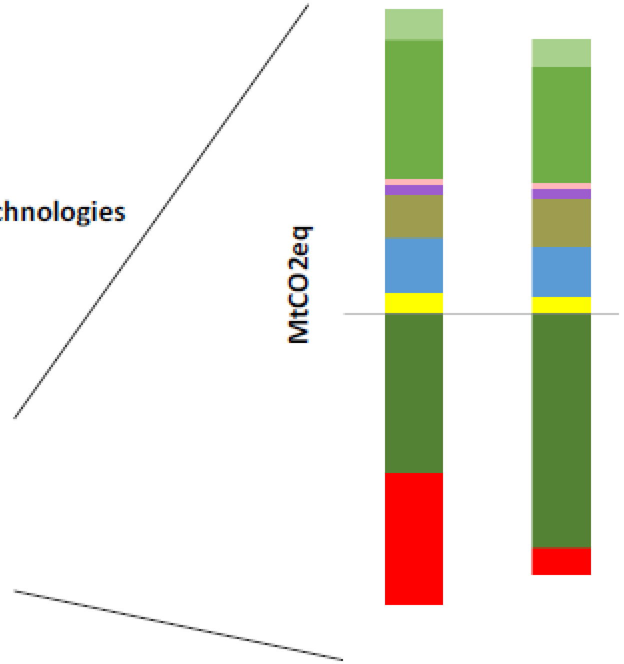
A Clean Planet for all

Climate Neutral

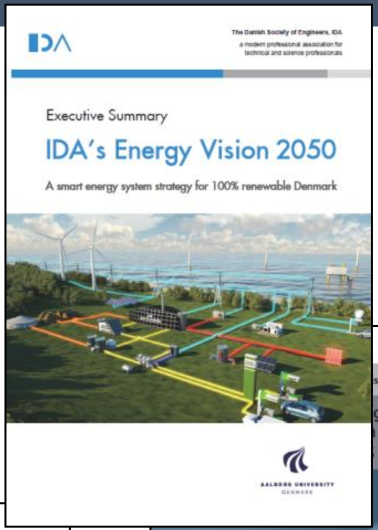
A European long-term strategic vision
for a prosperous, modern, competitive and climate neutral economy



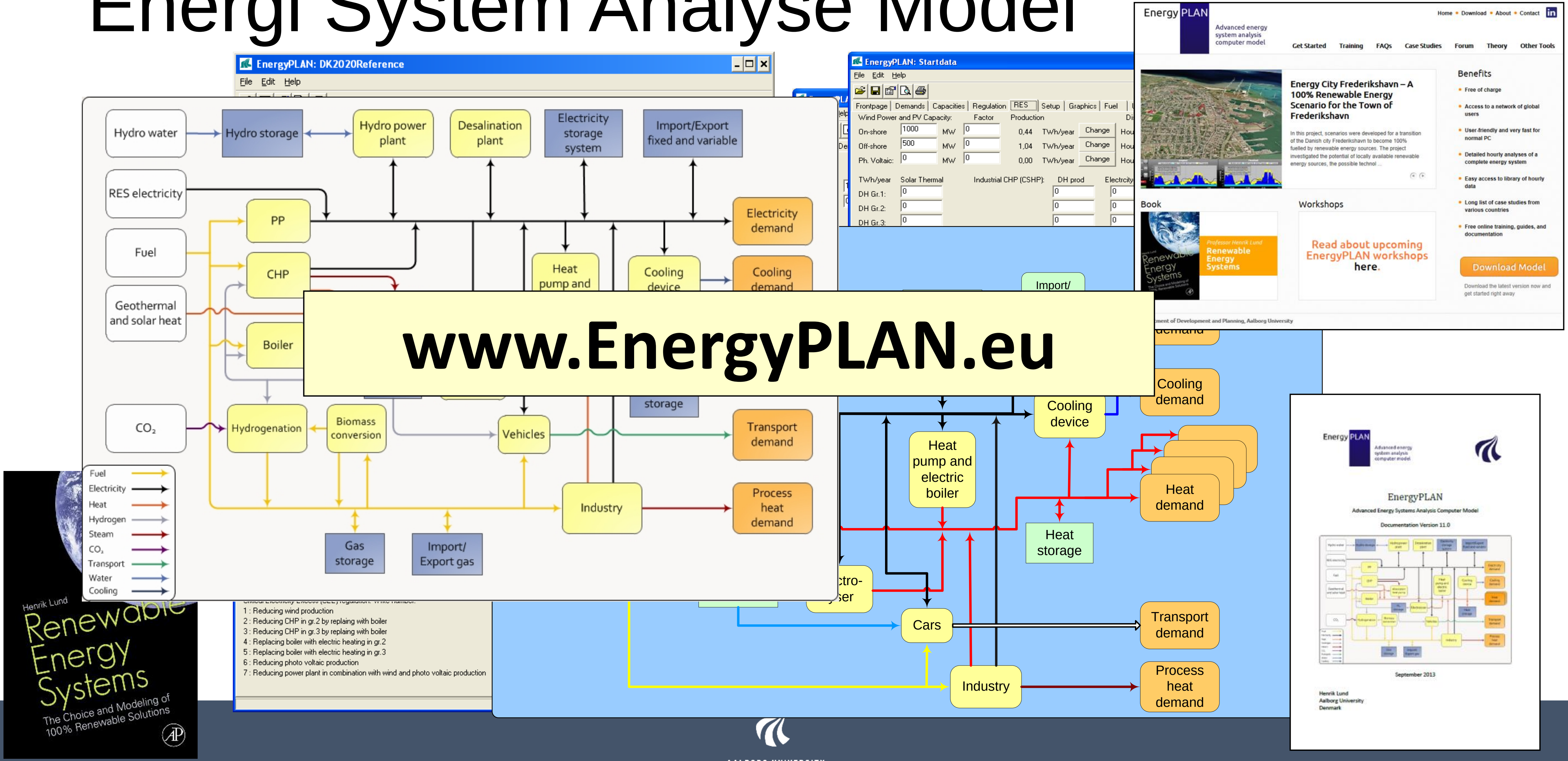
Different zero GHG pathway
lead to different levels of
remaining emissions and
absorption of GHG emission



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



Energi System Analyse Model

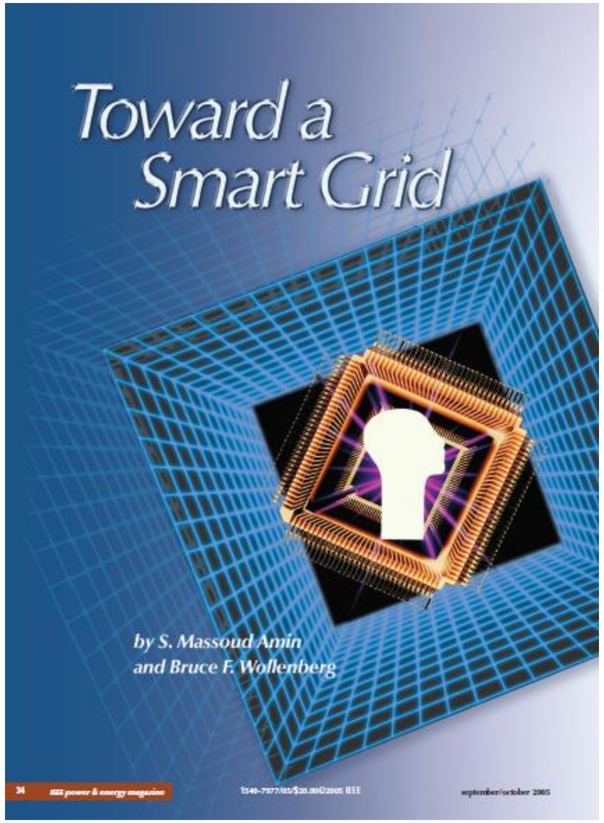


www.EnergyPLAN.eu

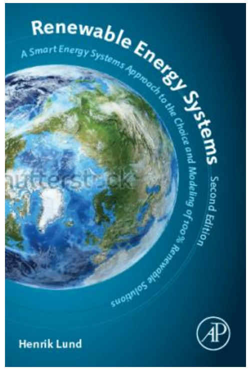
Smart Grid (2005)

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.

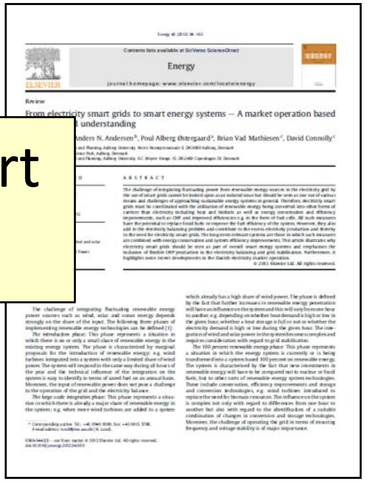


Smart Energy Systems

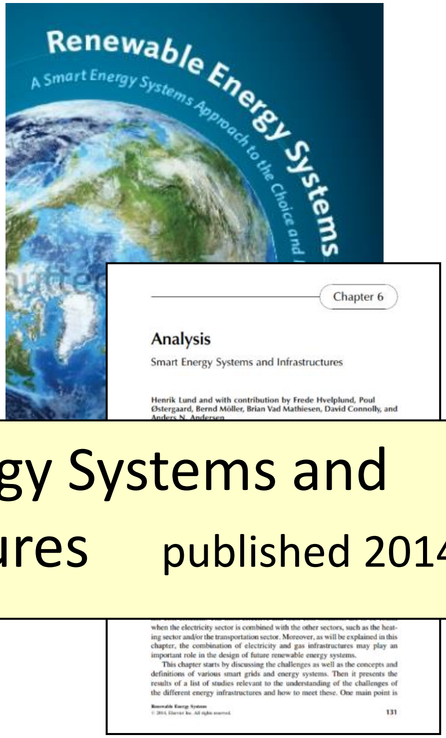


- **Smart Electricity Grids** are electricity infrastructures that can intelligently integrate the actions of all users connected to it - generators, consumers and those that do both - in order to efficiently deliver sustainable, economic and secure el
- **Smart Thermal Grids** are a network of pipes in a neighbourhood, town centre or whole c served from centralised plants as well as fro distributed heating or cooling production ur contributions from the connected buildings.
- **Smart Gas Grids** are gas infrastructures that integrate the actions of all users connected consumers and those that do both - in order to efficiently deliver sustainable, economic and secure gas supplies and storage.

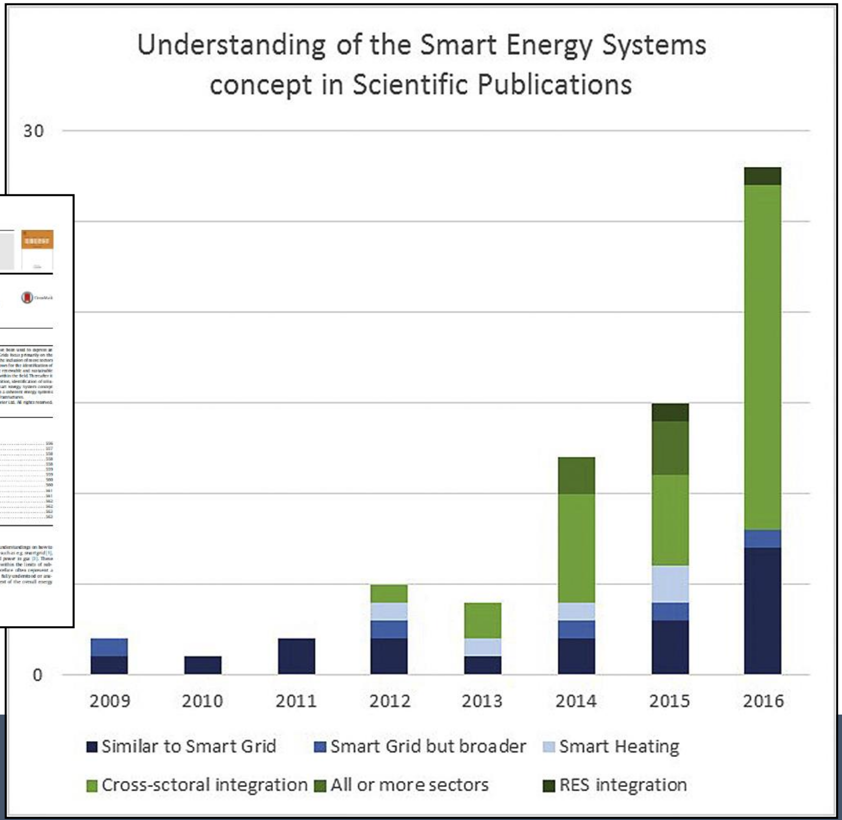
- **Smart Energy System** is defined as an approach in which smart Electricity, Thermal and Gas Grids are combined and coordinated to identify synergies between them in order to achieve an optimal solution for each individual sector as well as for the overall energy system.

