100 % Renewable Energies for Bavaria

Potentials and Structures of a Full Supply in the Sectors Electricity, Heat and Mobility

Please cite the Bayernstudie, which can be found at https://www.mw.tum.de/es/publikationen/bayernstudie
ZAE Bayern – Mission and Vision

Since 1991, ZAE has been conducting

- Research,
- Implementation in Practice,
- Education, Training and Further Education
- Consulting and Information

in significant areas of energy technology

Target:
CO₂-neutral energy supply
through the use of renewable energies and
increased energy efficiency

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ZAE Bayern – Energy Storage

~ 85 Employees
~ 5.5 m € R&D Funds/Year
~ 3500 m² Research Area

Energy Storage
Flexibility for Electricity and Heat

System Engineering
Energy Concepts
Studies & Scenarios

Solar thermal & Geothermal
Solar and Geothermal District Heating

Thermal Energy Storage
Cold and Heat Storage Materials

Electric Energy Storage
Redox Flow Batteries
Electrolysis

Heat Transformation
Heat Pumps
Chillers
Chair of Energy Systems I

- Located on the TUM Campus Garching, north of Munich
- Campus Garching: over 3,500 employees and 15,000 students
- Faculty of Mechanical Engineering
- Staff: approx. 54 employees (approx. 35 PhD students, 4 postdocs)
- Mission: Efficient and low emission fossil and renewable power generation
Chair of Energy Systems II

Renewable Sources
- Biomass, Residue, Waste, Geothermal, Solar thermal, Excess power (Wind, PV)

Fossil Sources
- Coal, Residue, Waste

Vision: Efficient and Renewable Energy System

Processes & Components
- Power Generation and Thermodynamic Cycles
  - Steam generation, ORC, Flexibility
- Power-to-X and Reversible Fuel Cells
  - CO2 utilization, Syntheses, SOFC
- Solid Fuel Conversion
  - Combustion, Gasification, Kinetics, Emissions, Deposition, Corrosion
- Energy Storage
  - Thermal and thermochemical storage, high temperature processes

System Studies

Power
- Residual load

Heat
- District heating

Fuels & Chemicals
- SNG, MeOH, H2, FT liquids, NH3
Overview
The Energy System Model I

Scope:
- 100 % renewable energy system in 2040 for Bavaria

Methodology:
- Mathematical model with hourly resolution of the Bavarian energy system and direct neighboring regions
- Assumptions on costs, technologies and energy demands for 2040
- Scenario-based analysis

<table>
<thead>
<tr>
<th>Considered sectors</th>
<th>Assumptions for 2040</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity</td>
<td>Conventional applications</td>
</tr>
<tr>
<td>Mobility</td>
<td>Constant</td>
</tr>
<tr>
<td>Heat</td>
<td>Space/domestic water heating</td>
</tr>
<tr>
<td></td>
<td>Process heat</td>
</tr>
</tbody>
</table>
The Energy System Model II

**Demand**
- Electricity, Heat & Mobility
- Demand on hourly basis

**Technologies**
- Costs, efficiencies
- CO₂-emissions

**Energy Sources**
- Renewable energies, based on weather data
- Import/export

**Optimisation of the Energy System**
- Optimisation objective: minimisation of the overall costs
- Restrictions due to boundary conditions
## Scenario Definition

<table>
<thead>
<tr>
<th></th>
<th>Base Case</th>
<th>Conventional Neighbours</th>
<th>Stand Alone System</th>
<th>Wind Limitation 15 GW</th>
<th>Synthetic Fuels</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fully renewable energy system for Bavaria</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Renewables in neighboring energy systems</td>
<td>80 %</td>
<td>50 %</td>
<td>No electricity exchange</td>
<td>80 %</td>
<td>80 %</td>
</tr>
<tr>
<td>Import/export balanced and limited</td>
<td>X</td>
<td>X</td>
<td>No electricity exchange</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Limited wind power capacities</td>
<td></td>
<td></td>
<td></td>
<td>15 GW</td>
<td></td>
</tr>
<tr>
<td>Mobility sector</td>
<td>E-mobility only</td>
<td>E-mobility only</td>
<td>E-mobility only</td>
<td>E-mobility only</td>
<td>Var. share of synfuels</td>
</tr>
</tbody>
</table>
Key Messages

• Self-sufficiency in Bavaria is demanding

• A strong expansion of photovoltaics, wind power and battery storage is necessary

• The import and export of electricity, combined heat and power (CHP), energy storage and power-to-gas are crucial for security of supply

• Mobility and heat supply will become major electricity consumers

• The future heat sector will rely on a variety of technologies, depending on local conditions

Bavaria 100 % renewable is technically possible, but represents a major challenge!!
Electricity Sector
Overview over the Electricity Sector

