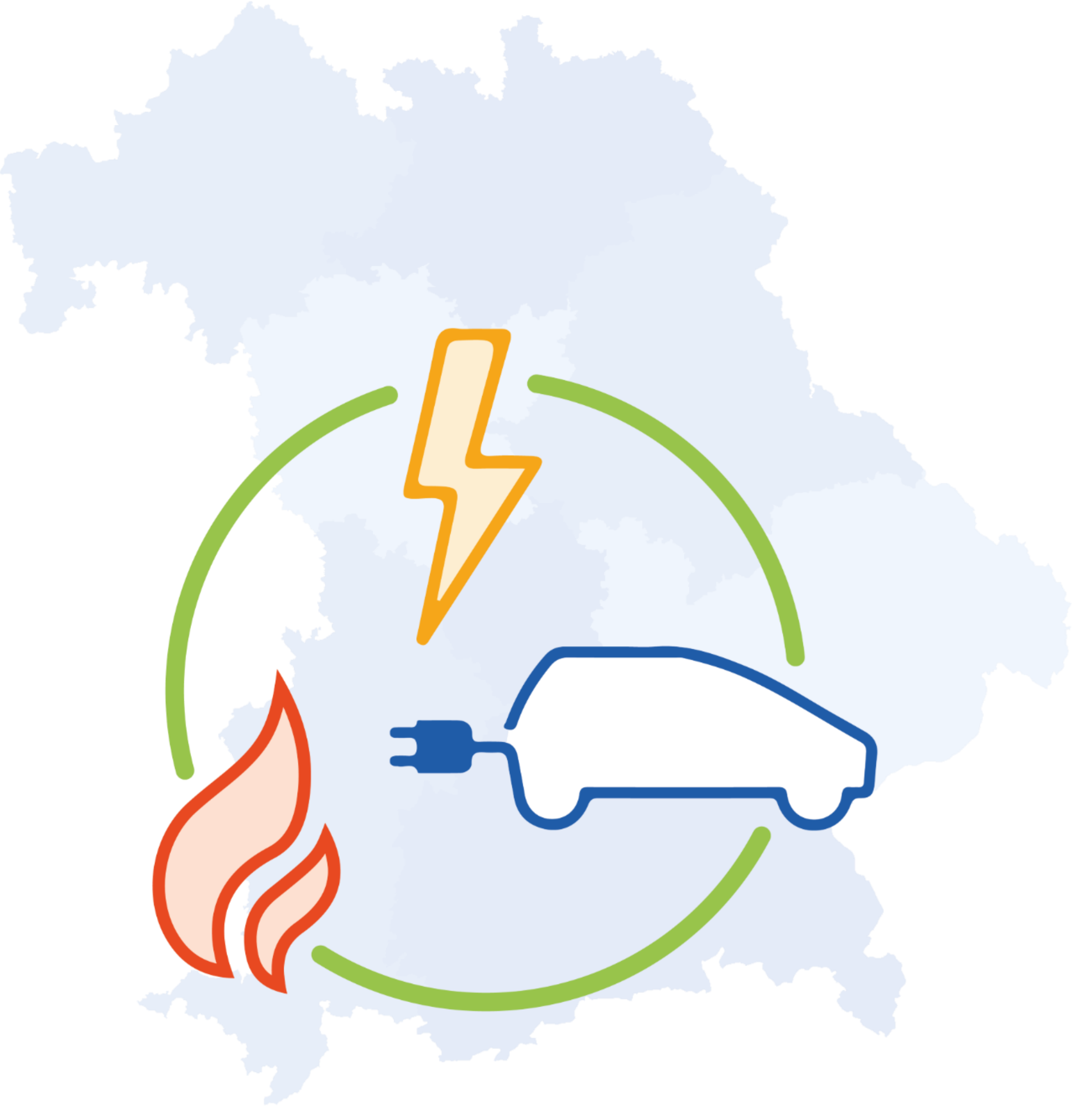
100 %
Renewable Energies for Bavaria

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



BUND Naturschutz in Bayern e.V.

ZAE BAYERN

TUM

Please cite the Bayernstudie, which can be found at https://www.mw.tum.de/es/publikationen/bayernstudie

ZAE Bayern – Mission and Vision

ZAE BAYERN

Scientific Fields

ENERGY STORAGE	ENERGY EFFICIENCY
Location Garching	Location Würzburg
Management Board: Dr. Hauer	Management Board : Dr. Ebert

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:
CO_2-neutral energy supply through the use of renewable energies and increased energy efficiency

ZAE Bayern – Energy Storage

~ 85 Employees
~ 5,5 m € R&D Funds/Year
~ 3500 m² Research Area

Chair of
Energy Systems

Chair of
Technical Electrochemistry

Chair of
Electrical Energy
Storage Technology

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

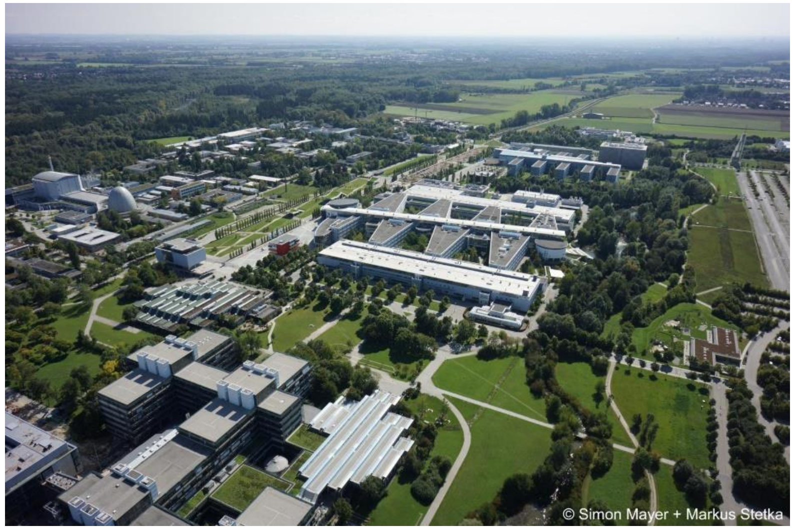
Electric Energy Storage
Redox Flow Batteries
Electrolysis

Heat Transformation
Heat Pumps
Chillers

Please cite the Bayernstudie; found at https://www.mw.tum.de/es/publikationen/bayernstudie