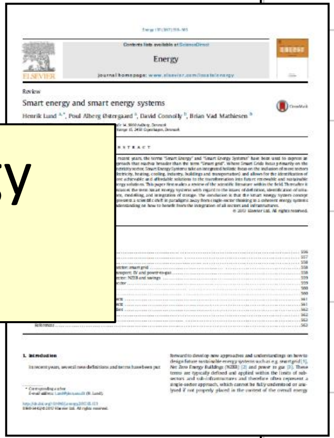


From electricity smart grids to smart energy systems published 2012



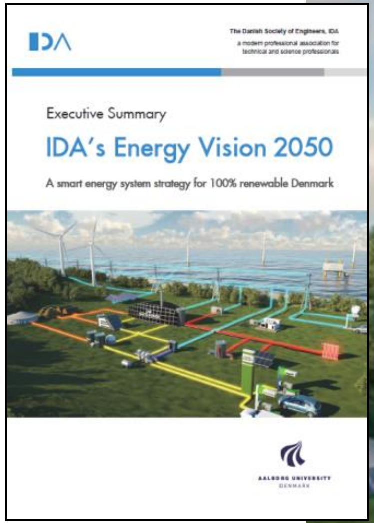
Smart Energy Systems and Infrastructures published 2014

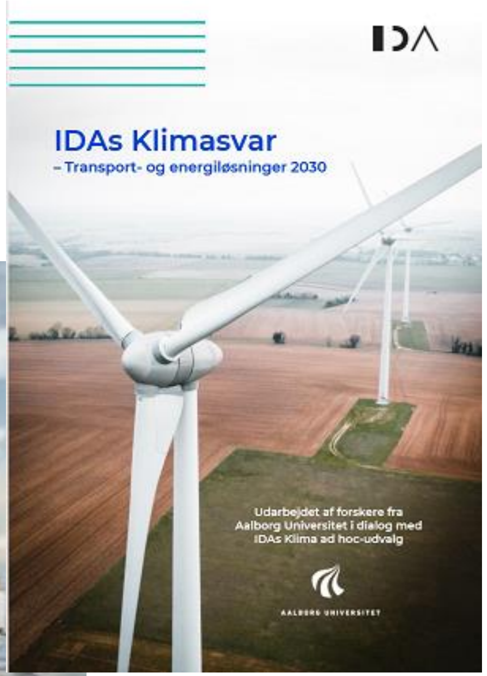


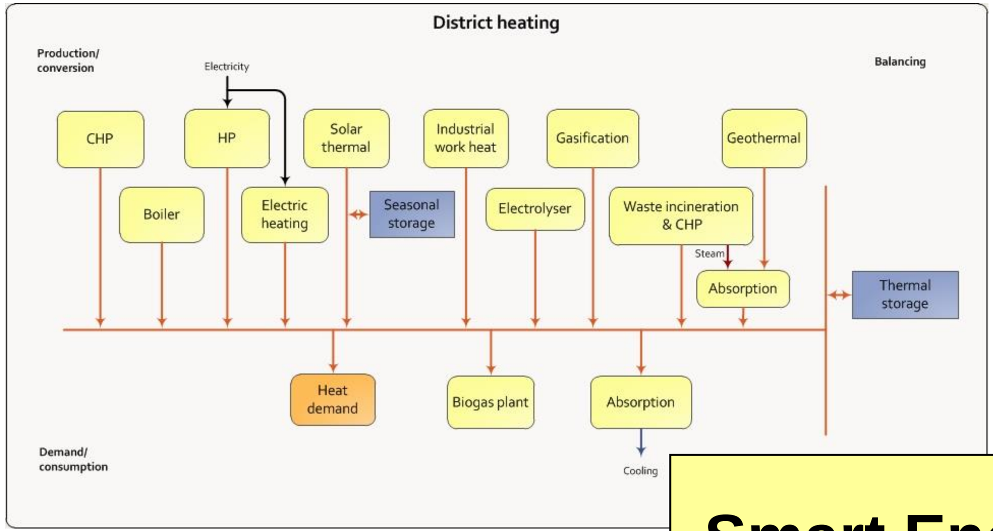


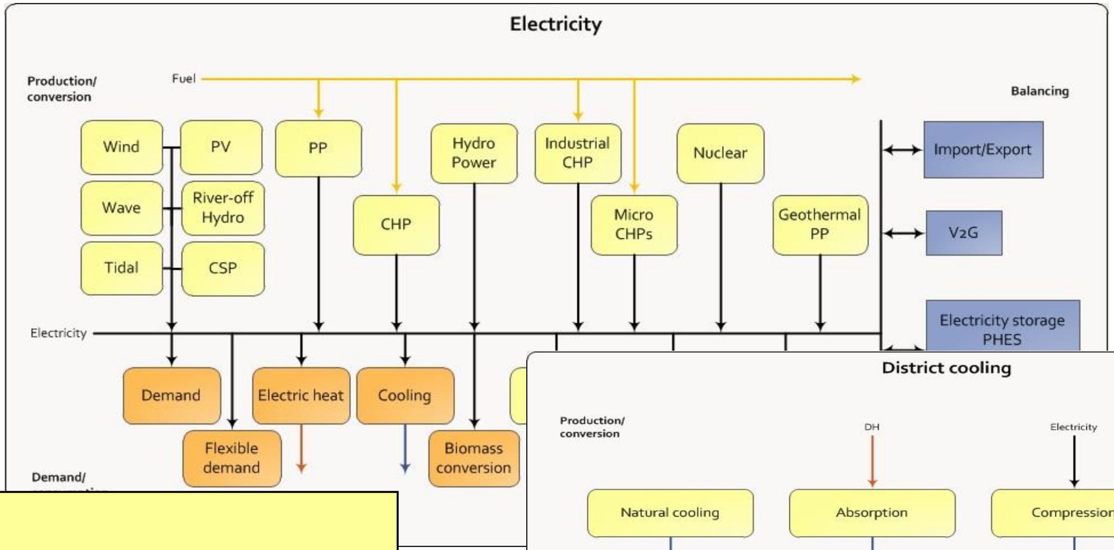
Smart Energy and Smart Energy Systems published 2017

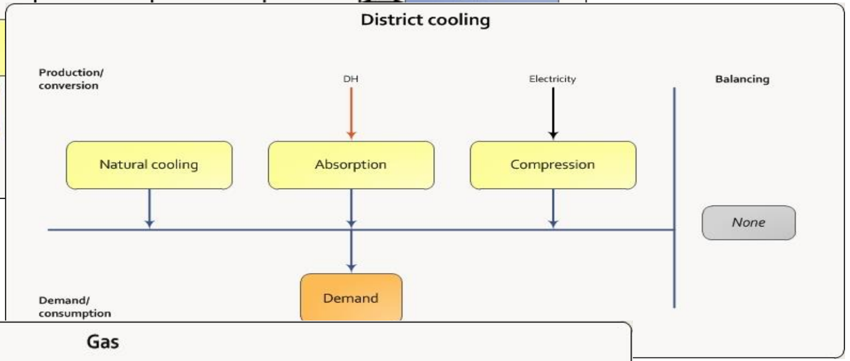
A Holistic Smart Energy Systems Approach

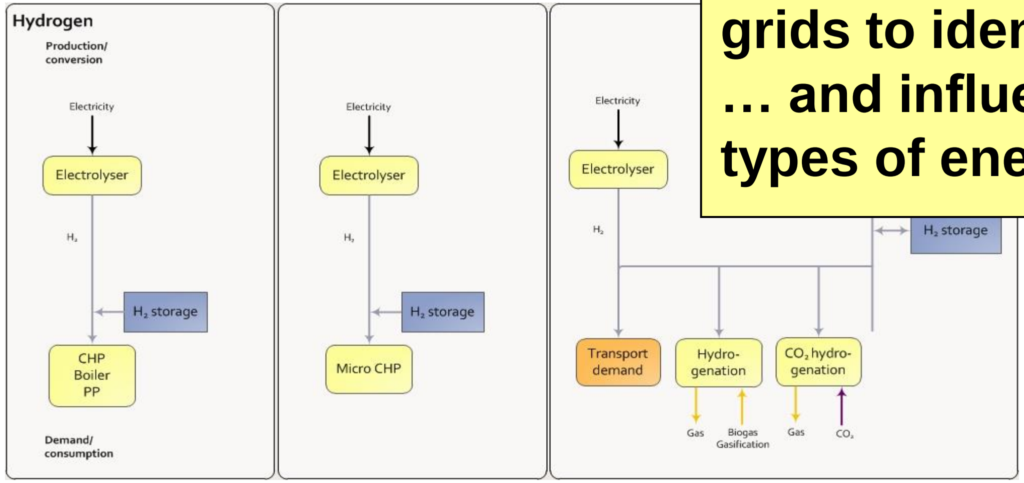


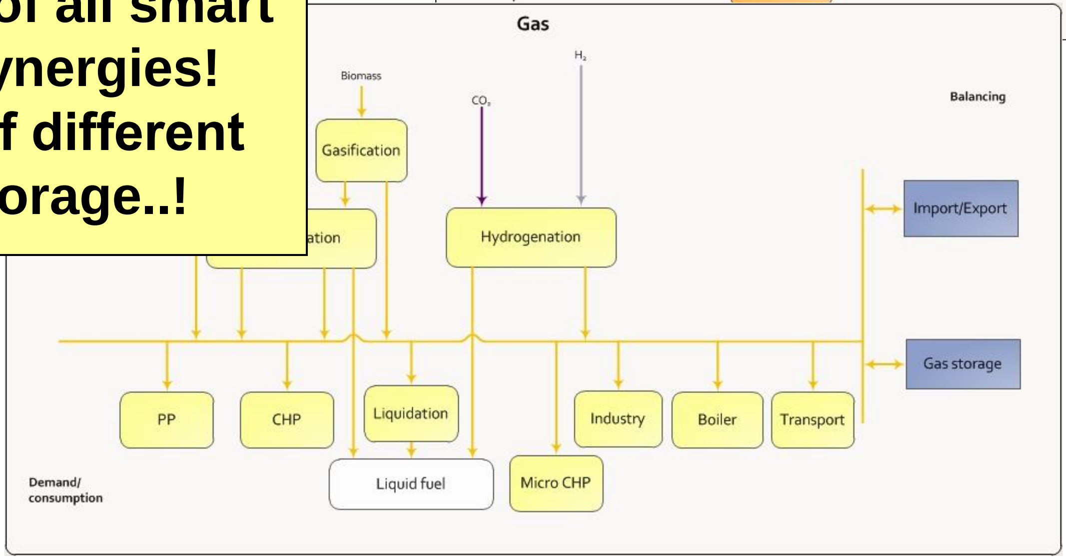








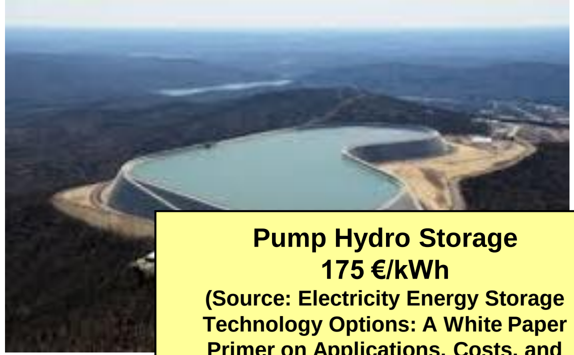




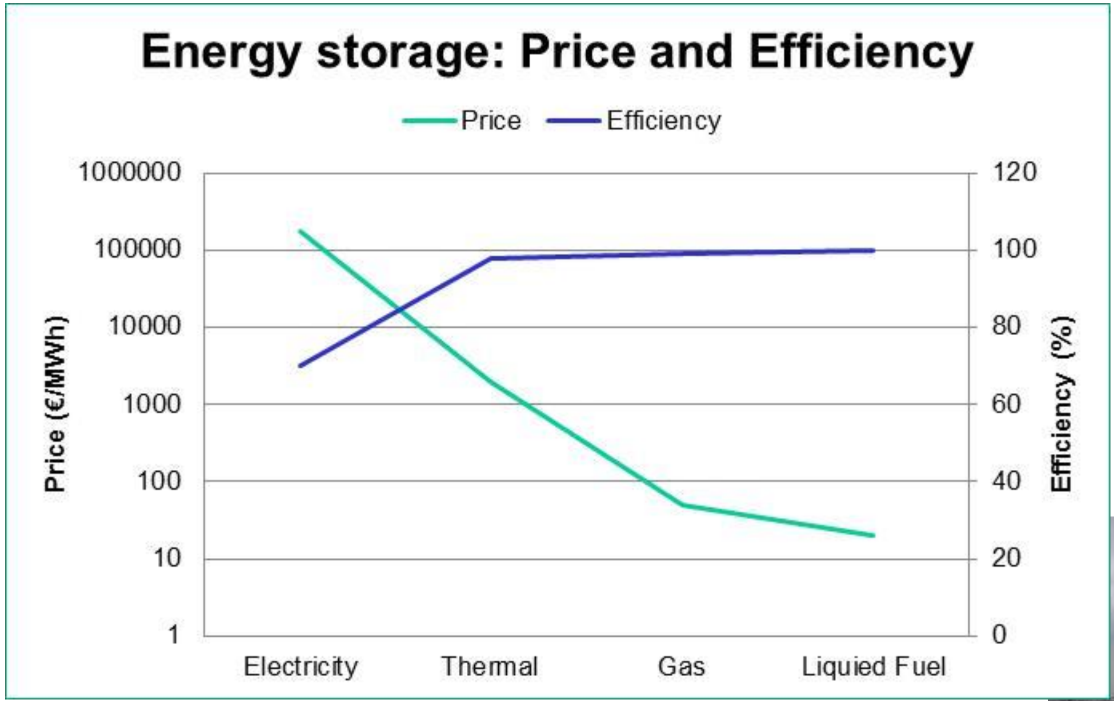
Smart Energy Systems:

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

Energy Storage



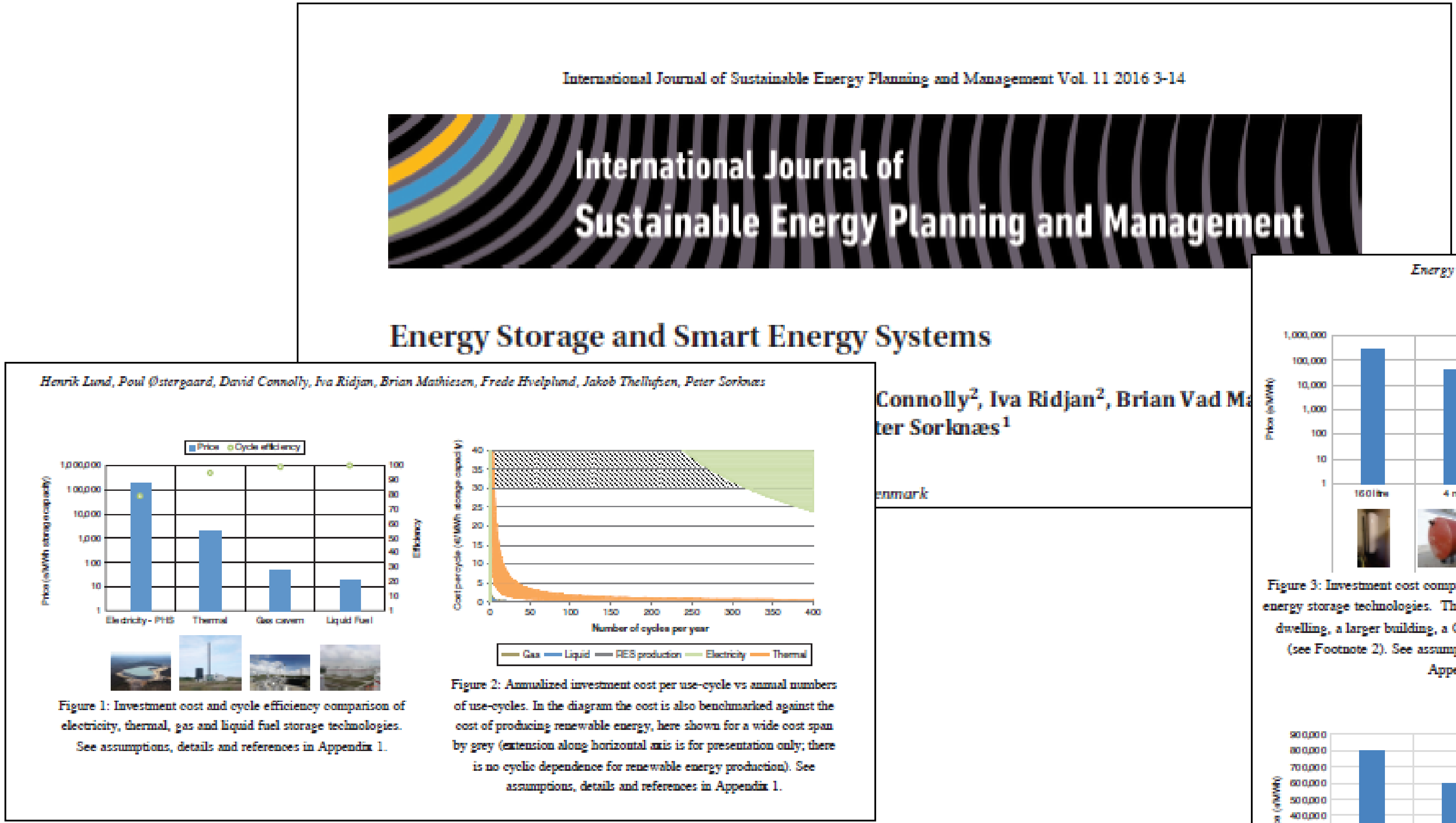
Pump Hydro Storage
175 €/kWh
(Source: Electricity Energy Storage Technology Options: A White Paper Primer on Applications, Costs, and Benefits. Electric Power Research Institute, 2010)



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)


International Journal of Sustainable Energy Planning and Management Vol. 11 2016 3-14

Energy Storage and Smart Energy Systems

Henrik Lund, Poul Østergaard, David Connolly, Iva Ridjan, Brian Mathiesen, Frede Hvelplund, Jakob Thellufsen, Peter Sorknæs

Figure 1: Investment cost and cycle efficiency comparison of electricity, thermal, gas and liquid fuel storage technologies. See assumptions, details and references in Appendix 1.

Figure 2: Annualized investment cost per use-cycle vs annual numbers of use-cycles. In the diagram the cost is also benchmarked against the cost of producing renewable energy, here shown for a wide cost span by grey (extension along horizontal axis is for presentation only; there is no cyclic dependence for renewable energy production). See assumptions, details and references in Appendix 1.

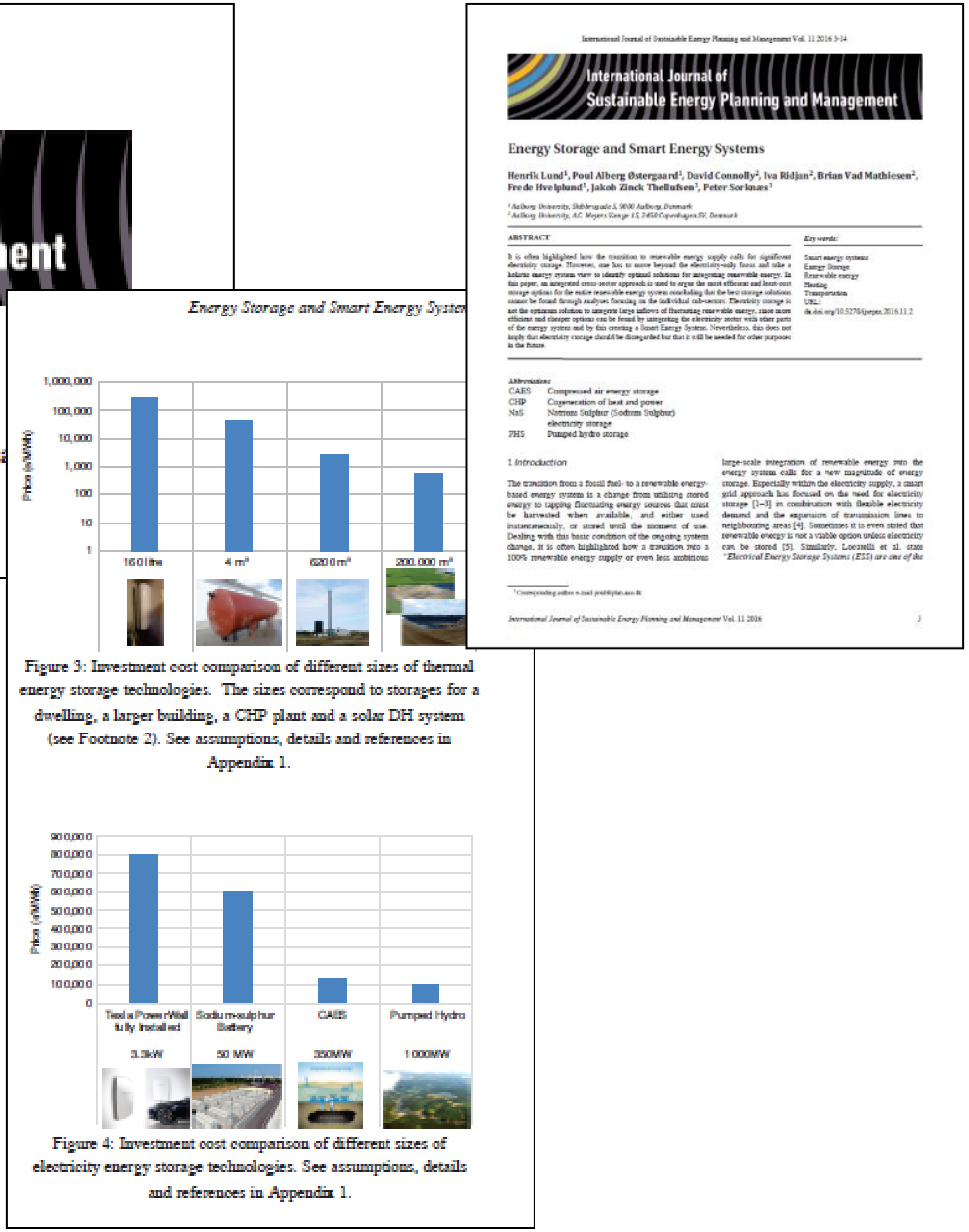

Energy Storage and Smart Energy Systems

Figure 3: Investment cost comparison of different sizes of thermal energy storage technologies. The sizes correspond to storages for a dwelling, a larger building, a CHP plant and a solar DH system (see Footnote 2). See assumptions, details and references in Appendix 1.

Figure 4: Investment cost comparison of different sizes of electricity energy storage technologies. See assumptions, details and references in Appendix 1.

