100% Renewable Smart Energy Systems

Henrik Lund
Professor in Energy Planning
Aalborg Universitet
Aalborg University, Denmark

Jutland/Denmark:

- > 40% wind power (local owners)
- High share of the world’s offshore power
- 30% Distributed Generation
- 50% of electricity supplied by CHP
- >50% District Heating
- 10% of Natural Gas produced from Biogas
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
The long-term Objective of Danish Energy Policy

Expressed by former Prime Minister Anders Fogh Rasmussen in his opening speech to the Parliament in 2006 and in several political agreements since then:

To convert to 100% Renewable Energy

Prime minister June 2019: "… 70% reductions in Green House gases by 2030.."

Prime minister 16 November 2008: "We will free Denmark totally from fossil fuels like oil, coal and gas"

Prime minister 16 November 2008: "... position Denmark in the heart of green growth"
2019 New Government and agreement:
70% reductions in Greenhouse gases by 2030

Climate Law and Action plan:
1. Energy savings in among others public buildings
2. National Strategy for Sustainable buildings
3. Strategy for electrification of transport, industry and society in general
4. More funds for green research and demonstration projects
5. Assessment of Danish and North Sea countries mutual expansion of offshore wind
6. Investigation of energy island of 10 GW wind before 2030
7. Support afforestation (new forest)
8. Climate adoption via coordination of coastal protection
100% Renewable Energy 2050
...... but how...???
Energi System Analyse Model

www.EnergyPLAN.eu
Members Map

This is a map of the people who have registered with the EnergyPLAN website. Select a country to identify all users from that country, and then select their name on the right hand side if you would like to contact them. We hope that this map will connect users that have a common interest with one another.
Smart Energy Systems
Smart Energy Systems:
Hourly modelling of all smart grids to identify synergies!
... and influence of different types of energy storage..!
Smart Energy Systems

www.energyplan.eu/smartenergysystems/
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 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

- 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).
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 Thermal Grids** are a network of pipes connecting the buildings in a neighbourhood, town centre or whole city, so that they can be served from centralised plants as well as from a number of distributed heating or cooling production units including individual contributions from the connected buildings.

- **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.

**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
Energy Storage

Pump Hydro Storage
175 €/kWh

Natural Gas Underground Storage
0.05 €/kWh

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

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

Henrik Lund1, Poul Alberg Østergaard1, David Connolly2, Iva Ridjan2, Brian Vad Math4, Frede Hvelplund1, Jakob Zinck Thellufsen1, Peter Sorknaes1

1 Aalborg University, Skåhøegade 5, 9000 Aalborg, Denmark

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.

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 comparisons of different sizes of electricity energy storage technologies. See assumptions, details and references in Appendix 1.
Existing distribution grids in DK
IDA Energiplan 2030

Primary energy supply

CO₂ emissions

Business

Aalborg University
Denmark
### Primary energy supply

#### Peta Joule (PJ)

<table>
<thead>
<tr>
<th>Year</th>
<th>Export</th>
<th>RE electricity</th>
<th>Solar thermal</th>
<th>Biomass</th>
<th>Natural gas</th>
<th>Oil</th>
<th>Coal</th>
</tr>
</thead>
<tbody>
<tr>
<td>2004</td>
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<td>Ref. 2030</td>
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<tr>
<td>IDA 2030</td>
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<tr>
<td>IDA 2050</td>
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</tr>
</tbody>
</table>

### Biomass potentials and consumption in IDA 2030, PJ

#### Potential Sources
- Waste
- Energy crops
- Slurry fibre fraction
- Slurry biogas
- Wood
- Straw

#### Consumption
- Max potential
- DEA potential

**CO₂ emissions:**
- Million ton per year
- 60.8
- 54
- 21

**Fuel demand and renewable energy consumption:**
- Renewable energy, TWh:
  - Wind power
  - Solar power
  - Wave power
  - Hydrogen electrolysis

**Total fuel demand classified according to source:**
- 1000
- 900
- 800
- 700
- 600
- 500
- 400
- 300
- 200
- 100
- 0

**CO₂ emissions:**
- 60.8
- 54
- 21

**Energy sources:**
- Wind
- IDA 2030
- IDA 2050
- Biomasse
- Naturgas
- Olie
- Kul

**Ref 2030**
- 74.1

**IDA 2030**
- 15.2
**Transport:**
Electric vehicles is best from an energy efficient point of view. But gas and/or liquid fuels is needed to transform to 100%.