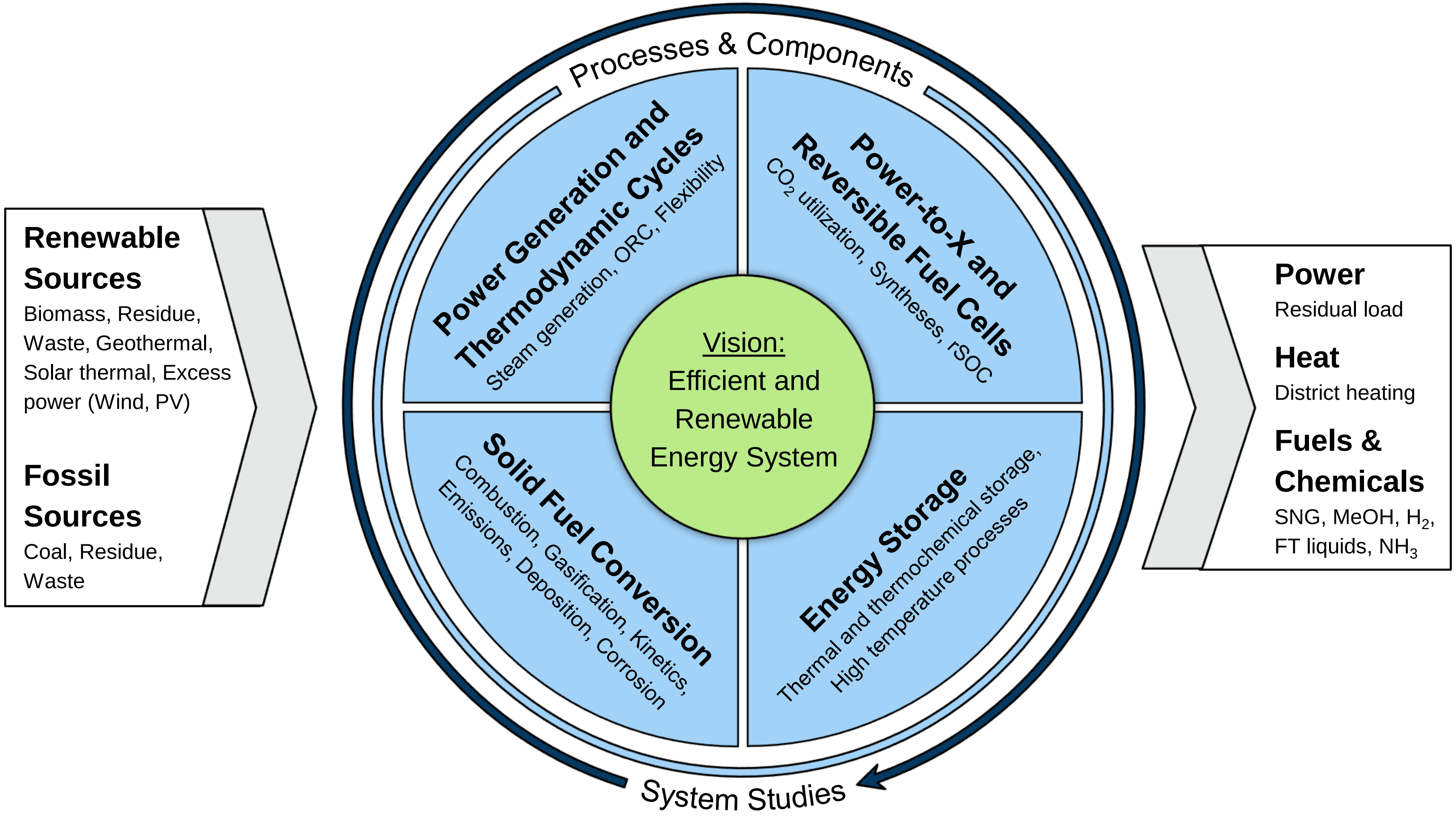
Chair of Energy Systems I

- 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**



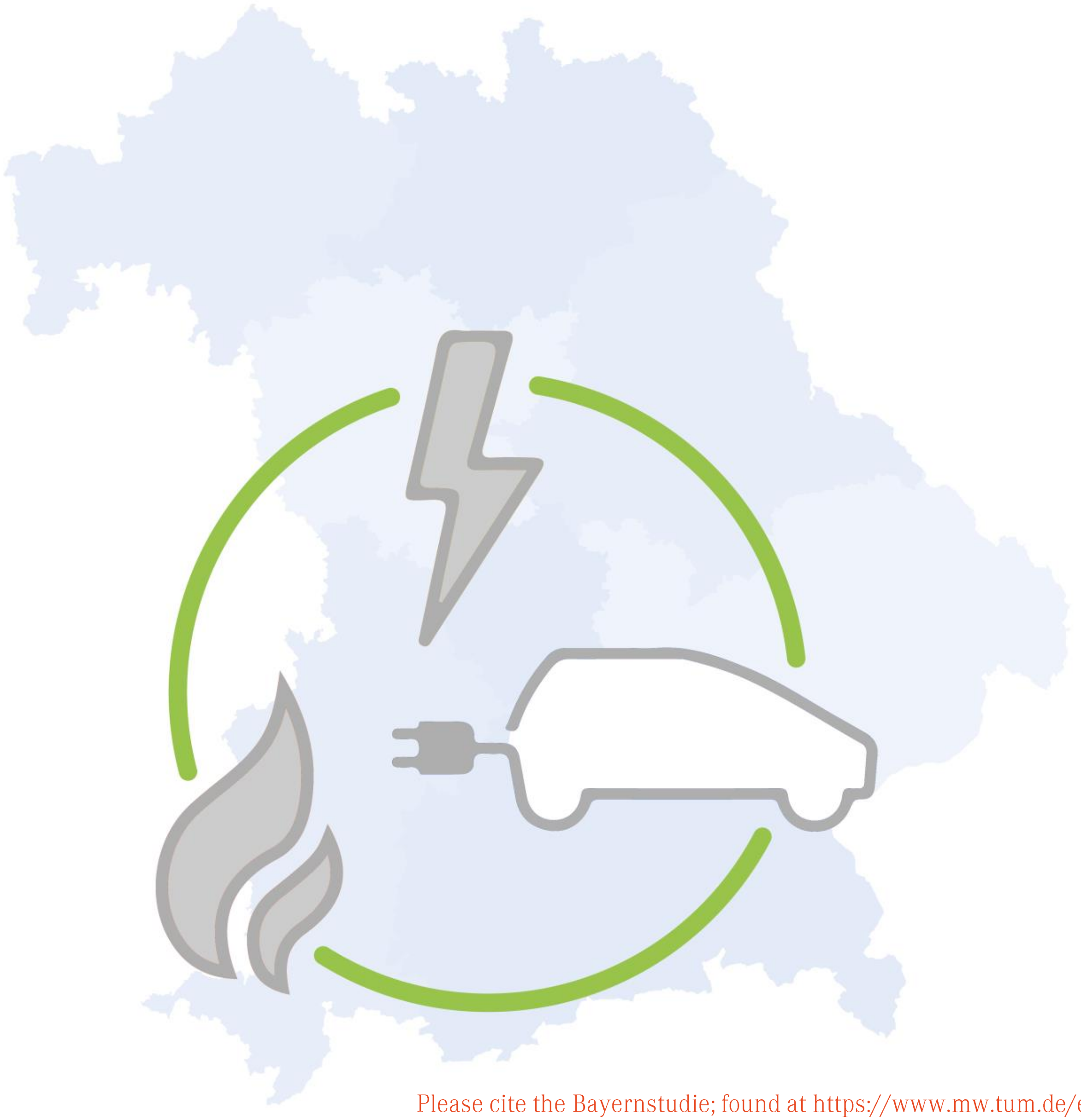
Please cite the Bayernstudie; found at https://www.mw.tum.de/es/publikationen/bayernstudie

Chair of Energy Systems II



Please cite the Bayernstudie; found at https://www.mw.tum.de/es/publikationen/bayernstudie

Overview



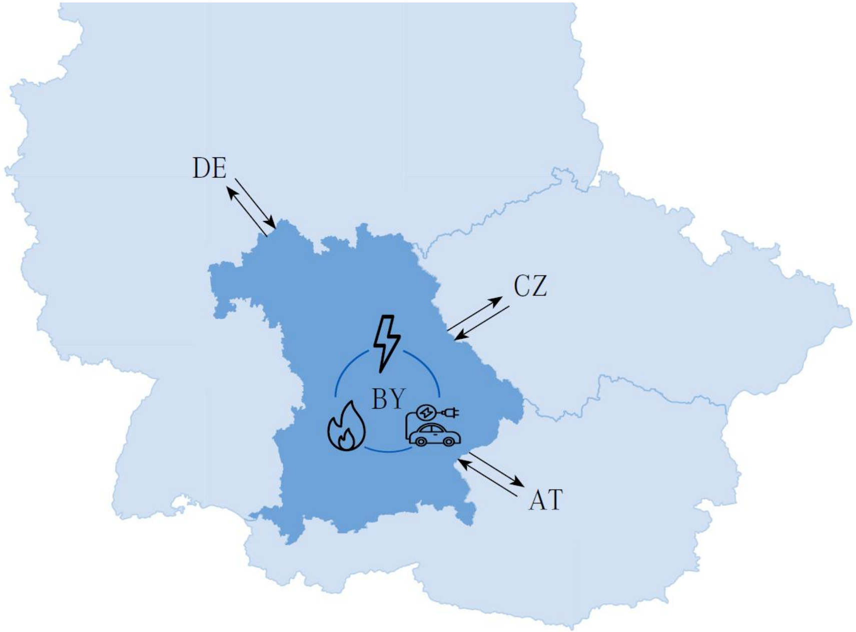
The Energy System Model I

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

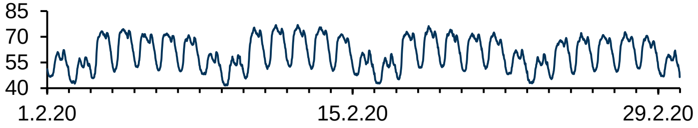


Considered sectors		Assumptions for 2040
Electricity	Conventional applications	-50 %
Mobility		constant
Heat	Space/domestic water heating	-54 %
	Process heat	-52 %

The Energy System Model II

Demand

- Electricity, Heat & Mobility
- Demand on hourly basis



Technologies

- Costs, efficiencies
- CO_2-emissions

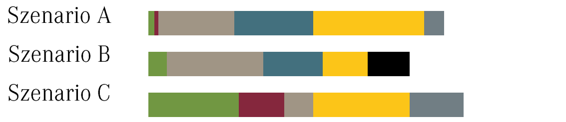
Energy Sources

- Renewable energies, based on weather data
- Import/export

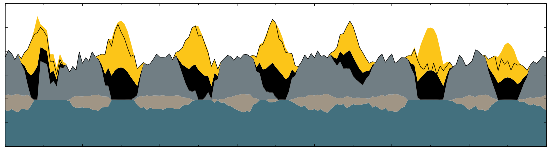
Optimisation of the Energy System

- Optimisation objective: minimisation of the overall costs
- Restrictions due to boundary conditions

Technology Portfolio



Load Profiles



Please cite the Bayernstudie; found at https://www.mw.tum.de/es/publikationen/bayernstudie

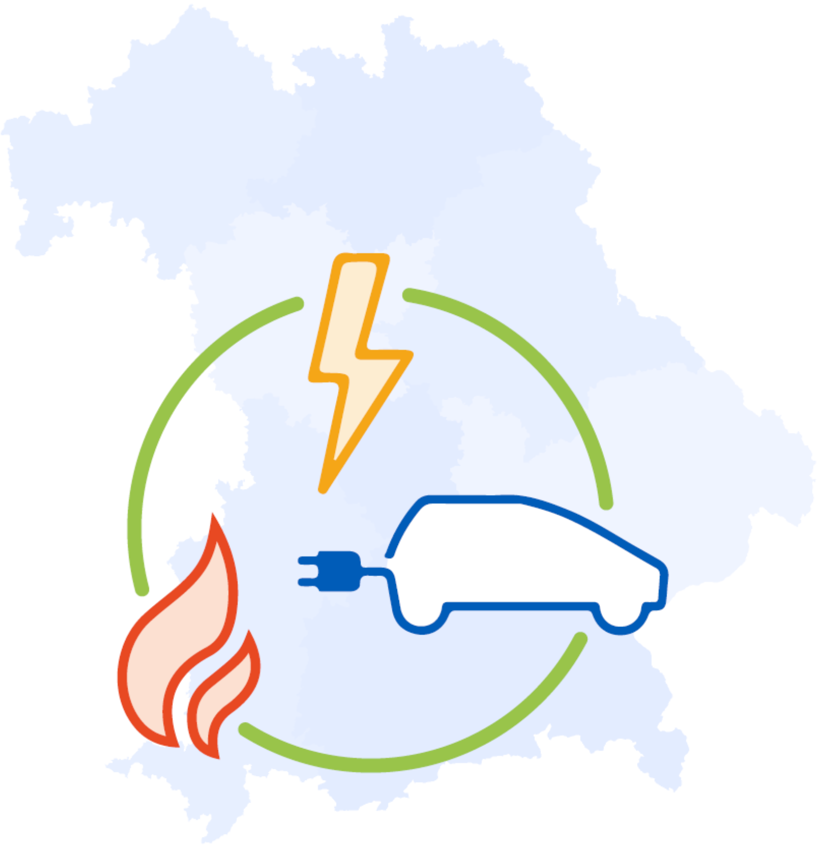
Scenario Definition

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

Please cite the Bayernstudie; found at https://www.mw.tum.de/es/publikationen/bayernstudie