- Hydro: 11.8 TWh
- CHP: 5.0 TWh
- Gas Turbine: 0.05 TWh
- Power-to-Gas: 9.5 TWh
- Photovoltaics: 68.4 TWh
- Wind: 80.0 TWh

Export: 27.8 TWh
Import: 26.5 TWh

- Electricity Transport: 52.7 TWh
- Electricity Heating: 45.6 TWh
- Electricity Conventional Usage: 53.4 TWh

100% Renewable Energies for Bavaria

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# Most Important Technologies and Electricity Consumption

## Most Important Technologies

<table>
<thead>
<tr>
<th>Technology</th>
<th>Installed</th>
<th>Specific</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind</td>
<td>32.3 GW</td>
<td>1335 Inhabitants/Wind Turbine kW</td>
</tr>
<tr>
<td>Photovoltaics</td>
<td>66.6 GW</td>
<td>5.1 kWh/Inhabitant</td>
</tr>
<tr>
<td>Battery Storage</td>
<td>105 GWh</td>
<td>8.1 kWh/Inhabitant</td>
</tr>
</tbody>
</table>

## Other Technologies

<table>
<thead>
<tr>
<th>Technology</th>
<th>Installed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biomass CHP</td>
<td>1.15 GW</td>
</tr>
<tr>
<td>SNG CHP</td>
<td>2.61 GW</td>
</tr>
<tr>
<td>SNG Turbine</td>
<td>1.57 GW</td>
</tr>
</tbody>
</table>

## Consumption

<table>
<thead>
<tr>
<th>Source</th>
<th>Consumption</th>
<th>Reduction of Final Energy Consumption</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional</td>
<td>53.4 TWh&lt;sub&gt;el&lt;/sub&gt;</td>
<td>50 %</td>
<td>Scenario Specification BUND</td>
</tr>
<tr>
<td>Transport</td>
<td>52.7 TWh&lt;sub&gt;el&lt;/sub&gt;</td>
<td>53 %</td>
<td>Due to Electrification</td>
</tr>
<tr>
<td>Heat</td>
<td>45.6 TWh&lt;sub&gt;el&lt;/sub&gt; (+ Q&lt;sub&gt;th&lt;/sub&gt;)</td>
<td>52 - 54 %</td>
<td>Own Calculations</td>
</tr>
</tbody>
</table>
Typical Course in Summer

- In summer high PV production
- PV, wind and hydro can meet electricity demand

- Battery storage largely in day-night rhythm
- Export surplus
Typical Course in Winter

- Hours with low PV and wind production occur in winter
- CHP and peak load SNG turbines are needed

- Storage discharged, but limited by capacity
- Import from Bavaria's neighbours
Wind Potential – Methodology

Dependencies of the wind potential

1) Usable areas for wind
   (= Total Bavarian area – area of exclusion)

2) Wind levels in usable areas
   (→ statistical evaluation of weather data)

3) Used wind turbine types
   (→ modern slow windspeed turbines)

BUT: There are more dependencies, which are not considered → calculated potential is only a theoretical maximum
Wind Potential – Results

- Distance more than 1,000 m: Potential up to 87 GW
- Distance more than 2,500 m: Potential up to 2 GW

→ Especially in the case of wind power, the existing potential should be maximally utilized

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Photovoltaic

Assumptions for the calculations
• Specifications of state of the art PV modules
• Different orientations and inclinations
  – South and east/west orientations
  – Inclination of 10°, 25° and 30°
• Solar irradiation based on weather data

<table>
<thead>
<tr>
<th>Calculated space demand for PV</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Open-field</td>
<td>133–199 km²</td>
</tr>
<tr>
<td>Rooftop</td>
<td>266 km²</td>
</tr>
</tbody>
</table>

Bavaria:
• Total area 70,000 km²
• Ground-plan area of all buildings 977 km²
Transport Sector
## Data Generation Methodology

<table>
<thead>
<tr>
<th>Type</th>
<th>Final Energy Share</th>
<th>Time Series Considered</th>
<th>Energy Demand Considered</th>
</tr>
</thead>
<tbody>
<tr>
<td>Road</td>
<td>82.1%</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>Air</td>
<td>15.4%</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td>Shipping</td>
<td>0.4%</td>
<td>no</td>
<td>yes</td>
</tr>
<tr>
<td>Rail</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>electrified</td>
<td>1.5%</td>
<td>via electricity sector</td>
<td>via electricity sector</td>
</tr>
<tr>
<td>diesel-powered</td>
<td>0.5%</td>
<td>no</td>
<td>yes</td>
</tr>
<tr>
<td>Public Transport</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>City buses</td>
<td>1.2%</td>
<td>no</td>
<td>yes</td>
</tr>
<tr>
<td>Subway</td>
<td></td>
<td>via electricity sector</td>
<td>via electricity sector</td>
</tr>
<tr>
<td>City rail</td>
<td></td>
<td>via electricity sector</td>
<td>via electricity sector</td>
</tr>
</tbody>
</table>