**Biomass:**
.. is a limited resource and can not satisfy all the transportation needs.

**Consequence**
… Electricity from Wind (and similar resources) needs to be converted to gas and liquied fuels in the long-term perspective…
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)

Danish Oil Storage ~50 TWh

Danish Gas Storage ~11 TWh

Danish H₂ Storage ~0.550 TWh

Danish Thermal Storage ~0.200 TWh

Danish Electricity Storage ~0.015 TWh
Table 1: Overview of main scenario building blocks

<table>
<thead>
<tr>
<th>Long Term Strategy Options</th>
<th>1.5°C Technical (1.5TECH)</th>
<th>1.5°C Sustainable Lifestyles (1.5LIFE)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Main Drivers</strong></td>
<td>Electrification in all sectors</td>
<td>Based on COMBO with more BECCS, CCS</td>
</tr>
<tr>
<td><strong>GHG target in 2050</strong></td>
<td>-80% GHG (excluding sinks) [<em>well below 2°C</em> ambition]</td>
<td>-100% GHG (incl. sinks) [<em>1.5°C</em> ambition]</td>
</tr>
<tr>
<td><strong>Major Common Assumptions</strong></td>
<td>Higher energy efficiency post 2030</td>
<td>Market coordination for infrastructure deployment</td>
</tr>
<tr>
<td></td>
<td>Deployment of sustainable, advanced biofuels</td>
<td>BECCS present only post-2050 in 2°C scenarios</td>
</tr>
<tr>
<td></td>
<td>Moderate circular economy measures</td>
<td>Significant learning by doing for low carbon technologies</td>
</tr>
<tr>
<td></td>
<td>Digitisation</td>
<td>Significant improvements in the efficiency of the transport system.</td>
</tr>
<tr>
<td><strong>Power sector</strong></td>
<td>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.</td>
<td></td>
</tr>
<tr>
<td><strong>Industry</strong></td>
<td>Electrification of processes</td>
<td>Combination of most Cost-efficient options from &quot;well below 2°C&quot; scenarios with targeted application (excluding CIRC)</td>
</tr>
<tr>
<td></td>
<td>Use of H2 in targeted applications</td>
<td>COMBO but stronger</td>
</tr>
<tr>
<td></td>
<td>Use of e-gas in targeted applications</td>
<td>CIRC+COMBO but stronger</td>
</tr>
<tr>
<td></td>
<td>Reducing energy demand via Energy Efficiency</td>
<td>Combination of most Cost-efficient options from &quot;well below 2°C&quot; scenarios with targeted application (excluding CIRC)</td>
</tr>
<tr>
<td></td>
<td>Higher recycling rates, material substitution, circular economies</td>
<td>COMBO but stronger</td>
</tr>
<tr>
<td><strong>Buildings</strong></td>
<td>Increased deployment of heat pumps</td>
<td>CIRC+COMBO but stronger</td>
</tr>
<tr>
<td></td>
<td>Deployment of H2 for heating</td>
<td>CIRC+COMBO but stronger</td>
</tr>
<tr>
<td></td>
<td>Deployment of e-gas for heating</td>
<td>CIRC+COMBO but stronger</td>
</tr>
<tr>
<td></td>
<td>Increased renovation rates and depth</td>
<td>CIRC+COMBO but stronger</td>
</tr>
<tr>
<td></td>
<td>Sustainable buildings</td>
<td>CIRC+COMBO but stronger</td>
</tr>
<tr>
<td><strong>Transport sector</strong></td>
<td>Faster electrification for all transport modes</td>
<td>CIRC+COMBO but stronger</td>
</tr>
<tr>
<td></td>
<td>H2 deployment for HDVs and some for LDVs</td>
<td>CIRC+COMBO but stronger</td>
</tr>
<tr>
<td></td>
<td>E-fuels deployment for all modes</td>
<td>CIRC+COMBO but stronger</td>
</tr>
<tr>
<td></td>
<td>Increased modal shift</td>
<td>CIRC+COMBO but stronger</td>
</tr>
<tr>
<td></td>
<td>Mobility as a service</td>
<td>CIRC+COMBO but stronger</td>
</tr>
<tr>
<td><strong>Other Drivers</strong></td>
<td>H2 in gas distribution grid</td>
<td>Limited enhancement of natural sink</td>
</tr>
<tr>
<td></td>
<td>E-gas in gas distribution grid</td>
<td>Limited enhancement of natural sink</td>
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</tbody>
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A European long-term strategic vision for a prosperous, modern, competitive and climate neutral economy for all.
A Clean Planet for all
A European long-term strategic vision for a prosperous, modern, competitive and climate neutral economy
SMART ENERGY AALBORG
Energivision for Aalborg Kommune 2050
Guiding principle:
transitioning the current energy system in Aalborg to 100% Renewable Energy in a way so it fits into 100% RES in DK, then Europe and finally the World