Key Messages

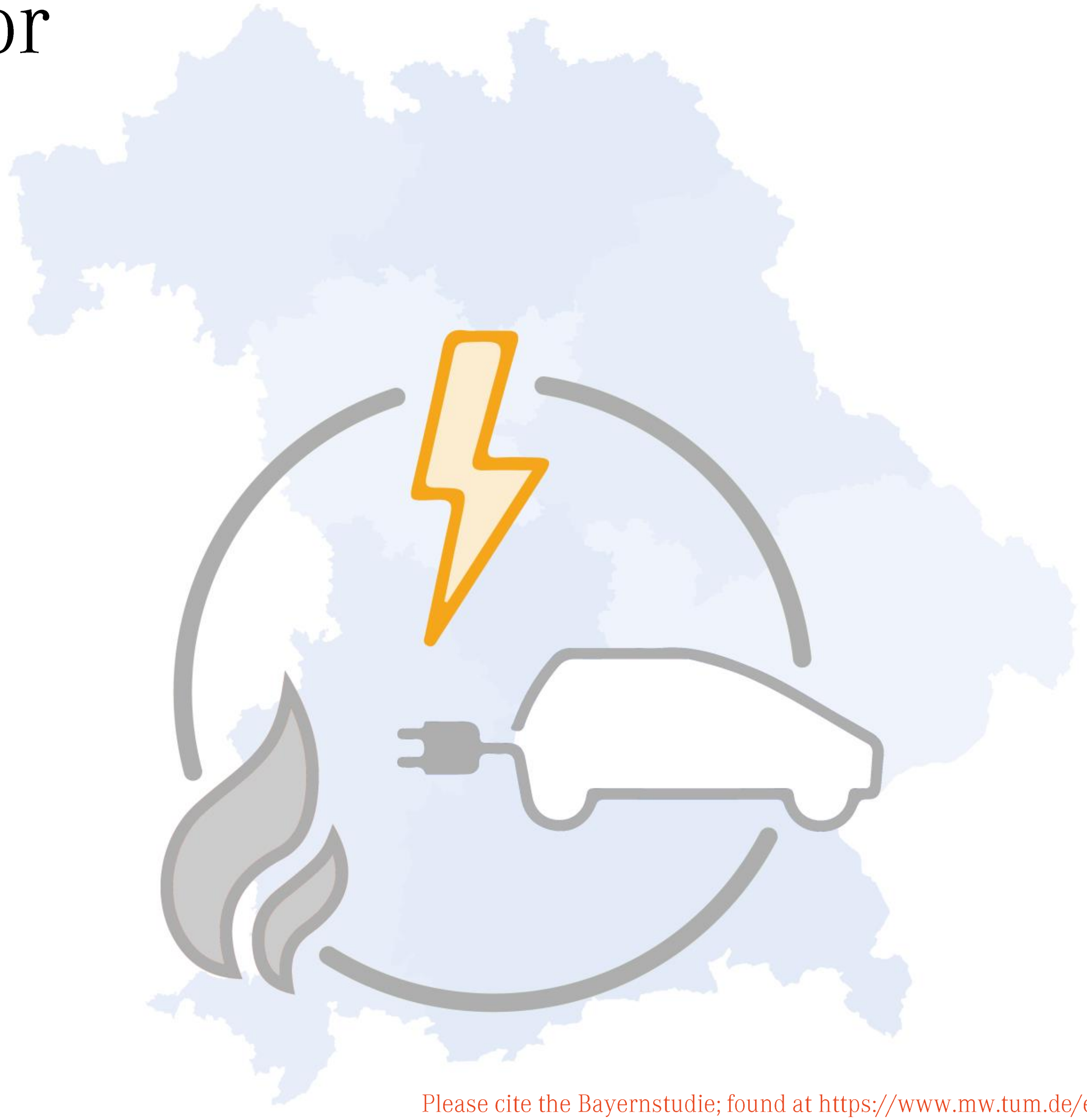
- Self-sufficiency in Bavaria is demanding
- A strong expansion of photovoltaics, wind power and battery storage is necessary
- The import and export of electricity, combined heat and power (CHP), energy storage and power-to-gas are crucial for security of supply
- Mobility and heat supply will become 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!!

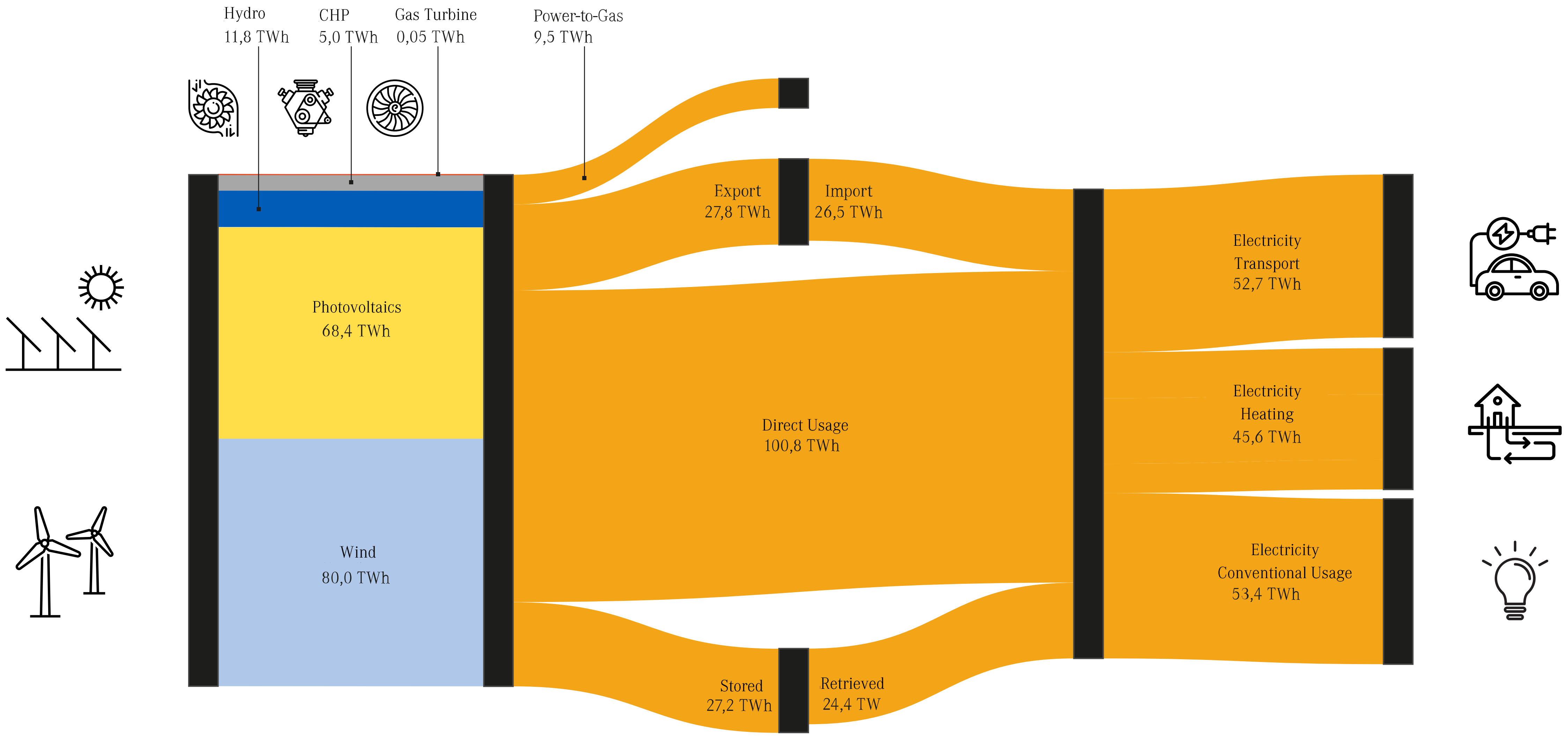
Please cite the Bayernstudie; found at https://www.mw.tum.de/es/publikationen/bayernstudie

Electricity Sector



Please cite the Bayernstudie; found at https://www.mw.tum.de/es/publikationen/bayernstudie

Overview over the Electricity Sector



Most Important Technologies and Electricity Consumption

Most Important Technologies

	Installed	Specific
Wind	32,3 GW	$1335 \frac{\text{Inhabitants}}{\text{Wind Turbine}}$
Photovoltaics	66,6 GW	$5{,}1 \frac{\text{kW}}{\text{Inhabitant}}$
Battery Storage	105 GWh	$8{,}1 \frac{\text{kWh}}{\text{Inhabitant}}$

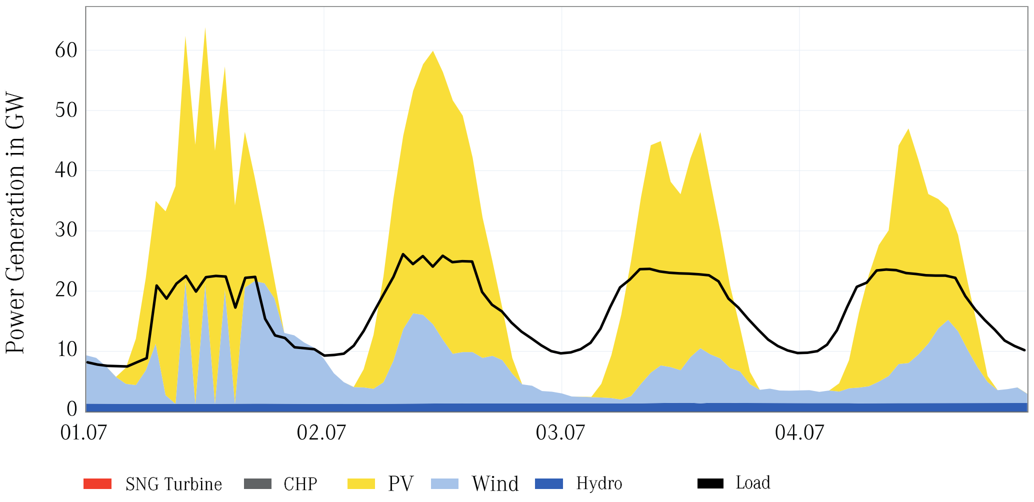
Other Technologies

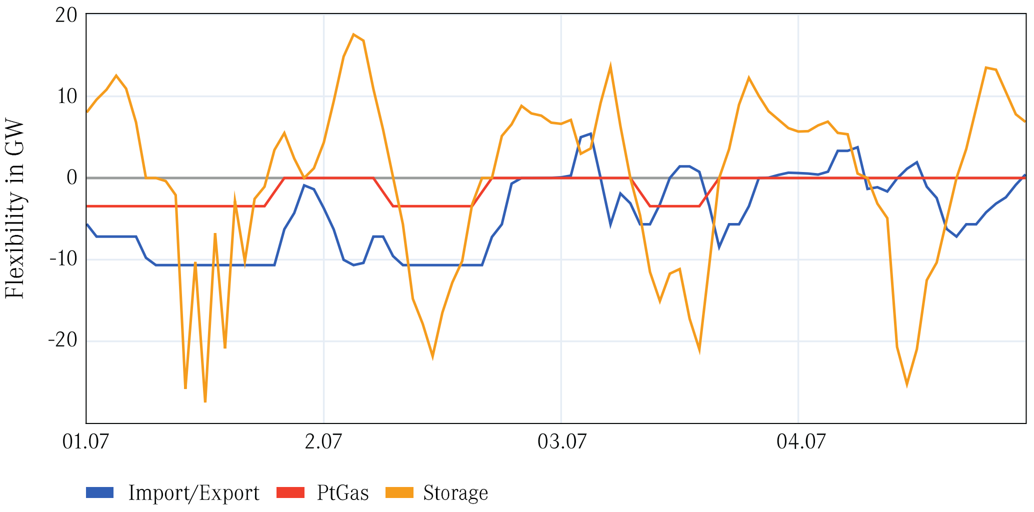
	Installed
Biomass CHP	1,15 GW
SNG CHP	2,61 GW
SNG Turbine	1,57 GW