100% Renewable Energies for Bavaria
Results Transport

Mix of Electricity for e-Mobility

- Electricity mainly from PV and wind (63 %)
- but also from import and storage (28 %)

Scenarios for Synthetic Fuels

- Strongly increased demand for renewable energies
- Significantly lower battery storage requirement, as synthetic fuels can be stored well
Heat Sector
Modelling the Heat Sector

Heat Demand

Space Heating & Domestic Hot Water

I. 65 °C

Process Heat

100 °C 150 °C 200 °C 500 °C 500+ °C
Modelling the Heat Sector

Heat Demand

Space Heating & Domestic Hot Water

I. 65 °C

Process Heat

100 °C 150 °C 200 °C 500 °C 500+ °C

II. 115 °C 80 °C

No Deep Geothermal Energy

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Modelling the Heat Sector

Heat Demand

Space Heating & Domestic Hot Water

- 65 °C

Process Heat

- 100 °C
- 150 °C
- 200 °C
- 500 °C
- 500+ °C

No Deep Geothermal Energy

I. 115 °C
II. 80 °C

III. Interconnected Area

City

Town

Rural Area

100 % Renewable Energies for Bavaria
Modelling the Heat Sector

Heat Demand

- Space Heating & Domestic Hot Water
  - I. 65 °C
- Process Heat
  - 100 °C
  - 150 °C
  - 200 °C
  - 500 °C
  - 500+ °C
  - No Deep Geothermal Energy

II. 115 °C
III. Interconnected Area
IV. Costs of potential district heating networks

City
Town
Rural Area
Heat Demand Load Profile

Year (daily average)

- Space heating dominant in winter
- Domestic hot water (DHW) dominant in summer
- Demand peaks in the morning and evening
The Bavarian Heat Supply
Heat Supply in the Type Areas

- Electrothermal
- Heat Pump
- SNG (CHP + Heat)
- Biomass (CHP + Heat)
- Deep Geothermal Energy

Building-specific
District Heating Network

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Areas with the Use of Hydrothermal Deep Geothermal Energy

- Hydrothermal deep geothermal energy for base and medium loads
- Biomass CHP and SNG CHP for peak load supply and to compensate for the inertially controllable deep geothermal energy
- Electrothermal heat supply by means of heating rods for peak load supply
District Heating Areas for the Provision of Electrical Flexibility

- When electricity production is high, heat is provided electrothermally
- Biomass CHP and SNG CHP provide more flexibility for the power sector
- Heat storage enables increased flexibility in the heat load of a type area
  → indirect effect on the power sector
Sector Coupling
Flexibility during Low Wind and PV Production

1. Windy Winter Day
   - Wind power greater than electricity demand
   - Charging of electricity storage and electrothermal heat supply

2. Low Wind and PV Production
   - Low wind & PV power output is compensated by storage and CHP electricity
   - Heat supply exceeds demand, heat is stored in district heating network storage facilities

3. Balanced Winter Day
   - Wind & PV meet demand, electric storage is charged
   - CHP plants shut down, heat storage is discharged
Scenario Comparison

Calculation of further observation scenarios

1) Lower share of renewable energies abroad
   - Neighbours provide more flexibility
   - Bavaria needs less flexible generators and storage

2) Bavaria as an insular system
   - Neighbours provide less flexibility
   - Bavaria needs more flexible generators and storage

3) Wind limit of 15 GW
   - Bavaria is much more dependent on PV
   - Bavaria needs more flexible generation and storage
Summary / Conclusions

- Strong reduction in consumption and strong expansion of photovoltaics, wind power and battery storage necessary for Bavaria's balance sheet self-sufficiency
- Self-sufficiency technically feasible, but implementation is challenging: the more self-sufficient, the more challenging!
- Imports can be useful, such as wind power from DE/EU or synthetic fuels from sunny regions
- Crucial for security of supply are import and export of electricity, cogeneration, energy storage and power-to-gas
- Coupled electricity, mobility and heat sectors indispensable
- Technologies in the optimized energy system change

Reduction of consumption and expansion of RE in Bavaria must be implemented
Thank you for your attention!

Download the study at [www.mw.tum.de/es/publikationen/bayernstudie](http://www.mw.tum.de/es/publikationen/bayernstudie)

Chair for Energy Systems
Sebastian Miehling*
Benedikt Schweiger*
Wolf Wedel
Andreas Hanel
Hartmut Spleithoff
* shared first authorship

ZAE Bavaria
Jakob Schweiger
Rene Schwermer
Maximilian Blume