www.journals.aau.dk/index.php/sepm

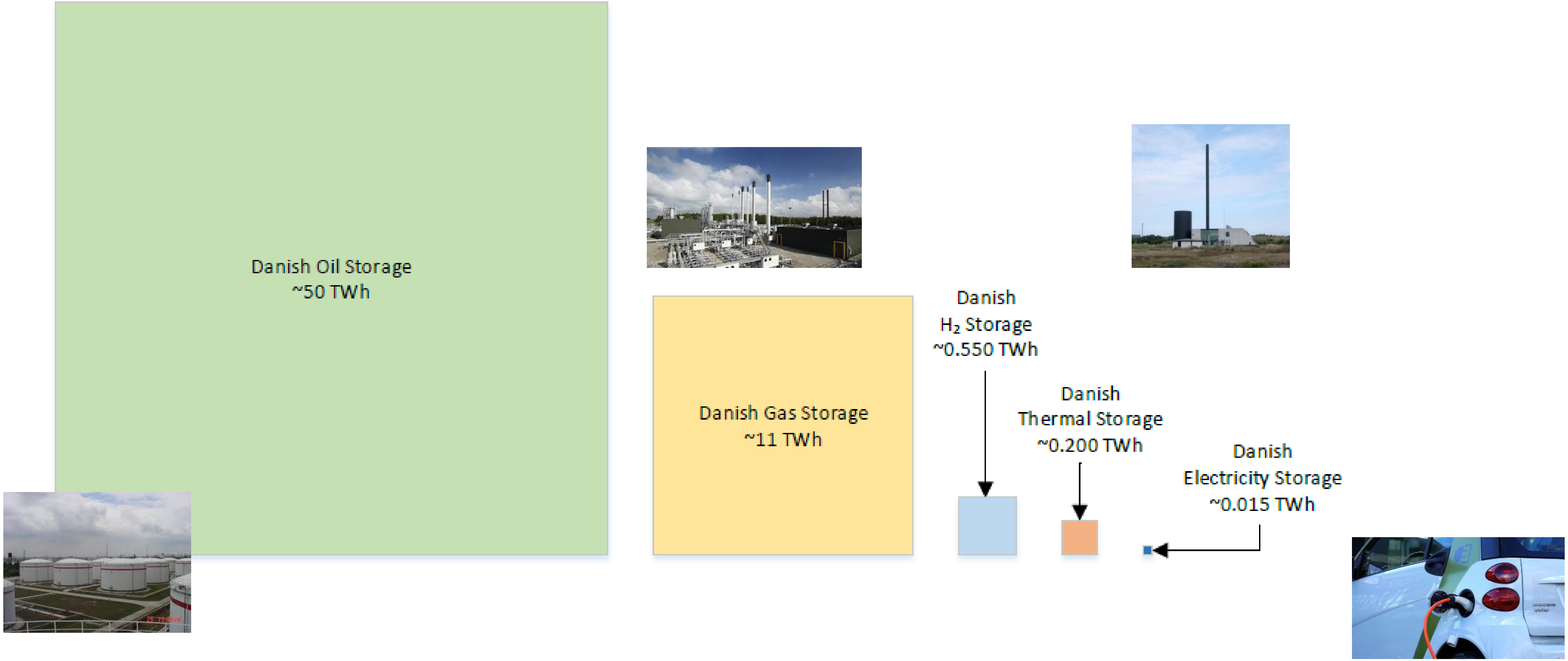
Energy Storage Capacities in Denmark

Danish Oil Storage
~50 TWh

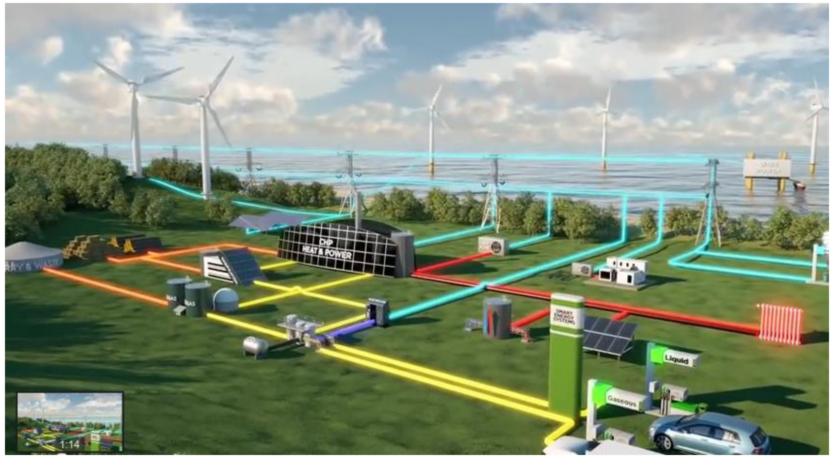
Danish Gas Storage
~11 TWh

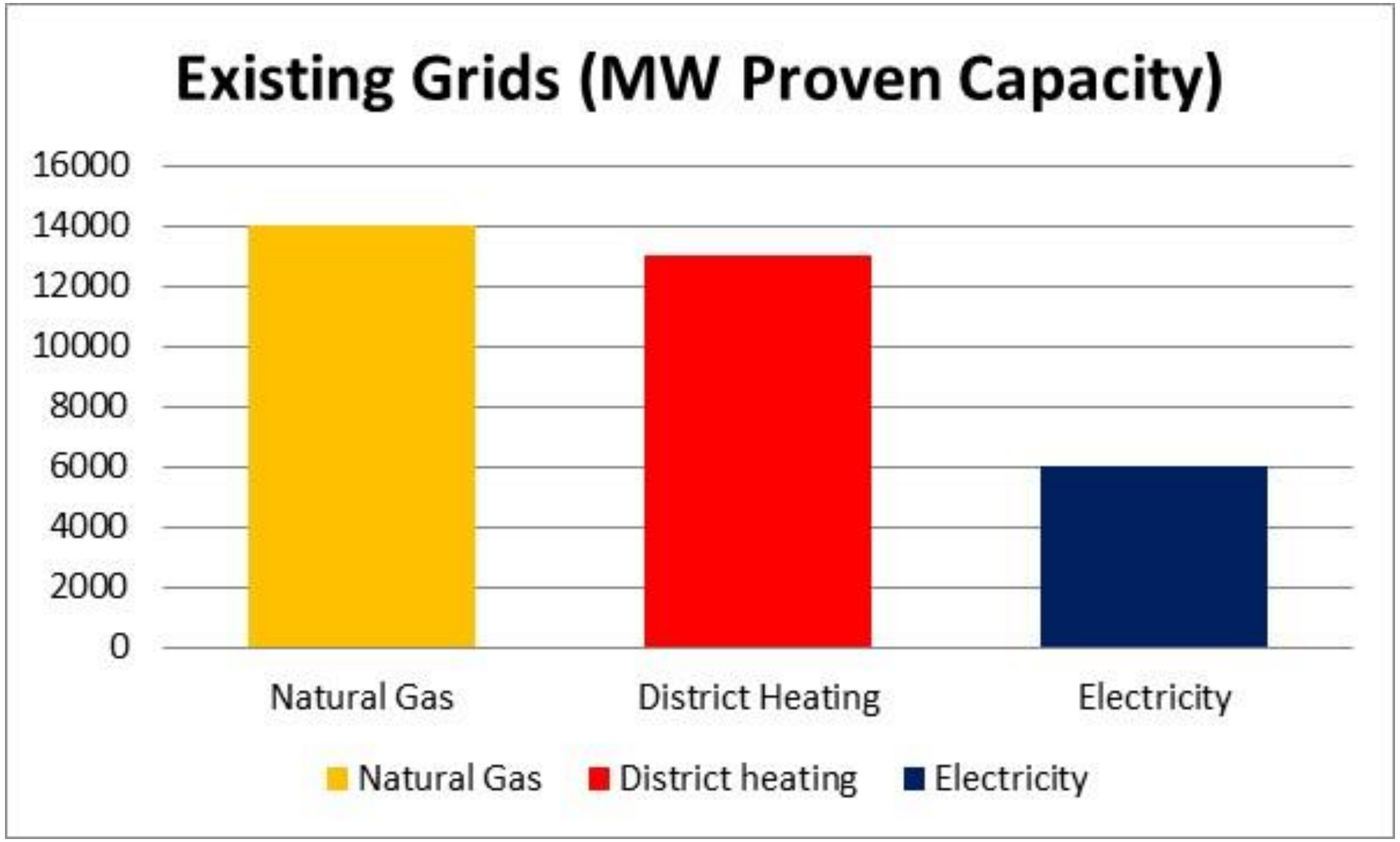
Danish
Thermal Storage
~0.090 TWh

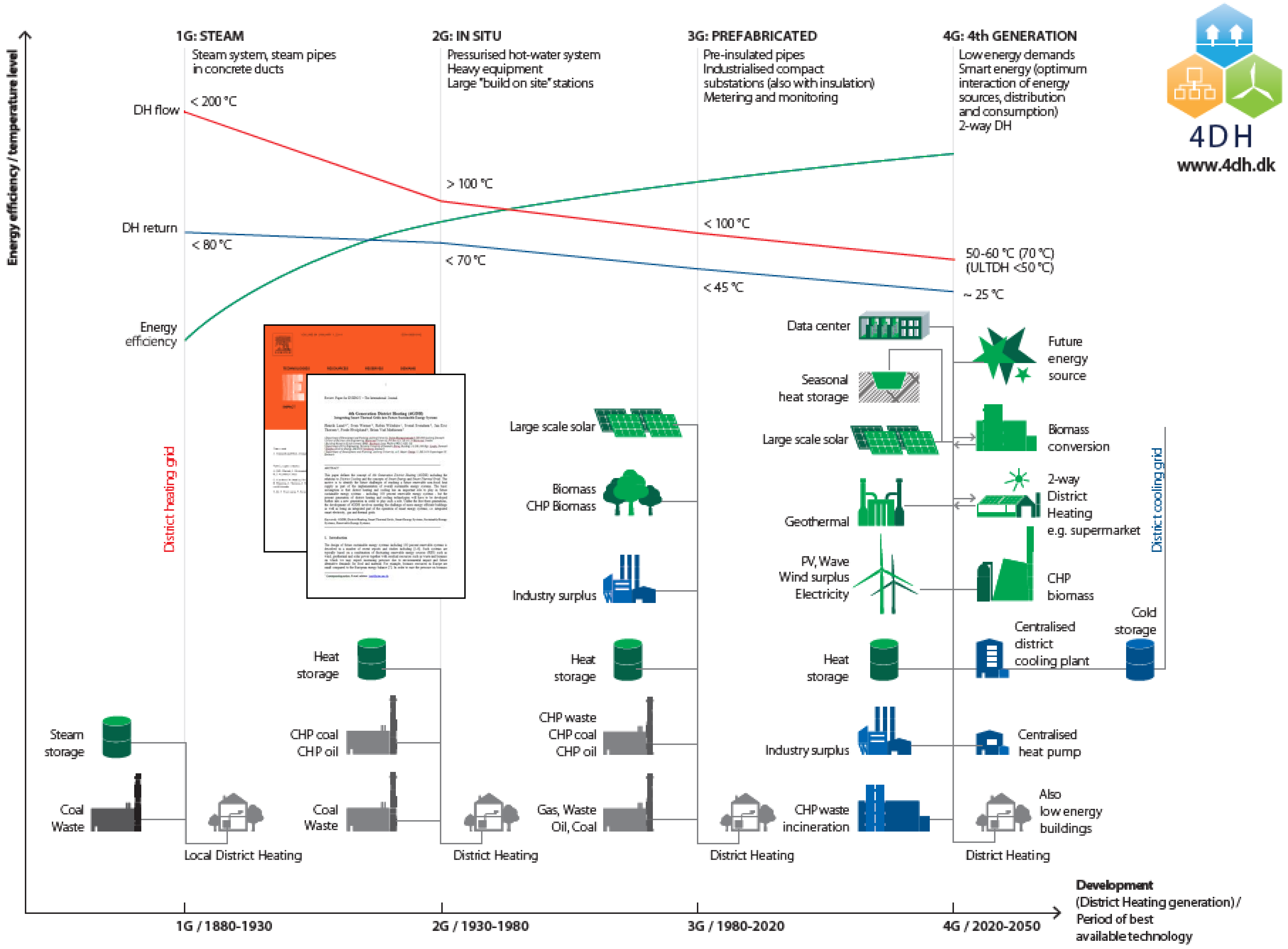
Energy Storage Capacities in 100 % RES Denmark 2050 (IDA)



Existing distribution grids

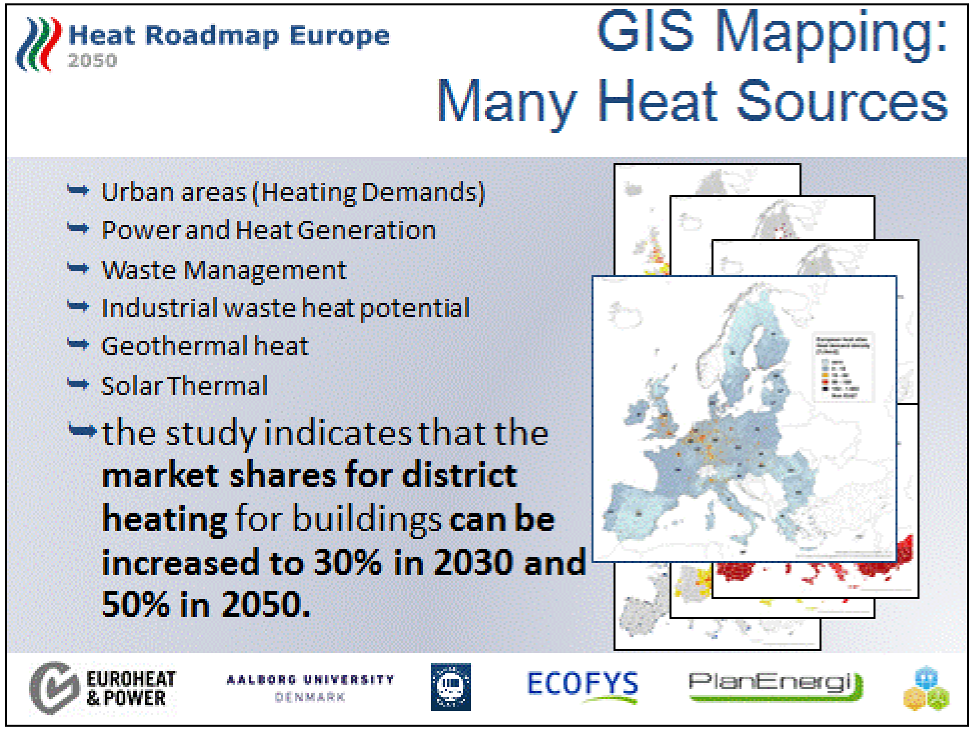






Energy efficiency / temperature level
1G: STEAM
Steam system, steam pipes in concrete ducts
2G: IN SITU
Pressurised hot-water system
Heavy equipment
Large "build on site" stations
3G: PREFABRICATED
Pre-insulated pipes
Industrialised compact substations (also with insulation)
Metering and monitoring
4G: 4th GENERATION
Low energy demands
Smart energy (optimum interaction of energy sources, distribution and consumption)
2-way DH
4DH
www.4dh.dk
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
Centralised heat pump
Coal Waste
Gas, Waste Oil, Coal
CHP waste incineration
Also low energy buildings
Local District Heating
District Heating
Development
(District Heating generation) / Period of best available technology
1G / 1880-1930
2G / 1930-1980
3G / 1980-2020
4G / 2020-2050

Heat Roadmap Europe



4DH
4th Generation District Heating Technologies and Systems

ECOFYS
sustainable energy for everyone

PlanEnergi

HÖGSKOLAN HALMSTAD

Smart Energy Europe

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

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

ELSEVIER

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

CrossMark

D. Connolly [a,*], H. Lund [b], B.V. Mathiesen [a]

[a] Department of Development and Planning, Aalborg University, A.C. Meyers Vænge 15, 2450 Copenhagen SV, Denmark
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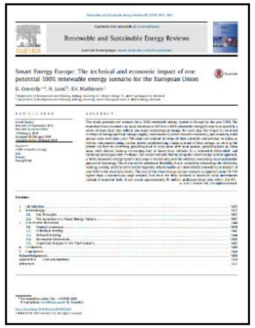
ABSTRACT

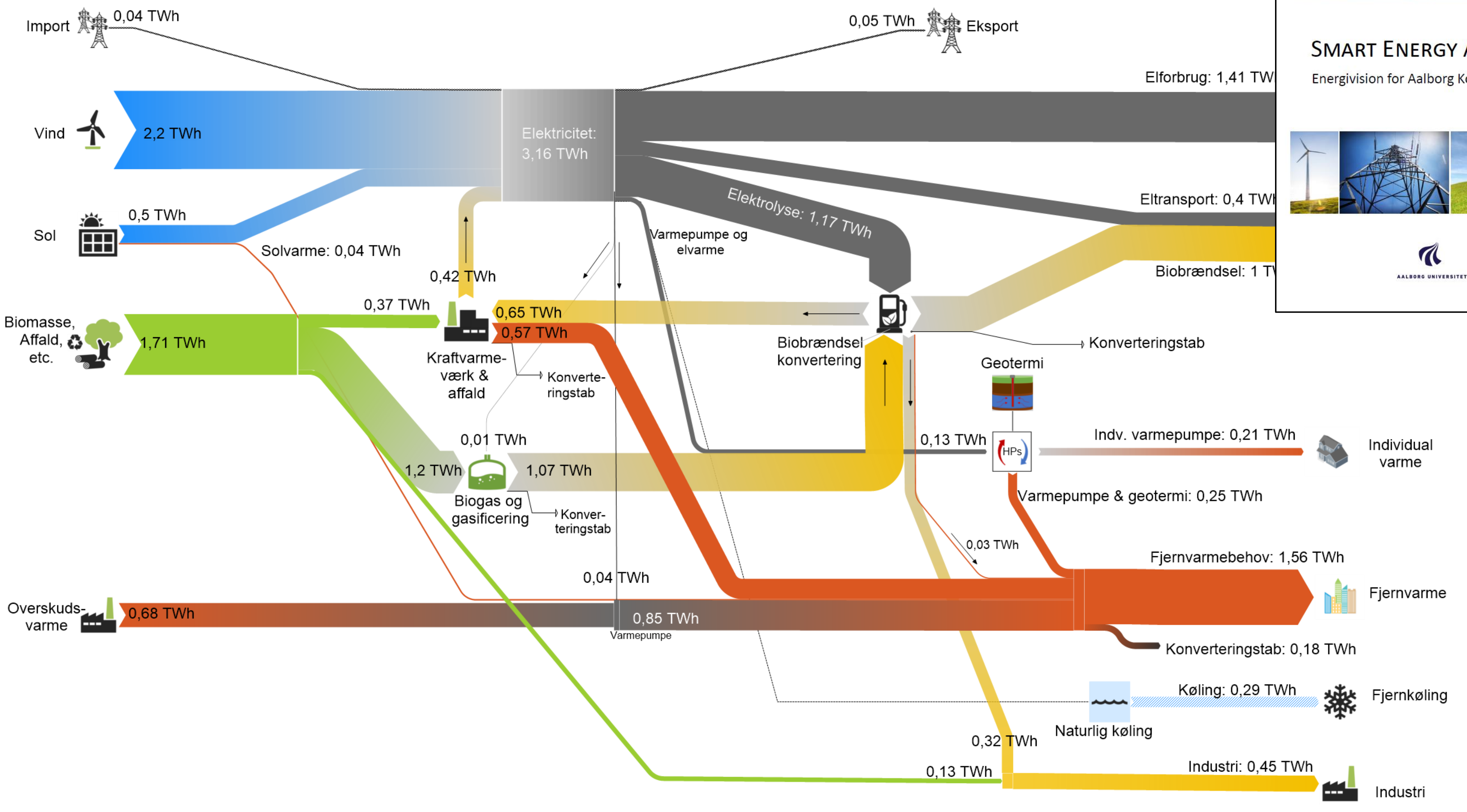
This study presents one scenario for a 100% renewable energy syste[m]
transition from a business-as-usual situation in 2050, to a 100% renew[able]