Consumption

	Consumption	Reduction of Final Energy Consumption	Note
Conventional	53,4 TWh_{el}	50 %	Scenario Specification BUND
Transport	52,7 TWh_{el}	53 %	Due to Electrification
Heat	45,6 TWh_{el} (+ Q_{th})	52 - 54 %	Own Calculations

Typical Course in Summer



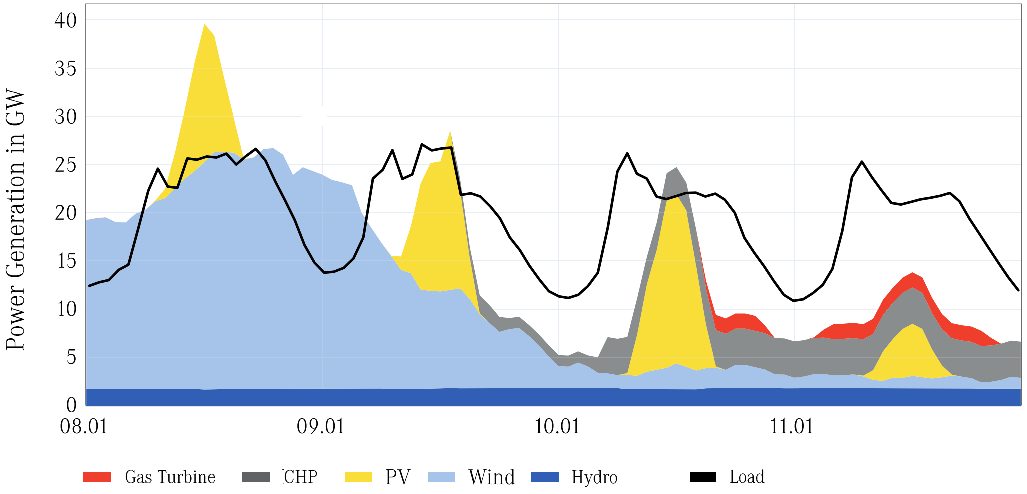


- In summer high PV production
- PV, wind and hydro can meet electricity demand

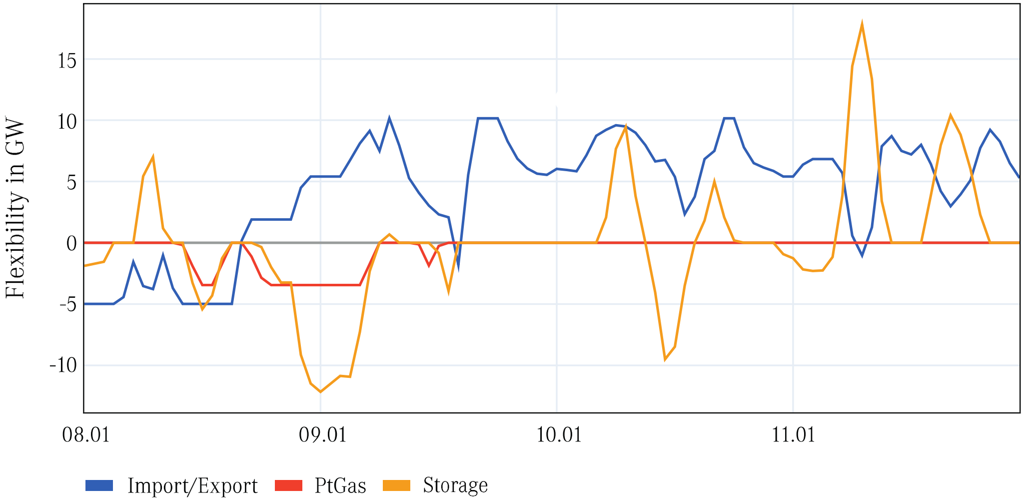
- Battery storage largely in day-night rhythm
- Export surplus

Please cite the Bayernstudie; found at https://www.mw.tum.de/es/publikationen/bayernstudie

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

Please cite the Bayernstudie; found at https://www.mw.tum.de/es/publikationen/bayernstudie

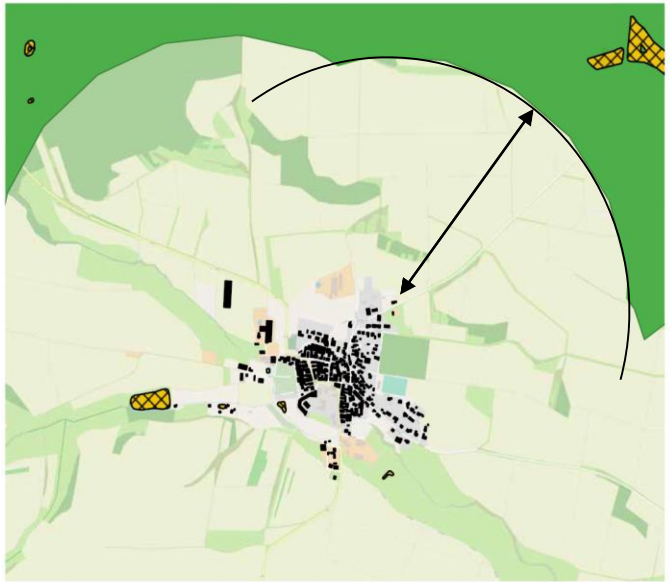
Wind Potential – Methodology

Dependencies of the wind potential

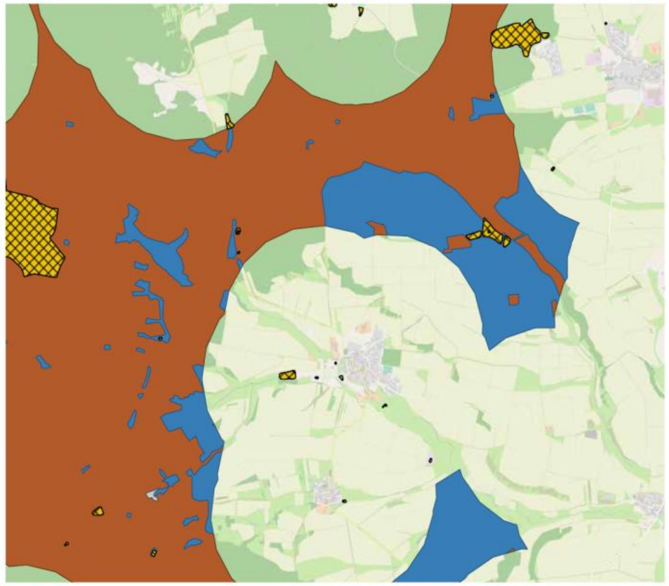
1) Usable areas for wind
   (= Total Bavarian area – area of exclusion)

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

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



Residential buildings
Wind potential area
Other excluded areas



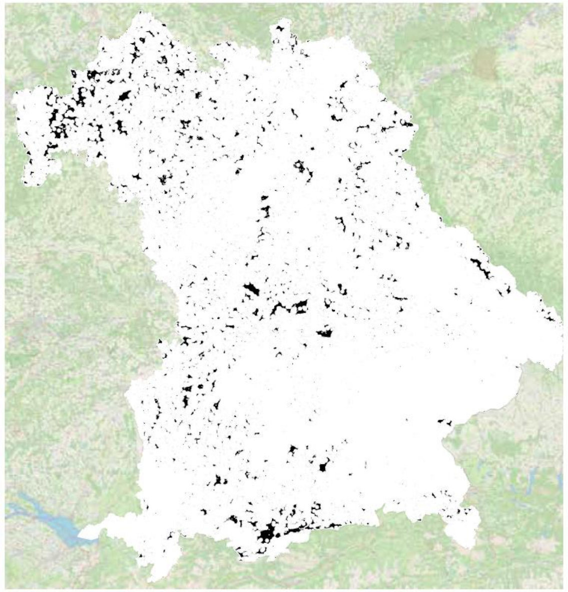
Wind potential area - agriculture
Wind potential area - forest
Wind potential area - other
Other excluded areas

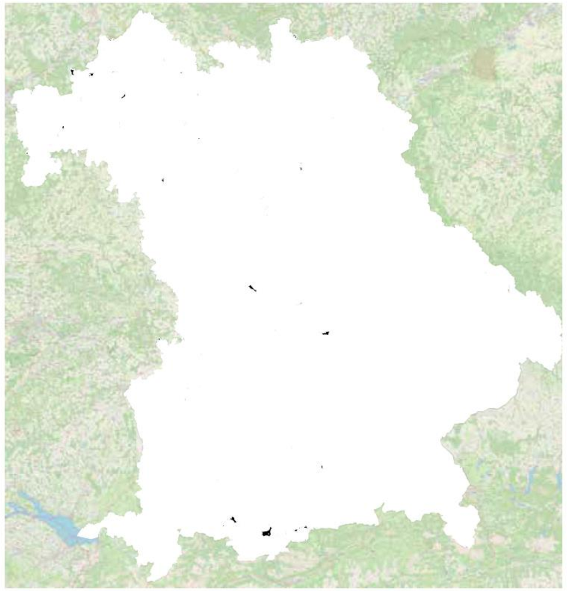
BUT: There are more dependencies, which are not considered → calculated potential is only a theoretical maximum