• Sustainable use of Biomass
• Definition of transport demands
• How to handle Industry
• How to balance electricity demand and supply as well as other fuels
Biomass in Denmark – Power and Heat

**Biomass Potential**
- Optimist: Ca. 300 PJ
- Pessimist: 165 PJ
- Realist: 200 PJ

30 GJ bio pr. capita is high globally.

**Biomass Sources**
- Træpiller - Import
- Brændende - Import
- Bioethanol - Import
- Biodiesel - Import
- Skovflis
- Affald, bionedbrydeligt
- Biodiesel
- Biollk
- Slagsmøl
- Affald, bionedbrydeligt - Import
- Bryned
- Træaffald
- Slagsmøl
- Sum - Import

**Import**
- 75 PJ
## The Danish and the Global Biomass Challenge

<table>
<thead>
<tr>
<th>Publication and Geography</th>
<th>Biomass per. person</th>
</tr>
</thead>
<tbody>
<tr>
<td>Today in DK (175 PJ)</td>
<td>30 GJ/capita</td>
</tr>
<tr>
<td>Recent research for EU (8500 PJ)</td>
<td>17 GJ/capita</td>
</tr>
<tr>
<td>EU 2050 scenario</td>
<td>15-21 GJ/capita</td>
</tr>
<tr>
<td>(A Clean Planet for all)</td>
<td></td>
</tr>
<tr>
<td>IDA 100% RES in DK in 2050</td>
<td>30 GJ/capita</td>
</tr>
<tr>
<td>(200 PJ)</td>
<td></td>
</tr>
<tr>
<td>Danish Energy Agency scenario 2014</td>
<td>35-45 GJ/capita</td>
</tr>
</tbody>
</table>

### Table: Biomass per Person

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<thead>
<tr>
<th>Publication and Geography</th>
<th>Biomass per. person</th>
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</thead>
<tbody>
<tr>
<td>IDA's Energy Vision 2050</td>
<td>30 GJ/capita</td>
</tr>
<tr>
<td>CEESA 2050</td>
<td>30 GJ/capita</td>
</tr>
<tr>
<td>Elbertsen et al. (2012)</td>
<td>30 GJ/capita</td>
</tr>
<tr>
<td>Gylling et al. (2014)</td>
<td>30 GJ/capita</td>
</tr>
<tr>
<td>L. Hamelin et al. (2019)</td>
<td>30 GJ/capita</td>
</tr>
<tr>
<td>BioBoost</td>
<td>30 GJ/capita</td>
</tr>
<tr>
<td>Smart Energy Europe</td>
<td>30 GJ/capita</td>
</tr>
<tr>
<td>PRIMES - 1.5TECH</td>
<td>30 GJ/capita</td>
</tr>
<tr>
<td>PRIMES - 1.5LIFE</td>
<td>30 GJ/capita</td>
</tr>
<tr>
<td>PRIMES - 1.5SUF-E</td>
<td>30 GJ/capita</td>
</tr>
<tr>
<td>JRC-EU-TIMES Model</td>
<td>30 GJ/capita</td>
</tr>
<tr>
<td>EU27 (not including Croatia and Switzerland)</td>
<td>30 GJ/capita</td>
</tr>
<tr>
<td>Current consumption in Denmark (2018)</td>
<td>17 GJ/capita</td>
</tr>
</tbody>
</table>

### Graph: Bioenergy Potential vs. Current Consumption

- **Bioenergy Potential per Capita (GJ/cap)**
- **Current Consumption in Denmark (2018)**

Hannemann et al. (2012) and the Danish Energy Agency: 35-45 GJ/capita

L. Hamelin et al. (2019) and the Danish Energy Agency: 30 GJ/capita
Biomass

- Local Biomass resources in Aalborg (incl. waste) 6100 TJ/year.