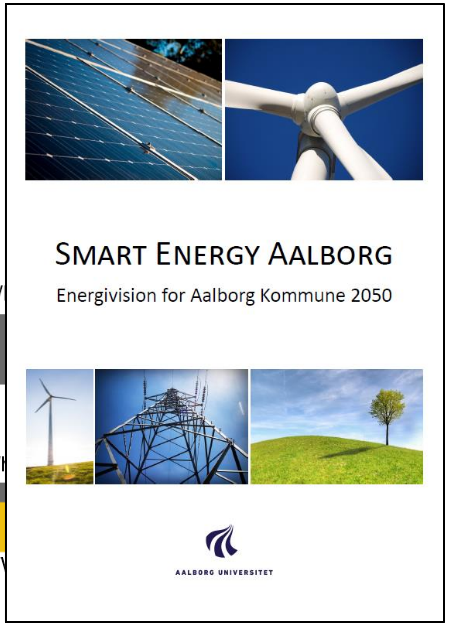


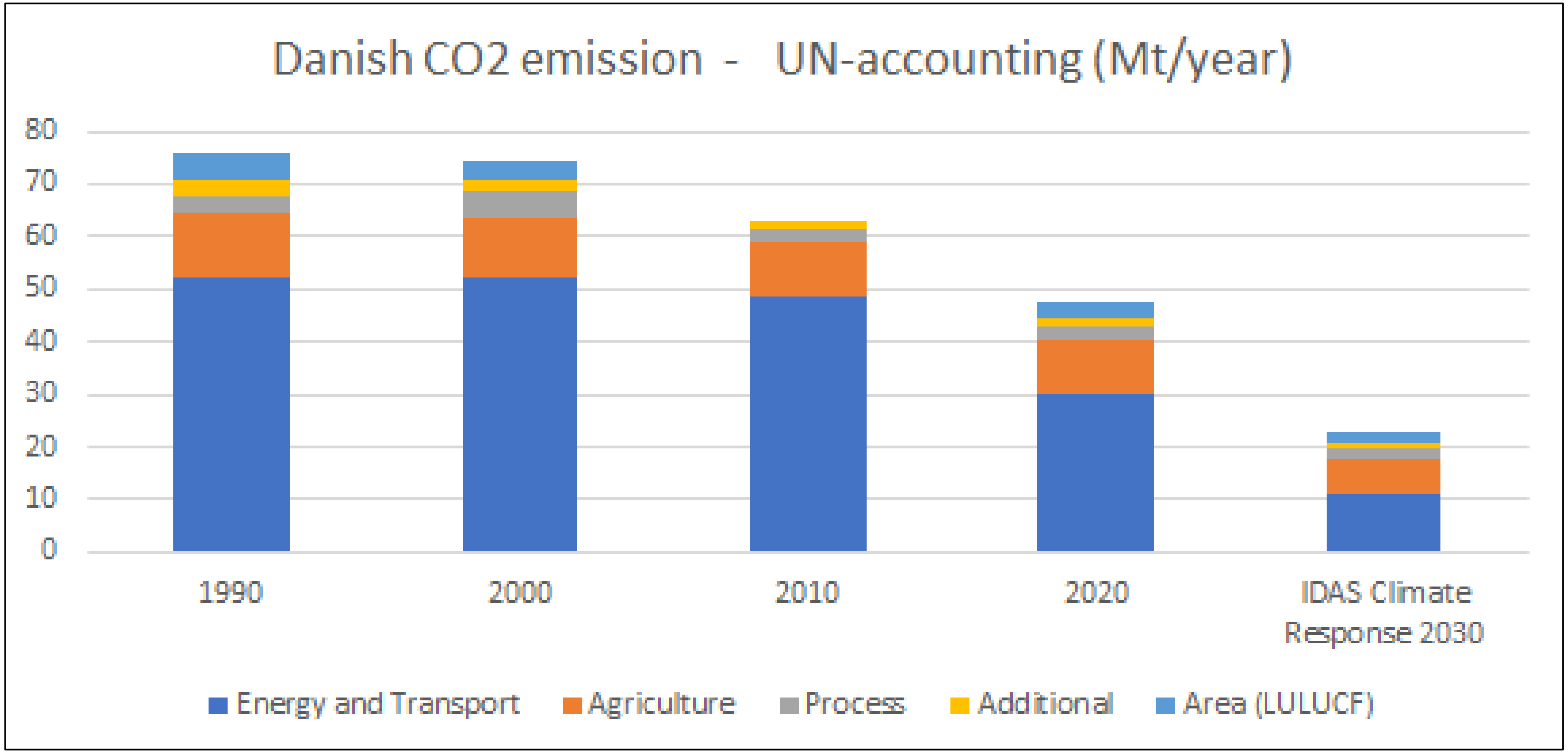
www.EnergyPLAN.eu/SmartEnergyEurope

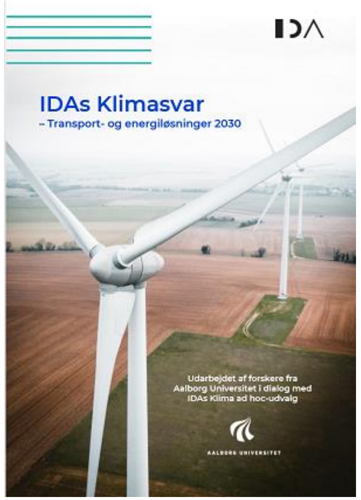
- Report Online
- Paper Published

Vision: Smart Energy Aalborg 2050






Danish CO2 emission - UN-accounting (Mt/year)
80
70
60
50
40
30
20
10
0
1990
2000
2010
2020
IDAS Climate Response 2030
Energy and Transport
Agriculture
Process
Additional
Area (LULUCF)

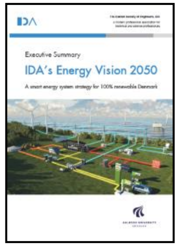

IDAs Klimasvar
– Transport- og energiløsninger 2030

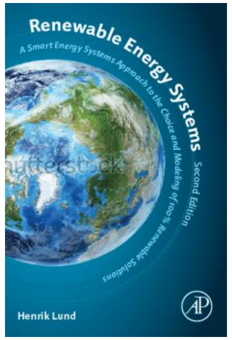
IDAs Climate Response: In a European context

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.

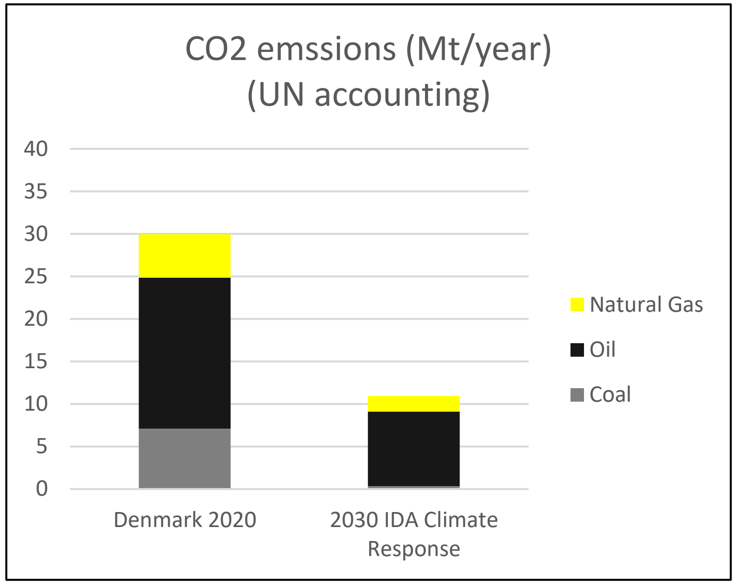
Therefore:

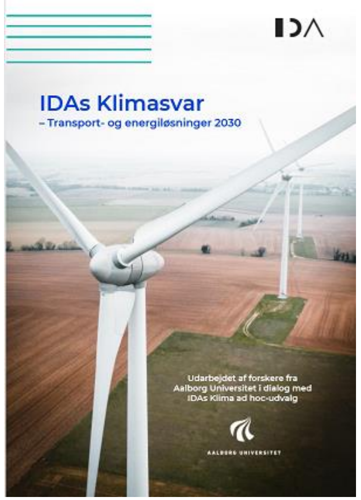
- Denmark should include the Danish share of ***international aviation and shipping*** even though it is not included yet in the UN way of calculating the Danish CO2 emissions.
- Denmark should not exceed our share of ***sustainable use of biomass*** in the world.
- Denmark should make our contribution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