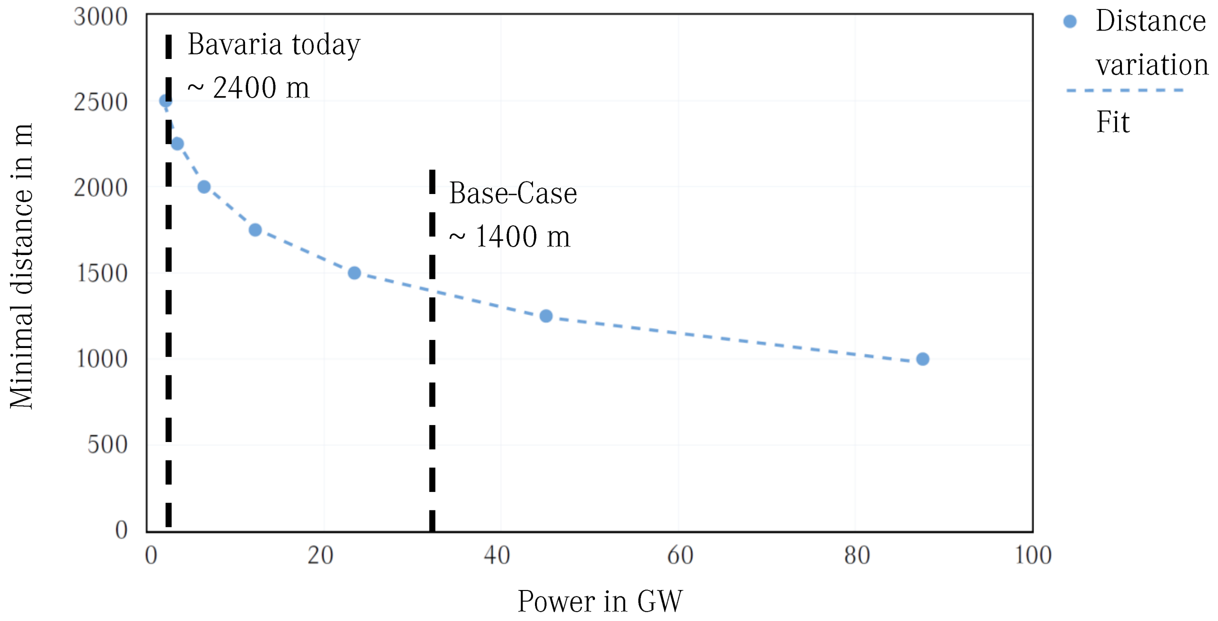
Please cite the Bayernstudie; found at https://www.mw.tum.de/es/publikationen/bayernstudie

Wind Potential – Results

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







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

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°

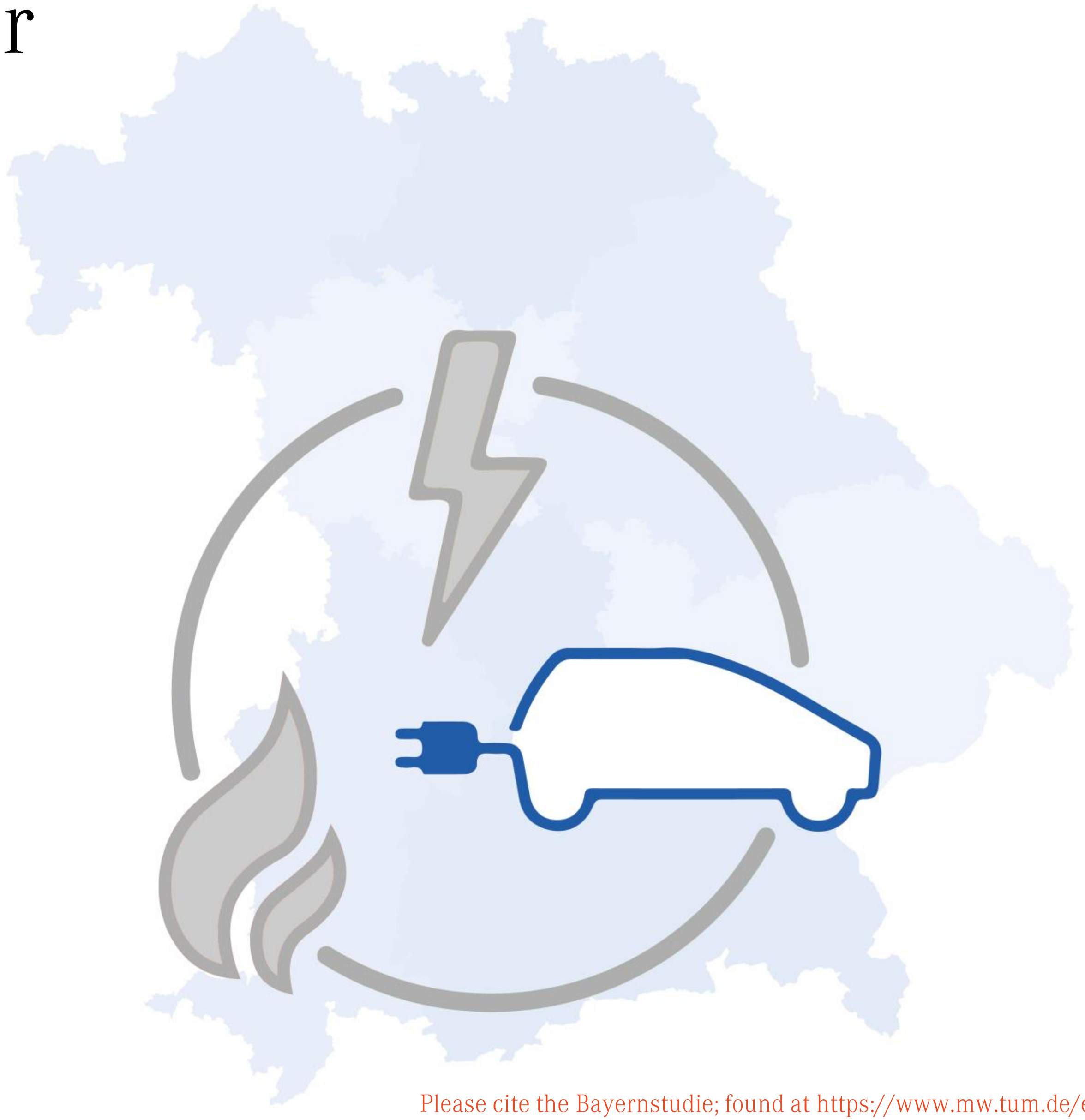
- Solar irradiation based on weather data

Calculated space demand for PV	
Open-field	133–199 km^2
Rooftop	266 km^2

Bavaria:

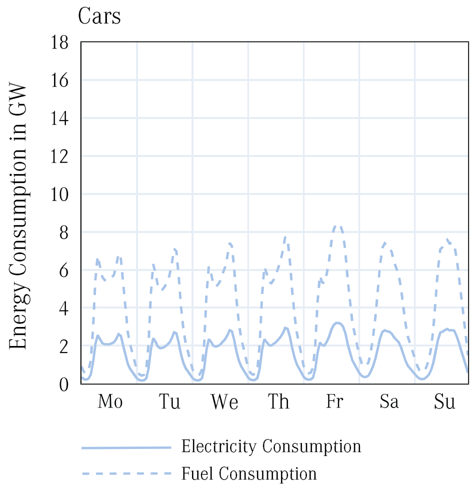
- Total area 70,000 km^2
- Ground-plan area of all buildings 977 km^2

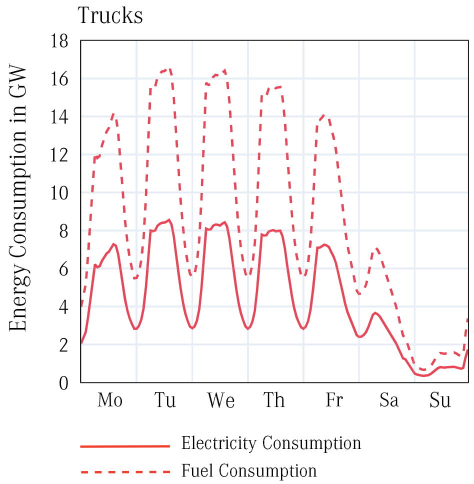
Transport Sector



Data Generation Methodology

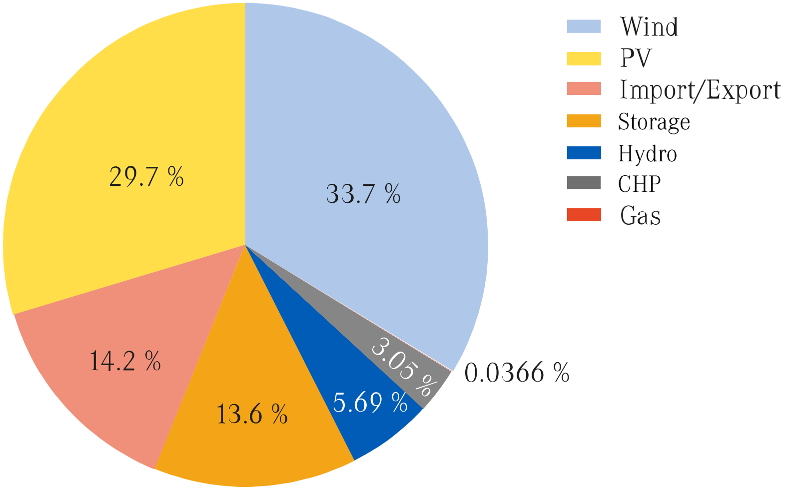
Type	Final Energy Share	Time Series Considered	Energy Demand Considered
Road	82,1 %	yes	yes
Air	15,4 %	no	no
Shipping	0,4 %	no	yes
Rail			
electrified	1,5 %	via electricity sector	via electricity sector
diesel-powered	0,5 %	no	yes
Public Transport			
City buses	1,2 %	no	yes
Subway		via electricity sector	via electricity sector
City rail		via electricity sector	via electricity sector