- Aalborg’s share of Danish sustainable biomass resources (incl. bio-share of waste, straw/wood and biogas) approx. 6200 TJ/year.
Transport

- Transport part/share of 100% RES in DK as a whole:
- IDA Energy Vision 2050: As much electric vehicles as possible. Supplemented by bio-fuels for aviation, trucks etc.
Industry

- Coal, oil and natural gas in Industry in Aalborg constitutes 3,750 GWh/year (incl. Portland).
- Aalborg’s share (population) of Danish consumptions are 990 GWh/year.
- IDA-plan: Savings, efficiencies, district heating and cooling, electricity and green gas.
PV versus Wind

![ Installed Capacity in MW ]

- **10% PV**
- **20% PV**
- **30% PV**

- Offshore wind
- Onshore wind
- PV

![ Electricity Balancing (GWh/year) ]

- **10% PV**
- **20% PV**
- **30% PV**

- Excess electricity production
- Import

![ System Total Costs - Million DKK/year ]

- **10% PV**
- **20% PV**
- **30% PV**

- Sum
Sankey diagram of the current system

- Wind: 0.24 TWh
- Solar: 0.34 TWh
- Excess heat: 0.34 TWh
- Coal: 3.51 TWh
- Oil: 2.33 TWh
- Natural gas: 0.42 TWh
- Biomass, waste, etc.: 0.92 TWh

Fossil fuels: 3.12 TWh

Electricity: 1.63 TWh
- Export: 0.39 TWh
- Electricity demand: 1.15 TWh
- DH demand: 2.06 TWh
- HPs & Electric heating: 0.09 TWh
- Indiv. heating: 2.5 TWh

Transport: 2.15 TWh
- Industry: 1.03 TWh
- 0.77 TWh
- 0.26 TWh

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Denmark
Sankey diagram of the 2050 system

- **Electricity demand:** 1.41 TWh
  - **Electricity Demand:** 0.4 TWh
  - **Electrofuels:** 1 TWh
  - **DH demand:** 1.56 TWh
    - **District Heating:** 0.45 TWh
    - **District Cooling:** 0.29 TWh
    - **Cooling:** 0.32 TWh
    - **Natural Cooling:** 0.18 TWh

- **Import:** 0.04 TWh
- **Export:** 0.05 TWh
- **Wind:** 2.2 TWh
- **Solar:** 0.5 TWh
- **Biomass, Waste, etc.:** 1.71 TWh
  - **CHP (incl. Boilers) & Waste:** 0.37 TWh
  - **Biogas & Gasification:** 1.2 TWh
    - **Loses:** 0.01 TWh
  - **Other Power:** 1.07 TWh
  - **Electrolyzers:** 1.17 TWh
  - **HPs & Electric heating:** 0.67 TWh
  - **HPs & Geothermal:** 0.26 TWh
  - **Individual HPs:** 0.21 TWh

- **Excess heat:** 0.68 TWh

**Aalborg University**
**Denmark**
Hourly balancing of electricity demand and supply

![Graph showing imbalances and total system costs over different steps.](image-url)
Vision results

Primary energy

![Graph showing primary energy distribution for 2018, 2050 BAU, 2050 Imbalanced, and 2050 Vision scenarios.](image)

- Coal
- Oil
- Gas
- Biomass
- Onshore wind
- Solar PV
- Offshore wind

Annual costs

![Graph showing annual costs for 2050 BAU, 2050 Ubalance, and 2050 Scenario.](image)

- Variable costs
- Fixed O&M
- Investments

TWh

- 2018
- 2050 BAU
- 2050 Imbalanced
- 2050 Vision
PV (570 GWh/y from 500 MW)

• Equal to 20% of electricity production
• Could in principle by on existing roofs:
  – 950 hektar out of 2200
  – 950 hektar could fully exploited produce 1060 GWh/year
• Or around 800 hektar fields (including roads etc. - based on “Vust Holme”)
• In the Energy Vision prices have been based on a mix between the two…
Wind: 1050 GWh/y from 300 MW

- Aalborg already has 158 MW
- New wind farm (Nørkær Enge) will increase to 220 MW
- Replacement by bigger wind turbines is expected before 2050
- Additional expected 280 MW offshore will produce 1270 GWh/year.
6TH INTERNATIONAL CONFERENCE ON
Smart Energy Systems
6-7 OCTOBER 2020 • AALBORG

Location:
NORDKRAFT

Save the date!

AALBORG UNIVERSITY
DENMARK