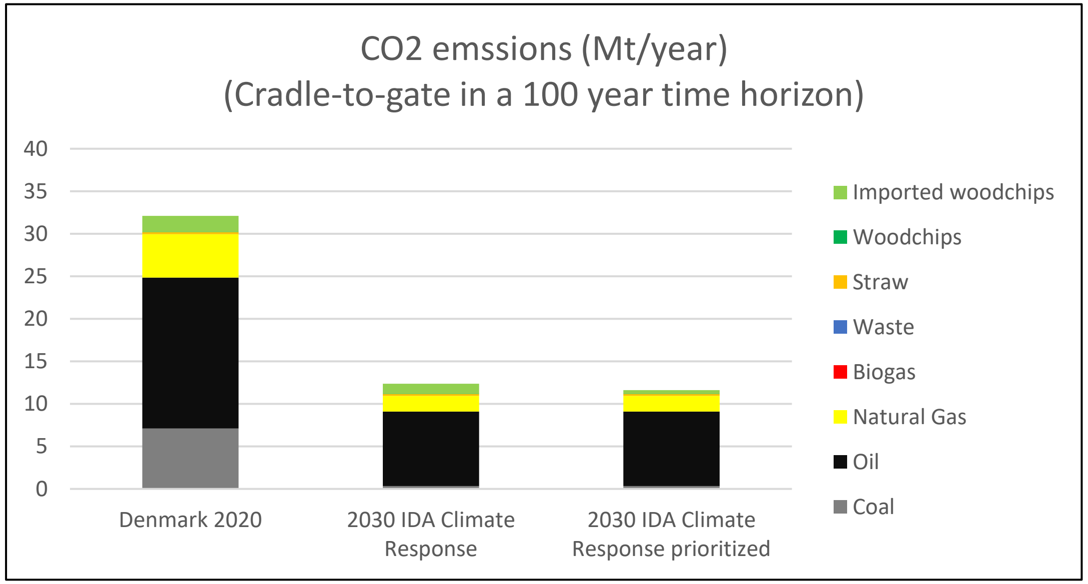


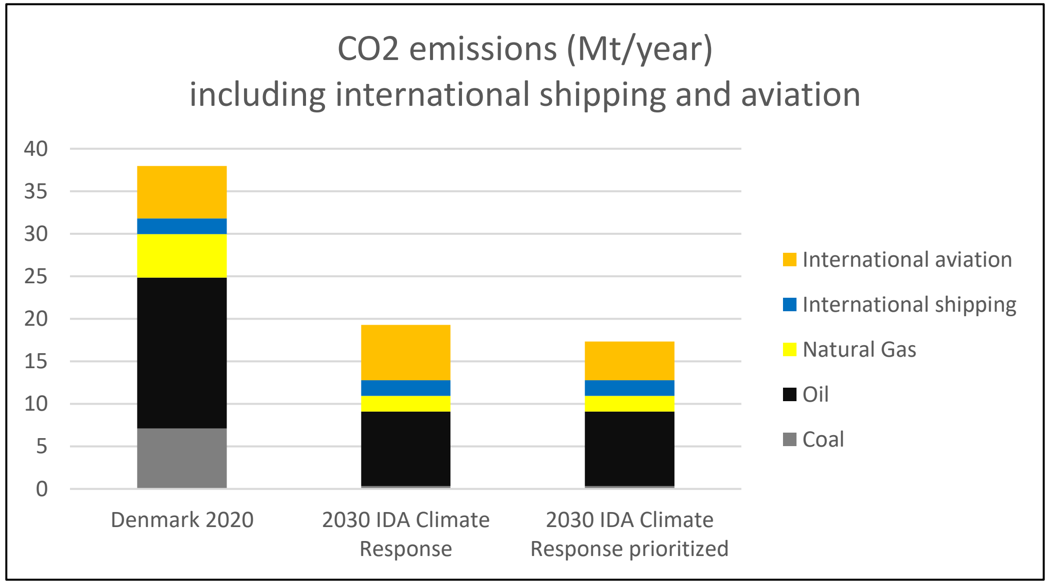


CO2 emissions in the UN accounting…

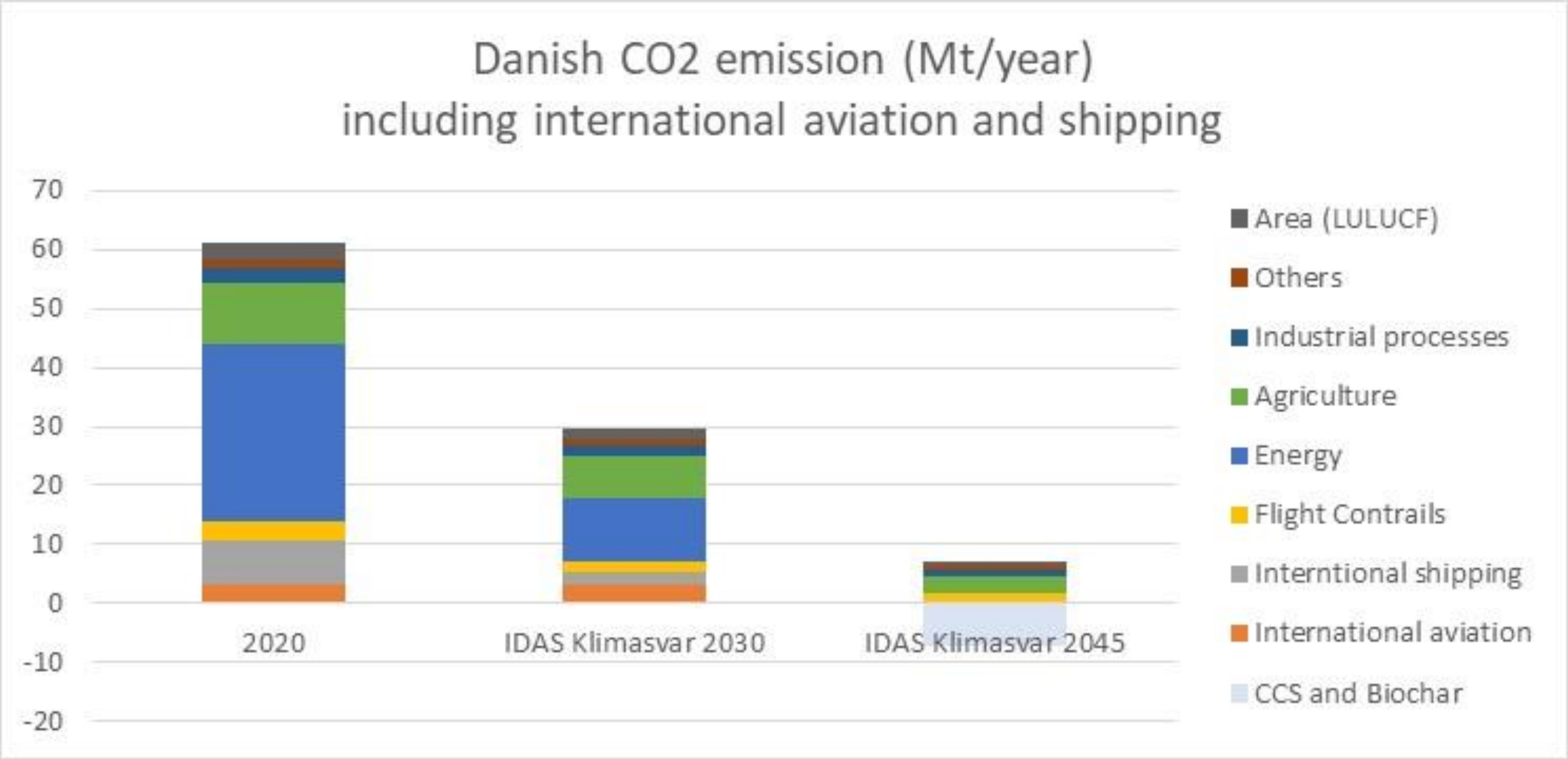


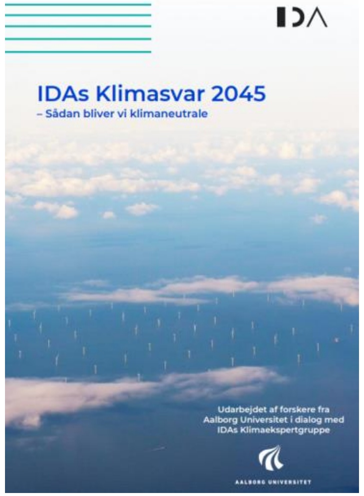






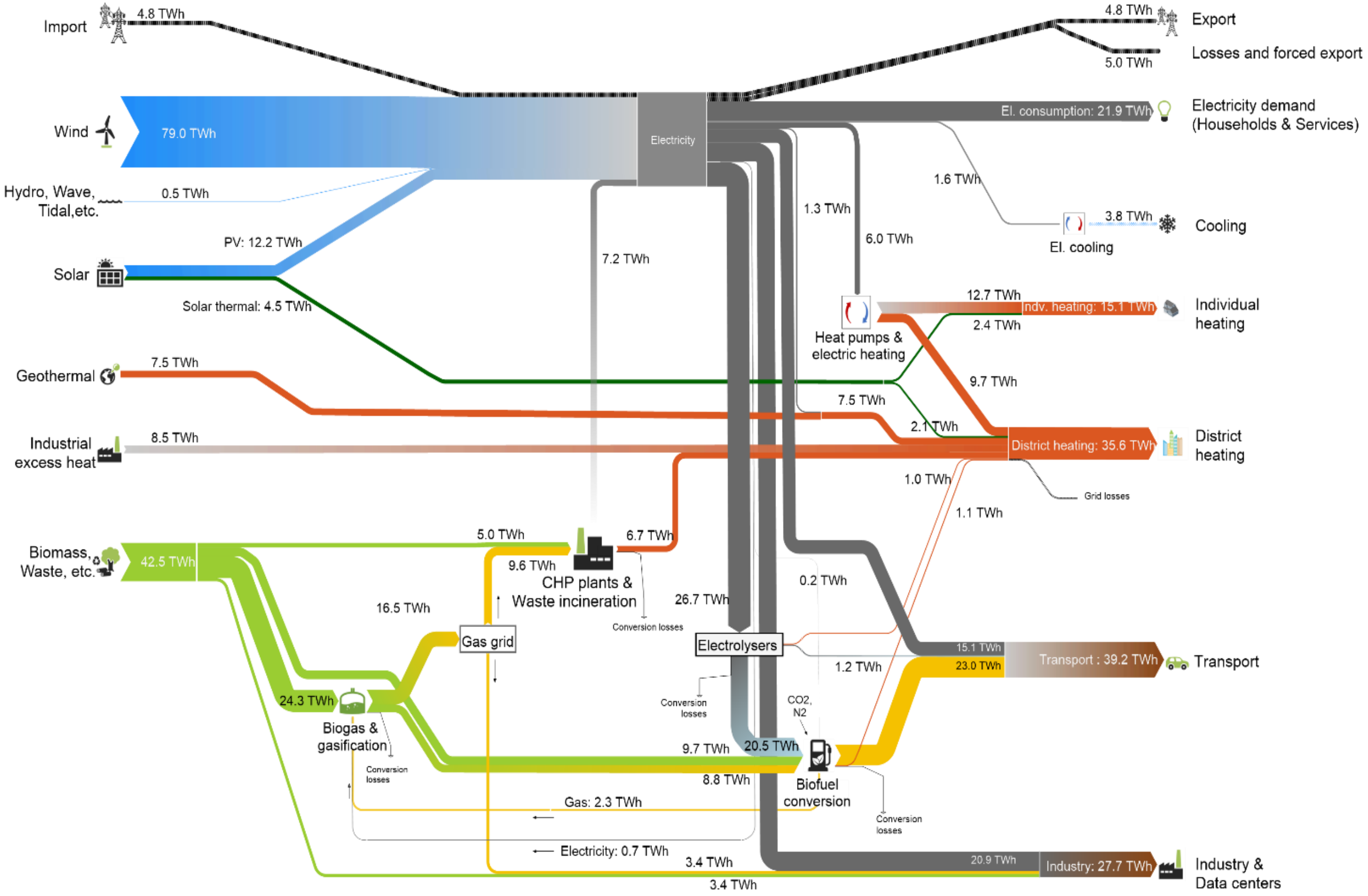
A fully decarbonized Denmark 2045





2045

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

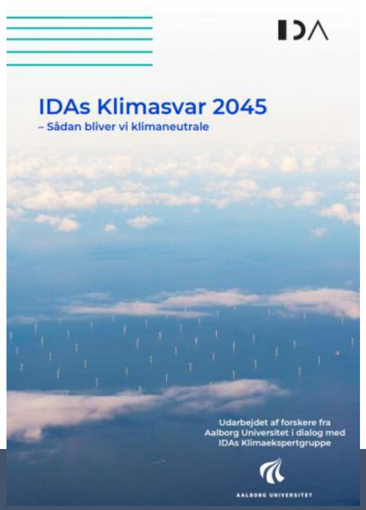


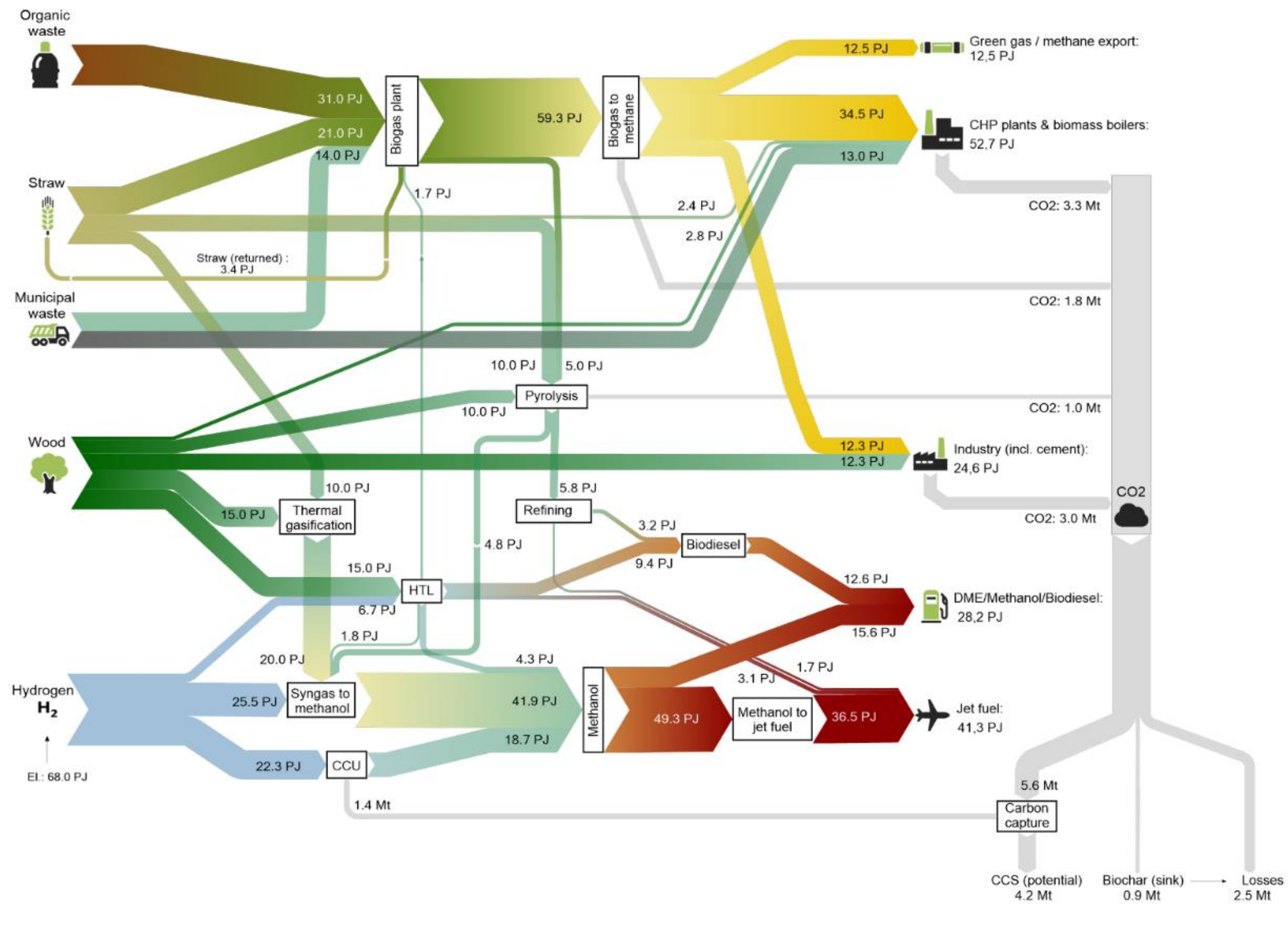
Import
4.8 TWh
Export
4.8 TWh
Losses and forced export
5.0 TWh
Wind
79.0 TWh
Electricity
El. consumption: 21.9 TWh
Electricity demand (Households & Services)
Hydro, Wave, Tidal,etc.
0.5 TWh
1.6 TWh
1.3 TWh
6.0 TWh
3.8 TWh
Cooling
El. cooling
PV: 12.2 TWh
Solar
7.2 TWh
Solar thermal: 4.5 TWh
12.7 TWh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

Biomasse 2045

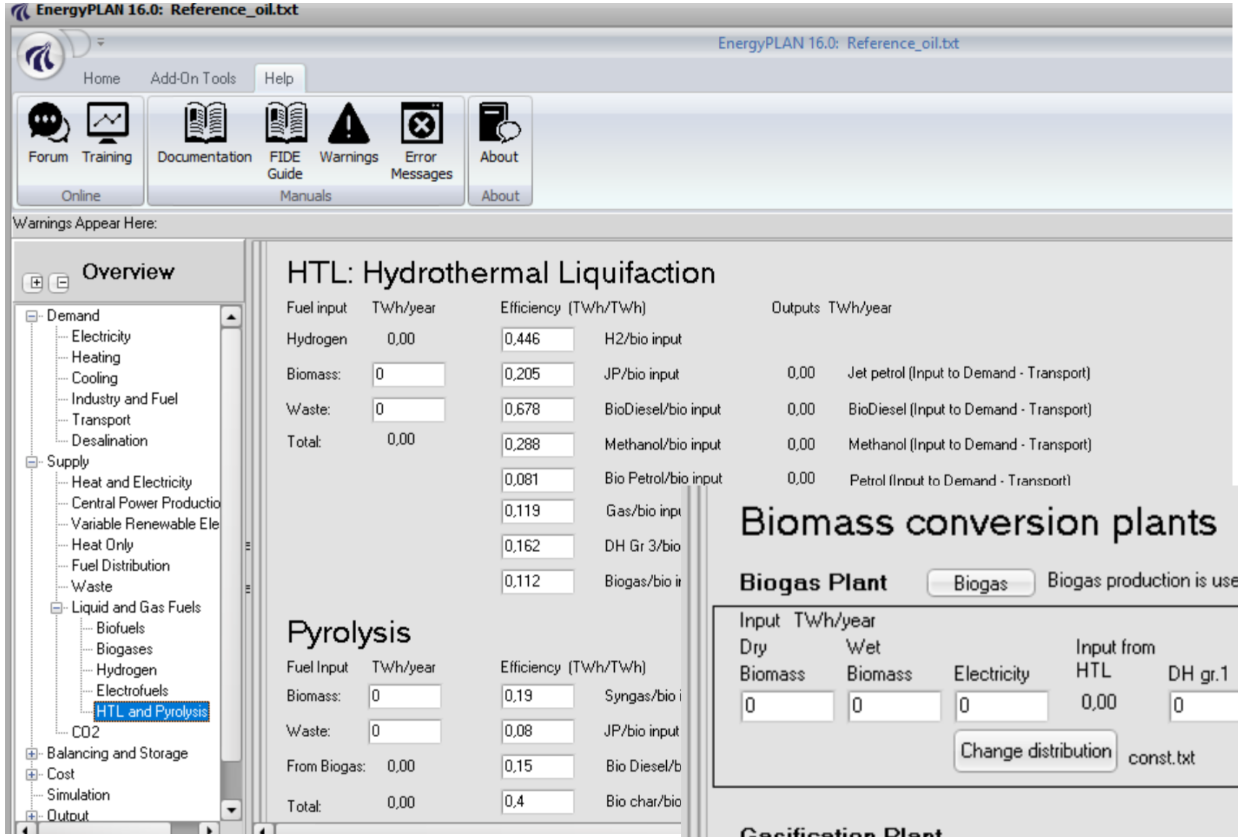
Overview:

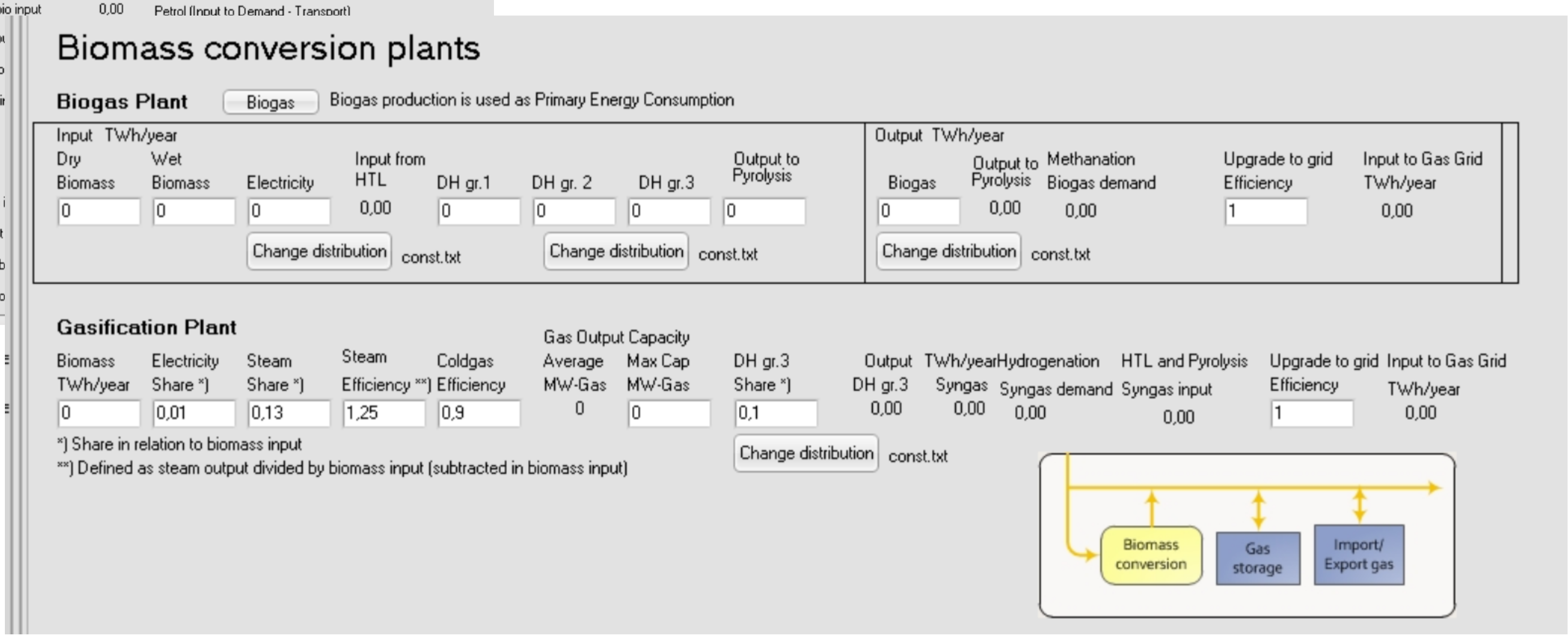
(153 PJ minus eksport 13 PJ = 140 PJ svarende til 23 GJ/capita)





Biomass conversion incl. HTL and Pyrolysis





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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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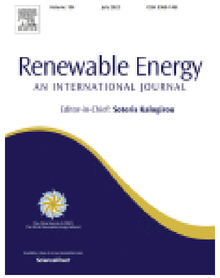
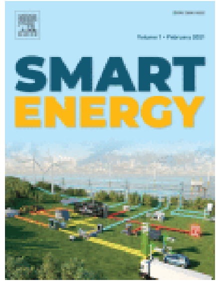
- Smart Energy Denmark. A consistent and detailed strategy for a fully decarbonized society. **Renewable and Sustainable Energy Reviews**
- Smart Energy Europe: **The technical and economic impact of one potential 100% renewable energy scenario for the European Union**. **Renewable and Sustainable Energy 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

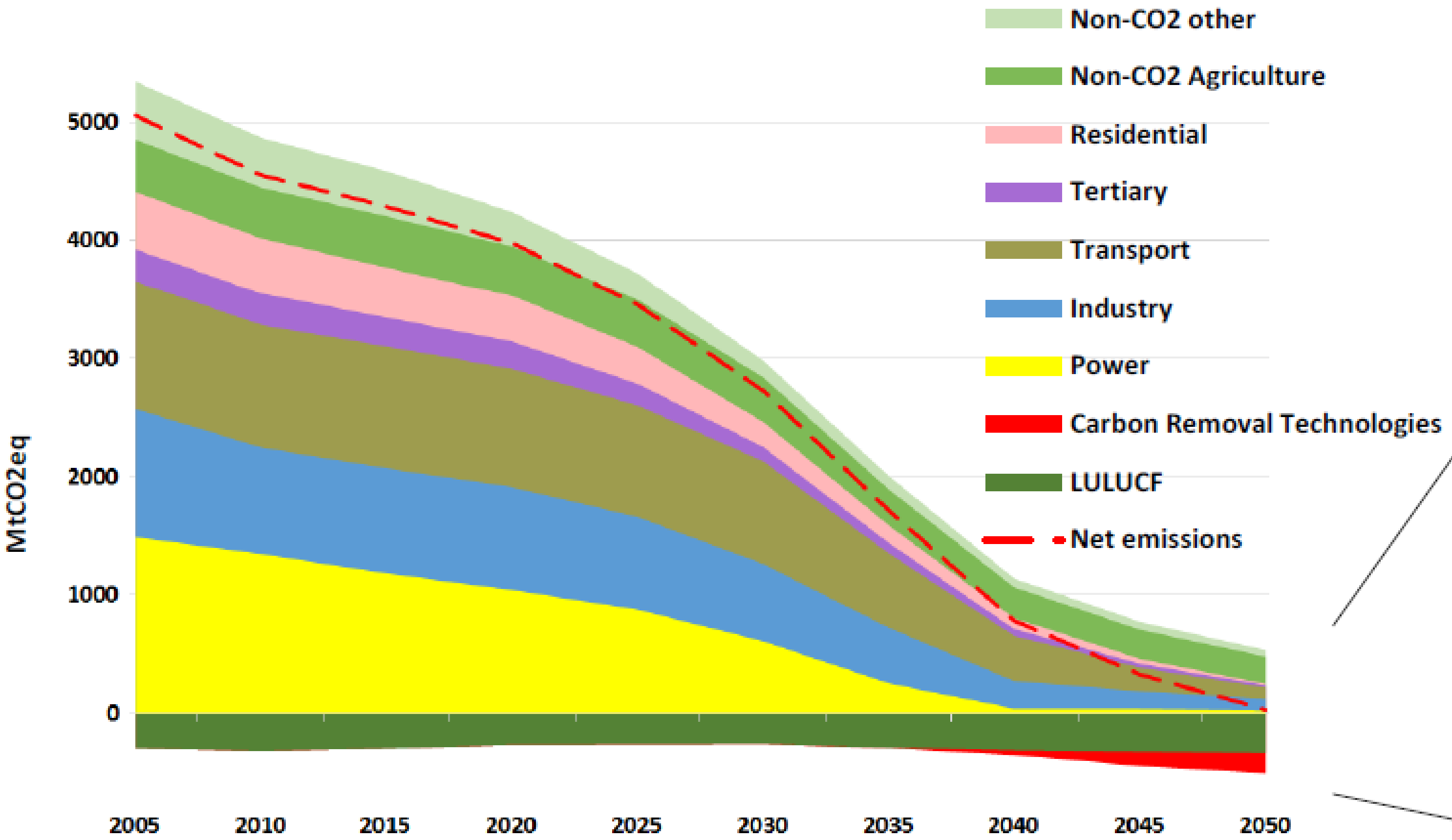




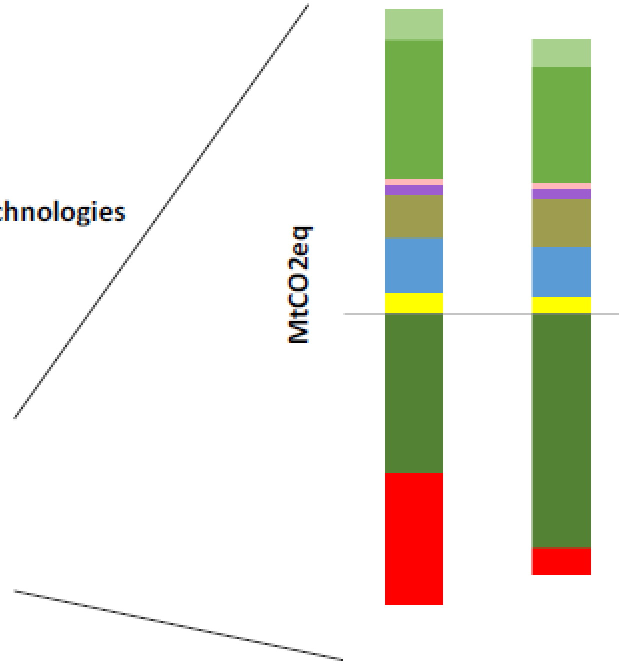
A Clean Planet for all

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



Long Term Strategy Options

	Electrification (ELEC)	Hydrogen (H2)	Power-to-X (P2X)	Energy Efficiency (EE)	Circular Economy (CIRC)	Combination (COMBO)	1.5°C Technical (1.5TECH)	1.5°C Sustainable Lifestyles (1.5LIFE)
Main Drivers	Electrification in all sectors	Hydrogen in industry, transport and buildings	E-fuels in industry, transport and buildings	Pursuing deep energy efficiency in all sectors	Increased resource and material efficiency	Cost-efficient combination of options from 2°C scenarios	Based on COMBO with more BECCS, CCS	Based on COMBO and CIRC with lifestyle changes
GHG target in 2050	-80% GHG (excluding sinks) ["well below 2°C" ambition]					-90% GHG (incl. sinks)	-100% GHG (incl. sinks) ["1.5°C" ambition]	
Major Common Assumptions	• Higher energy efficiency post 2030 • Deployment of sustainable, advanced biofuels • Moderate circular economy measures • Digitilisation				• Market coordination for infrastructure deployment • BECCS present only post-2050 in 2°C scenarios • Significant learning by doing for low carbon technologies • Significant improvements in the efficiency of the transport system.			
Power sector	Power is nearly decarbonised by 2050. Strong penetration of RES facilitated by system optimization (demand-side response, storage, interconnections, role of prosumers). Nuclear still plays a role in the power sector and CCS deployment faces limitations.							
Industry	Electrification of processes	Use of H2 in targeted applications	Use of e-gas in targeted applications	Reducing energy demand via Energy Efficiency	Higher recycling rates, material substitution, circular measures	Combination of most Cost-efficient options from "well below 2°C" scenarios with targeted application (excluding CIRC)	COMBO but stronger	CIRC+COMBO but stronger
Buildings	Increased deployment of heat pumps	Deployment of H2 for heating	Deployment of e-gas for heating	Increased renovation rates and depth	Sustainable buildings			CIRC+COMBO but stronger
Transport sector	Faster electrification for all transport modes	H2 deployment for HDVs and some for LDVs	E-fuels deployment for all modes	Increased modal shift	Mobility as a service			• CIRC+COMBO but stronger • Alternatives to air travel
Other Drivers		H2 in gas distribution grid	E-gas in gas distribution grid				Limited enhancement natural sink	• Dietary changes • Enhancement natural sink

Our replication

Long Term Strategy Options

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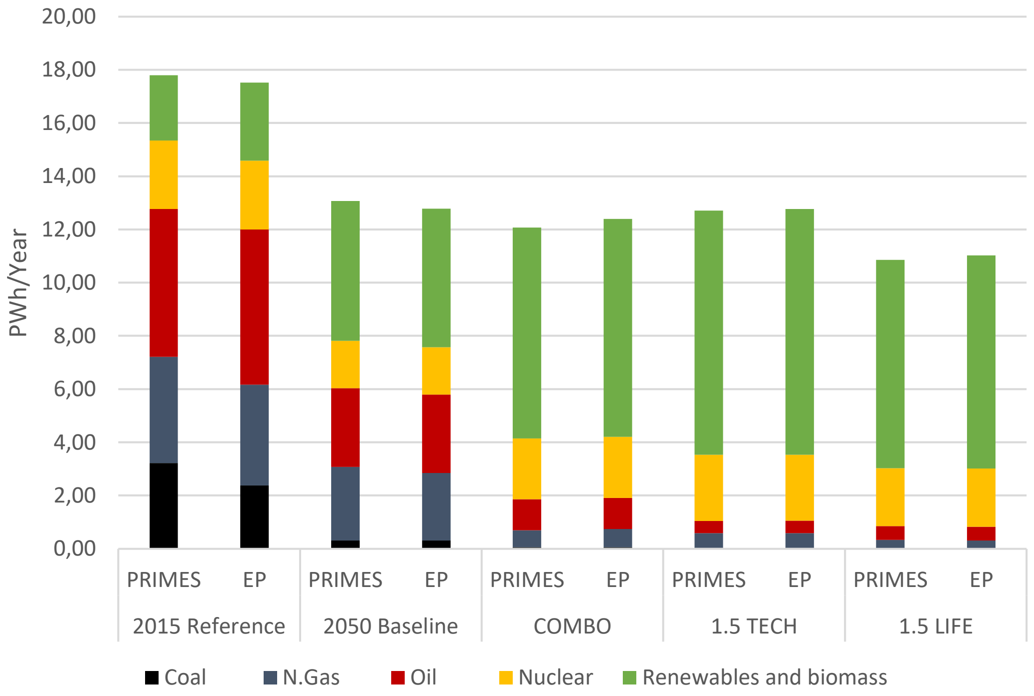
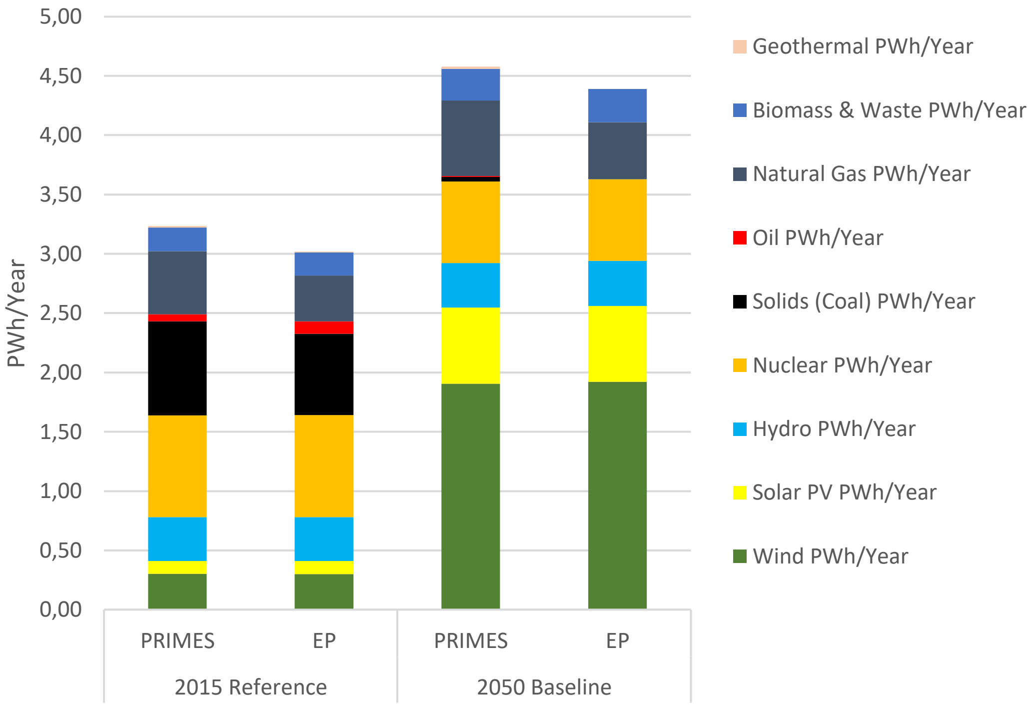