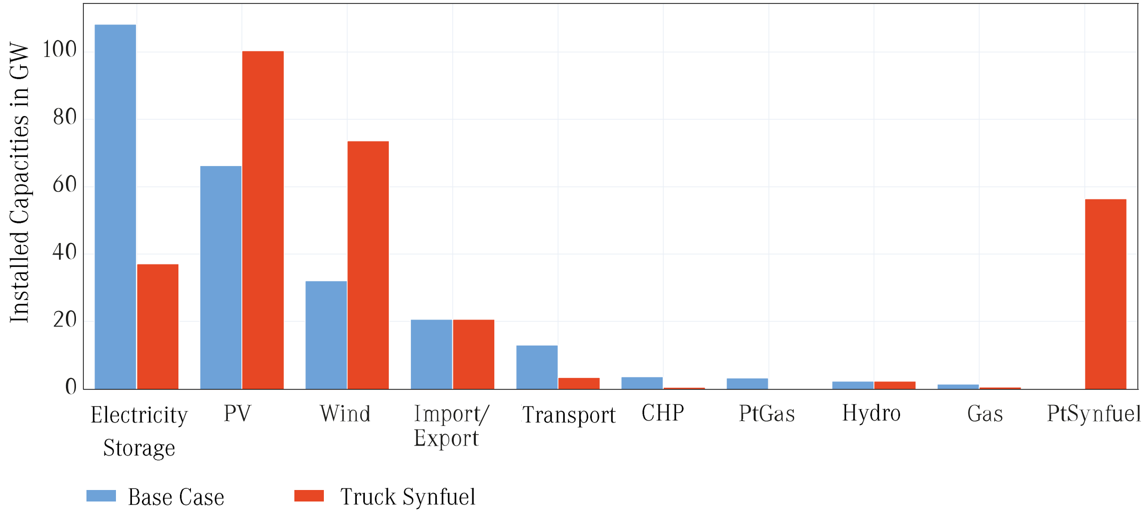
Results Transport

Mix of Electricity for e-Mobility



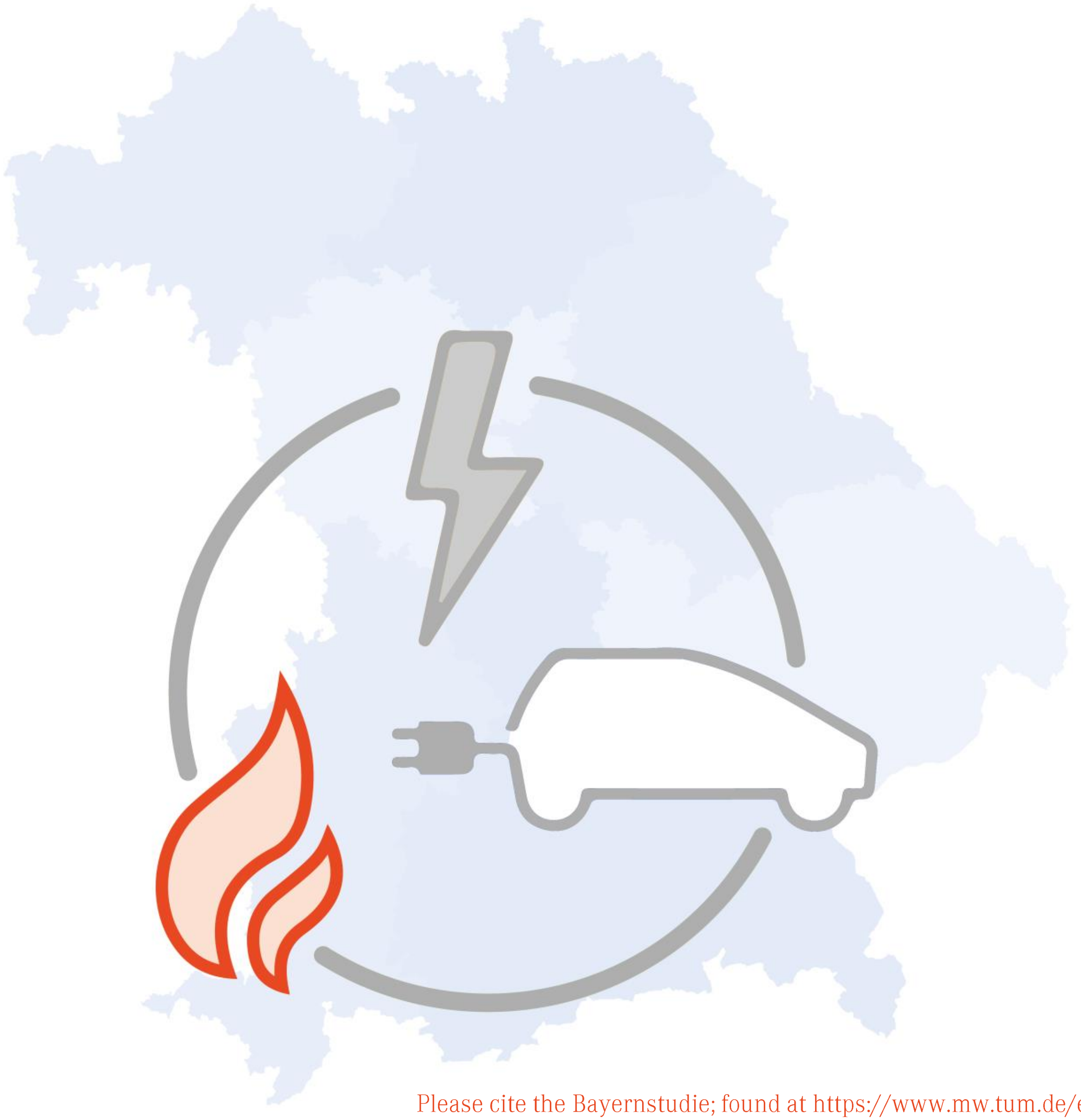
- Electricity mainly from PV and wind (63 %)
- but also from import and storage (28 %)

Scenarios for Synthetic Fuels



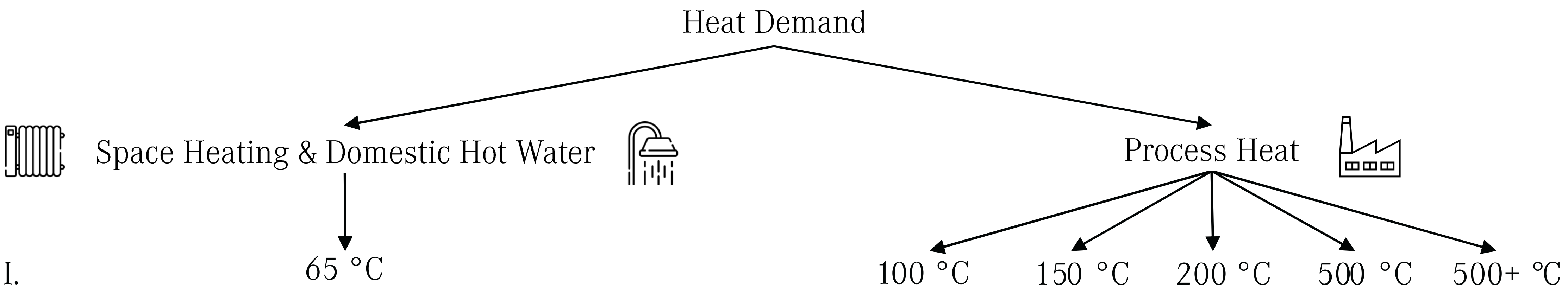
- Strongly increased demand for renewable energies
- Significantly lower battery storage requirement, as synthetic fuels can be stored well

Heat Sector

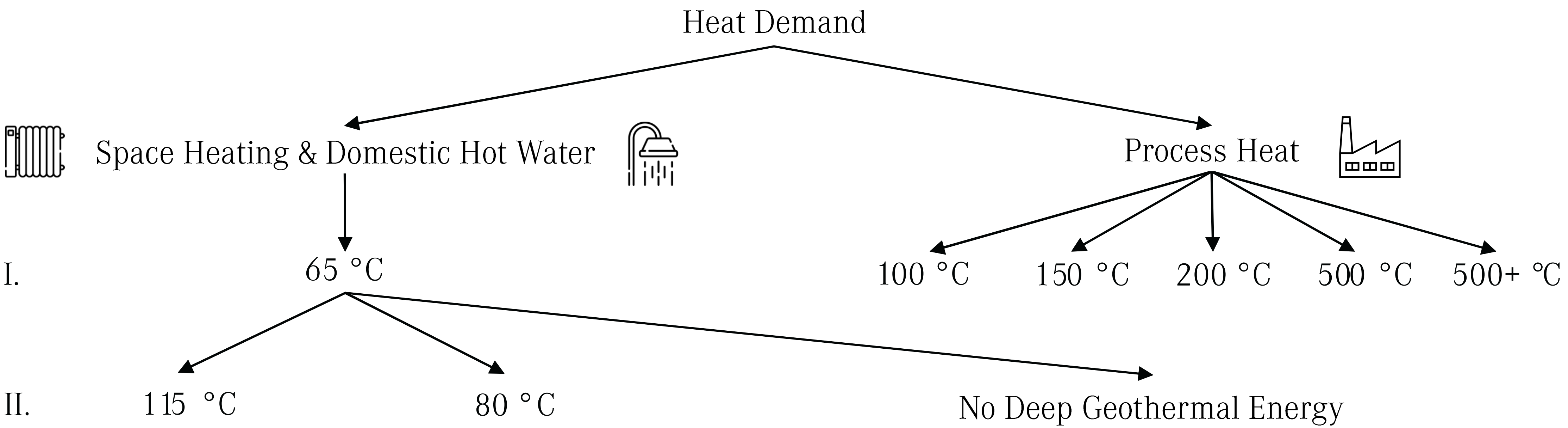


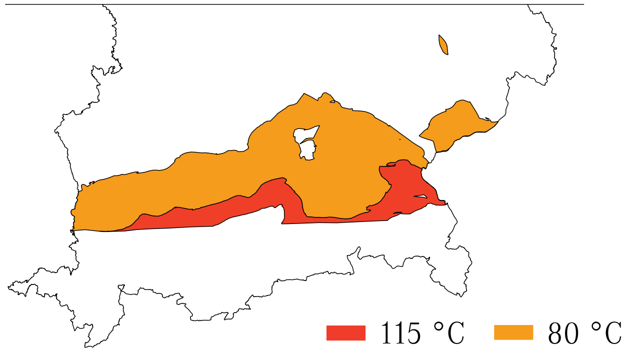
Please cite the Bayernstudie; found at https://www.mw.tum.de/es/publikationen/bayernstudie

Modelling the Heat Sector



Modelling the Heat Sector





Modelling the Heat Sector

Heat Demand

Space Heating & Domestic Hot Water

Process Heat

I. 65 °C

100 °C | 150 °C | 200 °C | 500 °C | 500+ °C

II. 115 °C | 80 °C | No Deep Geothermal Energy

III.

Interconnected Area

City

Town

Rural Area

Modelling the Heat Sector

Heat Demand

Space Heating & Domestic Hot Water

Process Heat

I. 65 °C

100 °C | 150 °C | 200 °C | 500 °C | 500+ °C

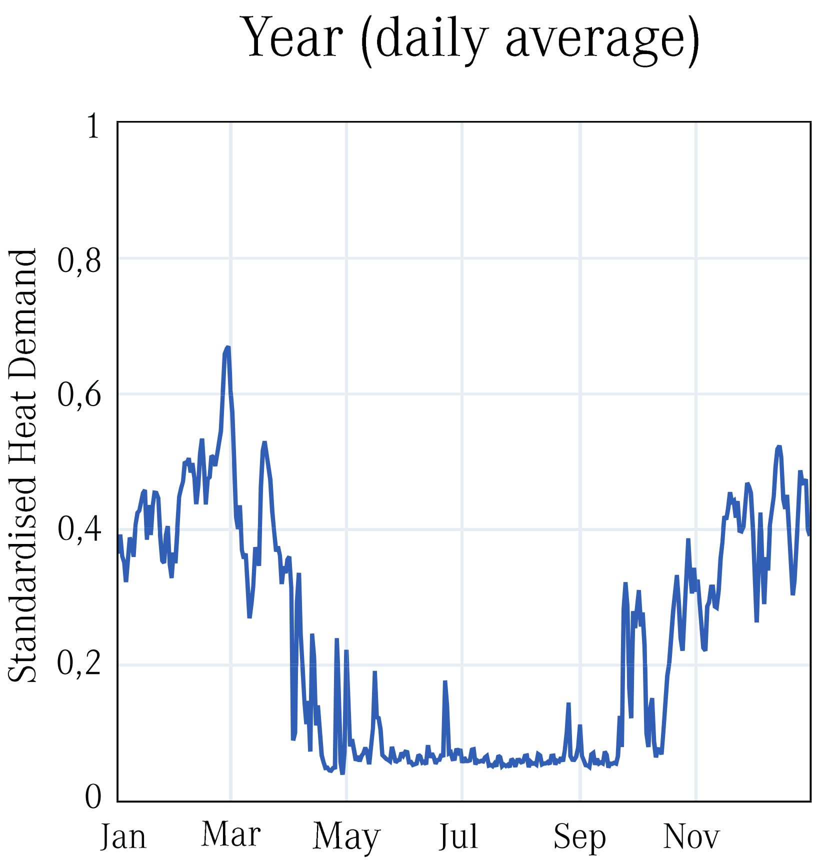
II. 115 °C | 80 °C | No Deep Geothermal Energy

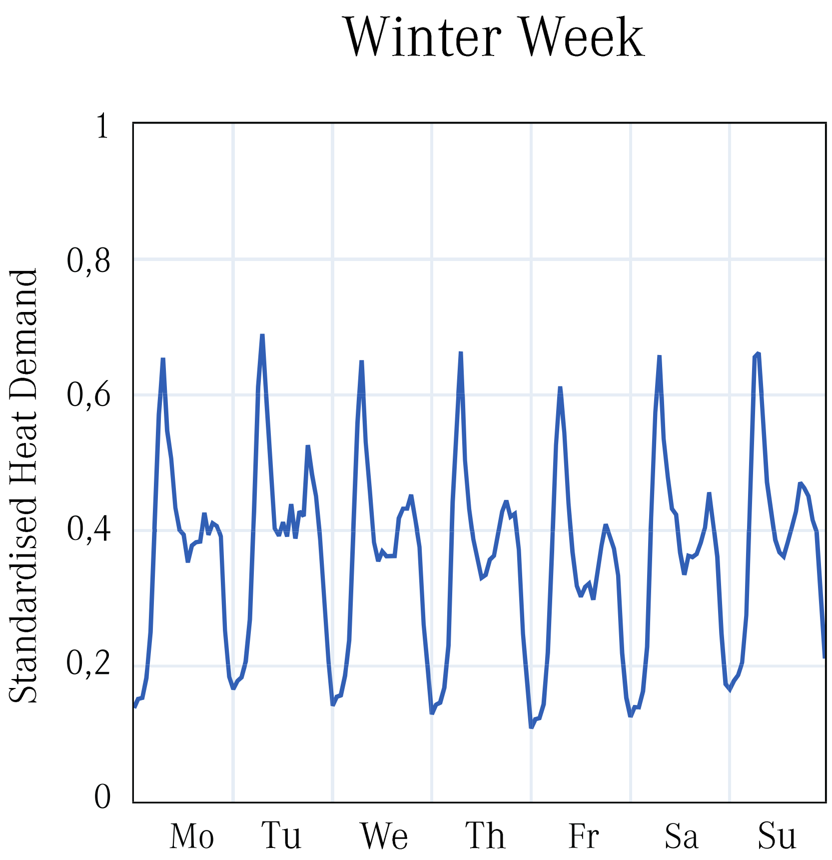
III. Interconnected Area | City | Town | Rural Area

IV. Costs of potential district heating networks

Please cite the Bayernstudie; found at https://www.mw.tum.de/es/publikationen/bayernstudie

Heat Demand Load Profile

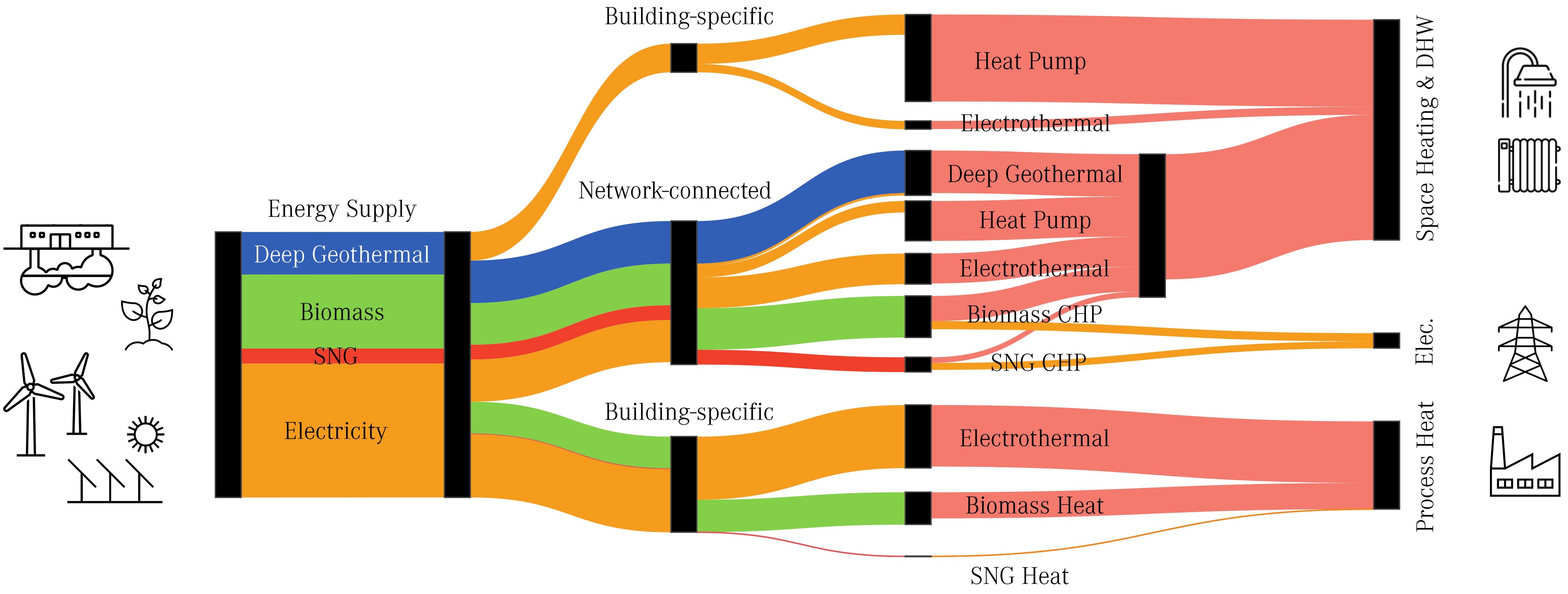




- Space heating dominant in winter
- Domestic hot water (DHW) dominant in summer
- Demand peaks in the morning and evening

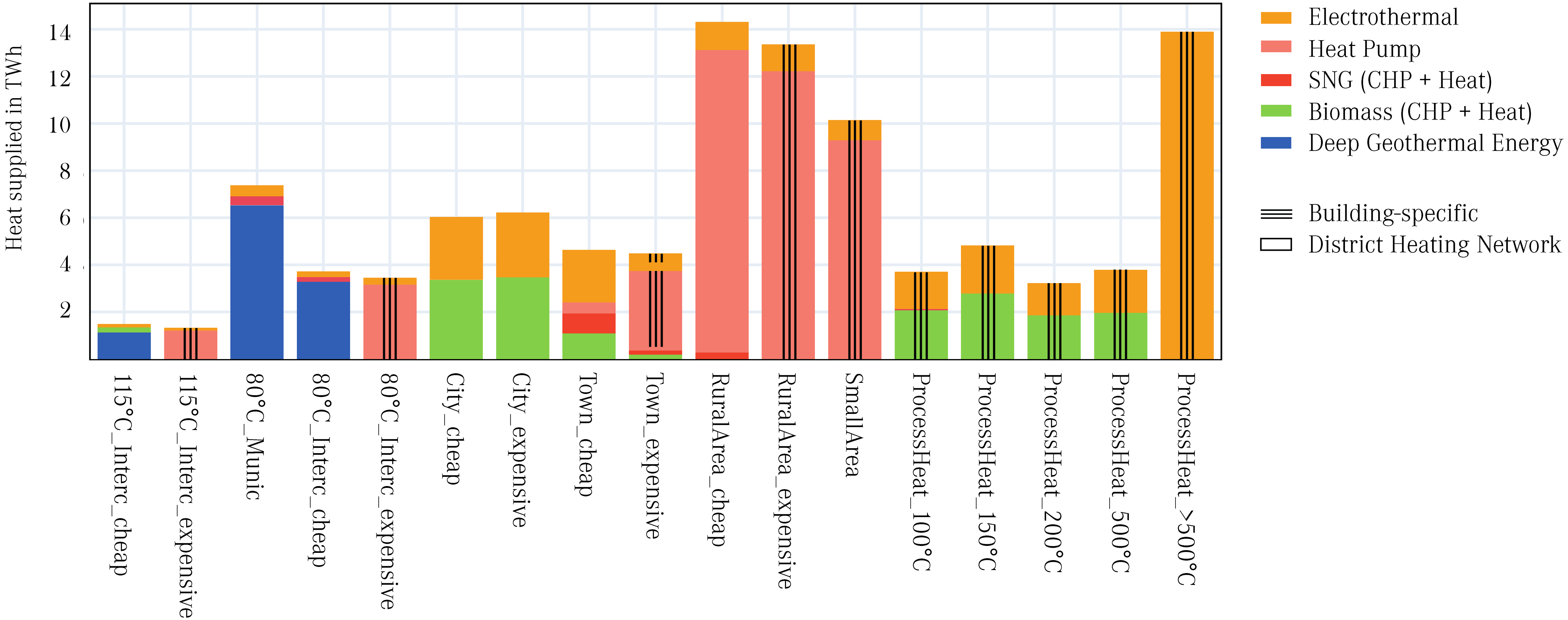
Please cite the Bayernstudie; found at https://www.mw.tum.de/es/publikationen/bayernstudie