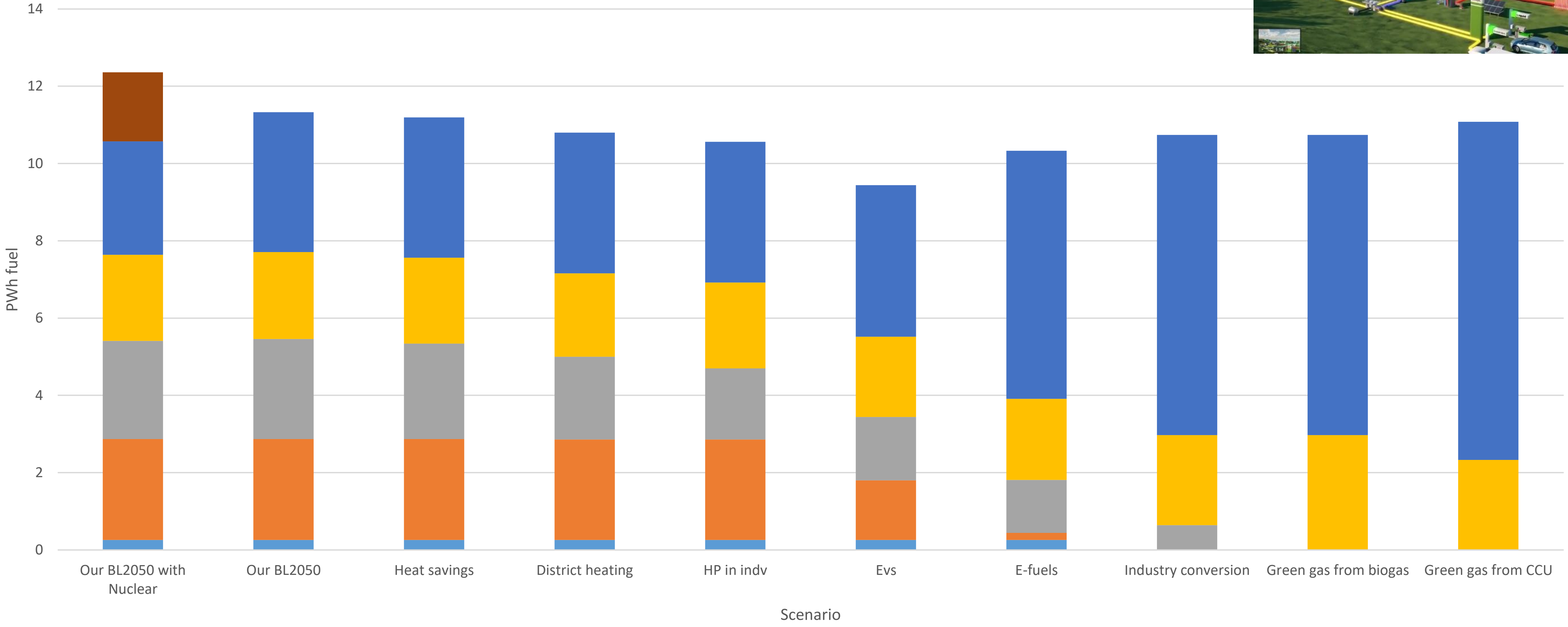


Stepwise implementation of smart energy systems

1. Specify reference scenario. PRIMES 2050 Business as Usual is used as a reference. Here a starting point with and without nuclear is discussed.
2. Energy savings in the different demand sectors
3. Implementation of district heating
4. Transition individual heating
5. Electrification of transport
6. E-fuels in transport
7. Replacing remaining fossil fuel with biofuels, biogas, e-gas and e-fuels

Increase renewable energy production

Step by step to a smart energy system



Energy balance

BAU Baseline

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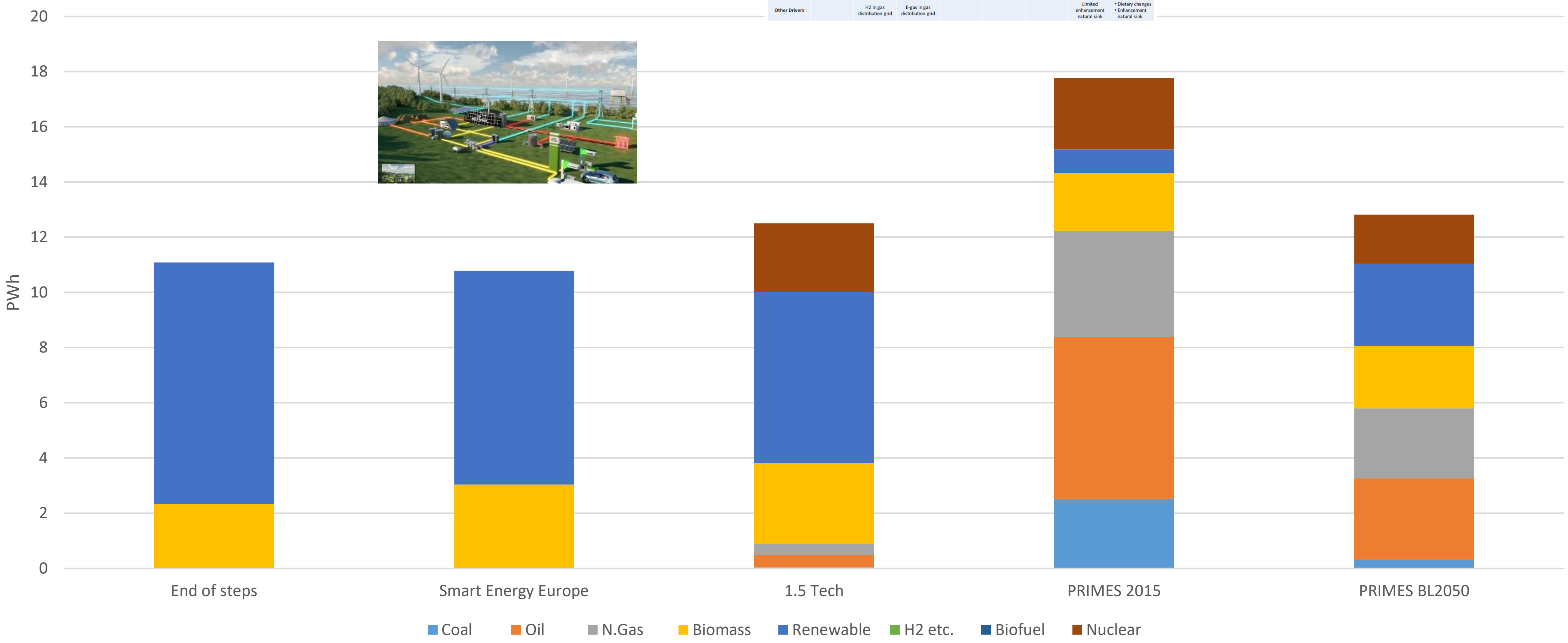
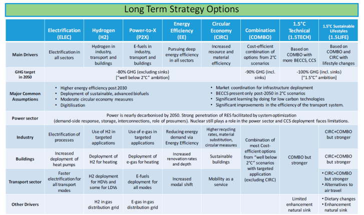
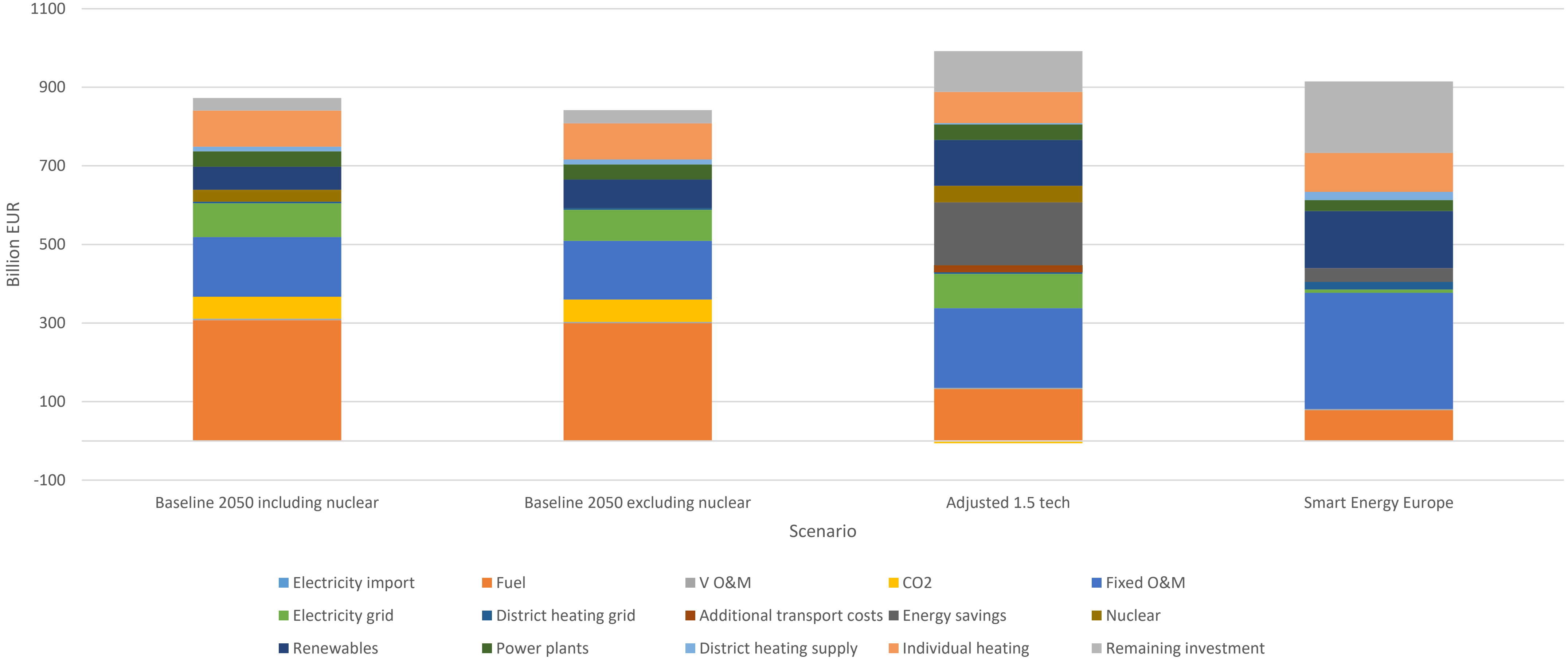


Costs


Long Term Strategy Options


1100
900
700
500
300
100
-100
Billion EUR
Baseline 2050 including nuclear
Baseline 2050 excluding nuclear
Adjusted 1.5 tech
Smart Energy Europe
Scenario
Electricity import
Fuel
V O&M
CO2
Fixed O&M
Electricity grid
District heating grid
Additional transport costs
Energy savings
Nuclear
Renewables
Power plants
District heating supply
Individual heating
Remaining investment

More information:

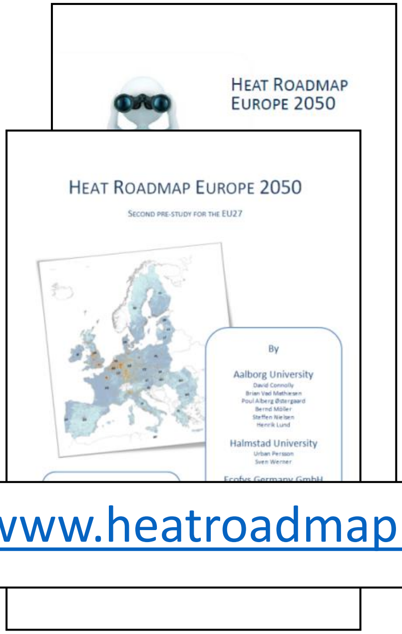
www.henriklund.eu

www.4DH.dk

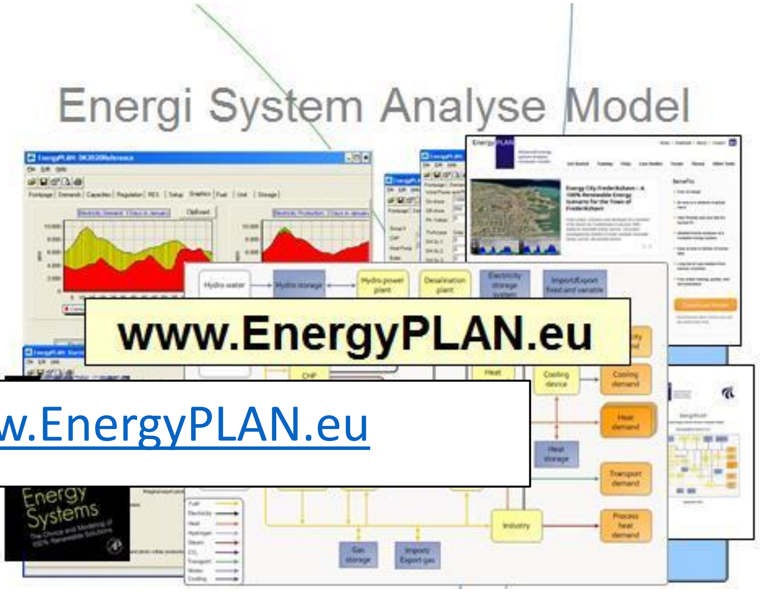
4DH
4th Generation District Heating Technologies and Systems

https://www.energyplan.eu/book2/

www.energyplan.eu/SmartEnergyEurope



www.heatroadmap.eu



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