The Bavarian Heat Supply



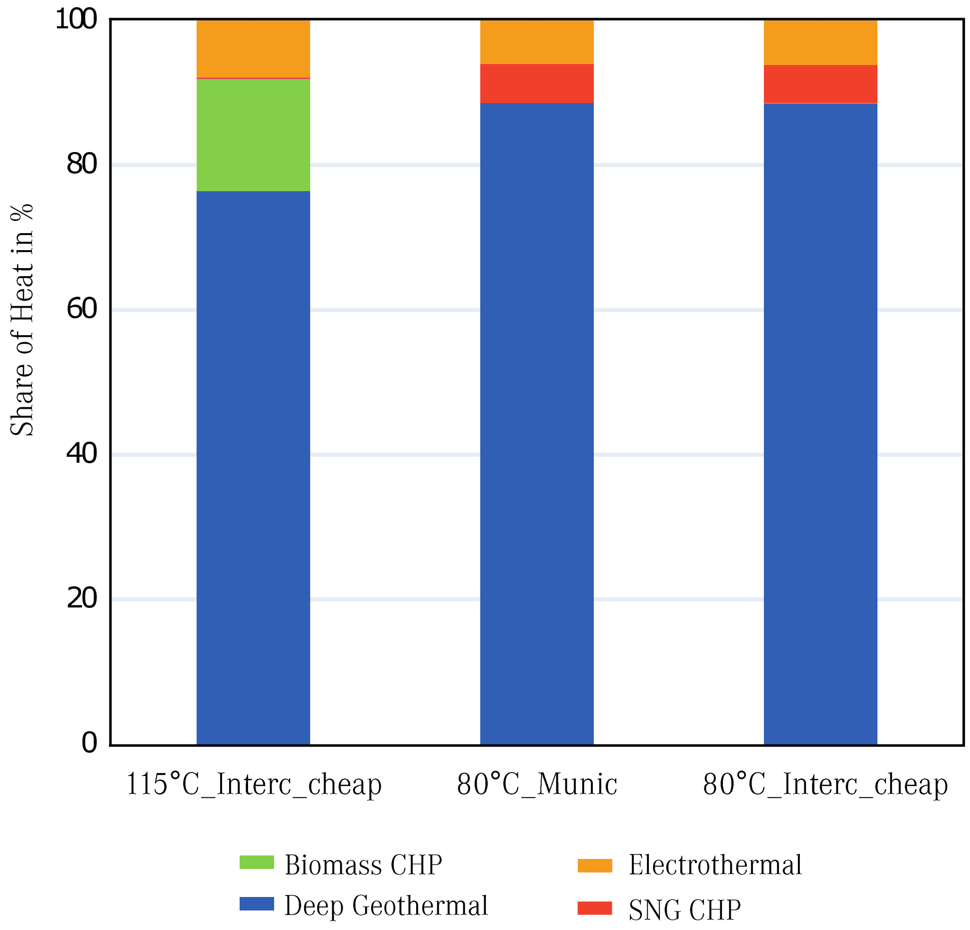
Please cite the Bayernstudie; found at https://www.mw.tum.de/es/publikationen/bayernstudie

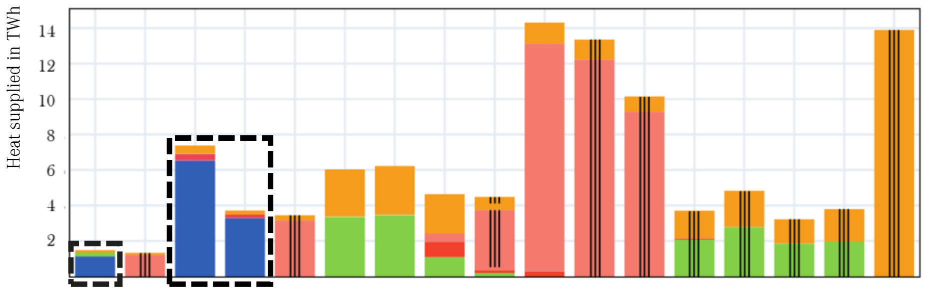
Heat Supply in the Type Areas



Please cite the Bayernstudie; found at https://www.mw.tum.de/es/publikationen/bayernstudie

Areas with the Use of Hydrothermal Deep Geothermal Energy

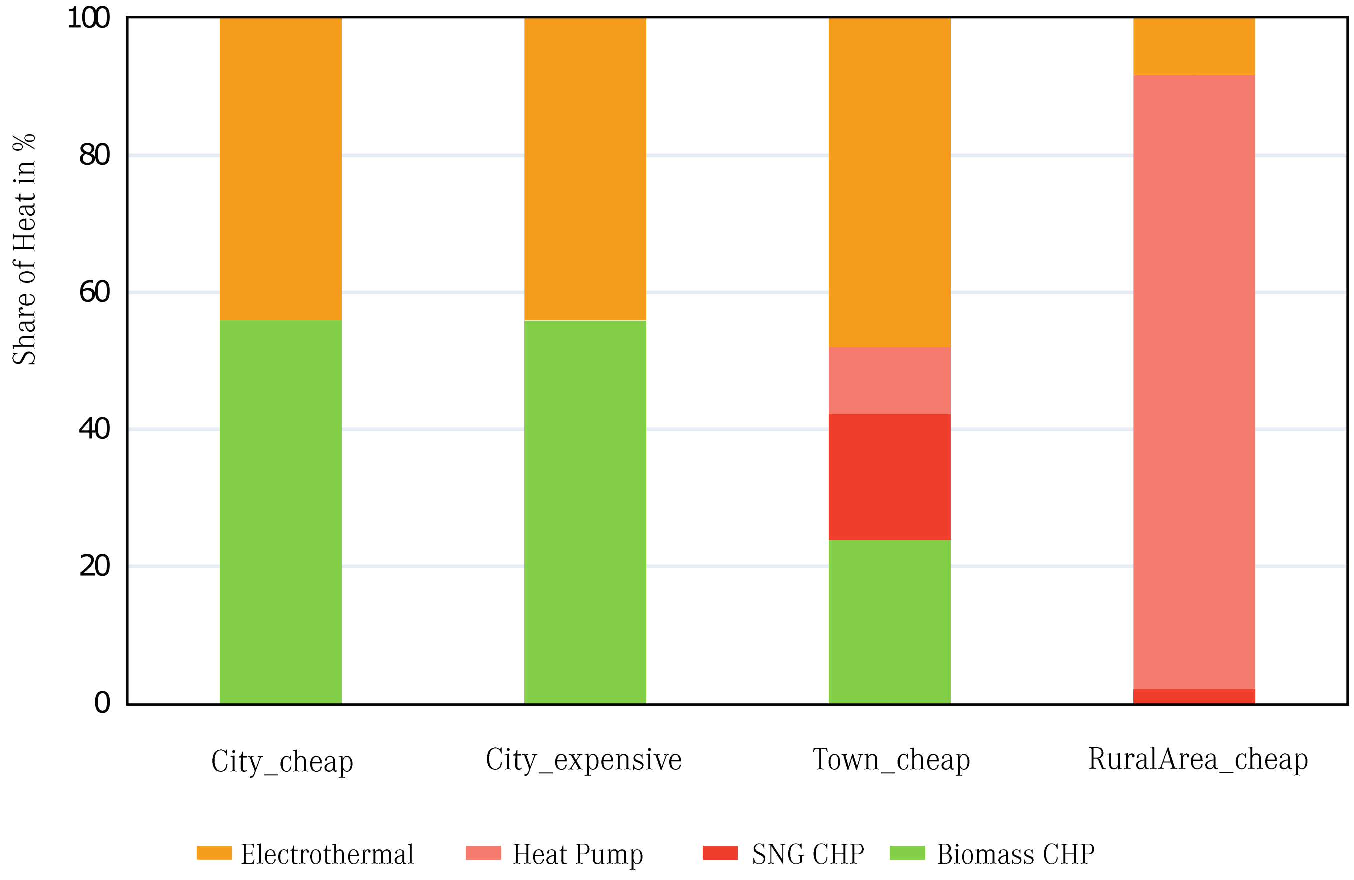


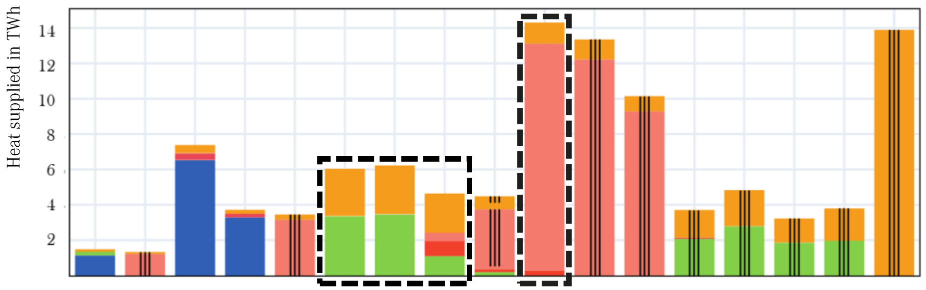


- Hydrothermal deep geothermal energy for base and medium loads
- Biomass CHP and SNG CHP for peak load supply and to compensate for the inertially controllable deep geothermal energy
- Electrothermal heat supply by means of heating rods for peak load supply

Please cite the Bayernstudie; found at https://www.mw.tum.de/es/publikationen/bayernstudie

District Heating Areas for the Provision of Electrical Flexibility



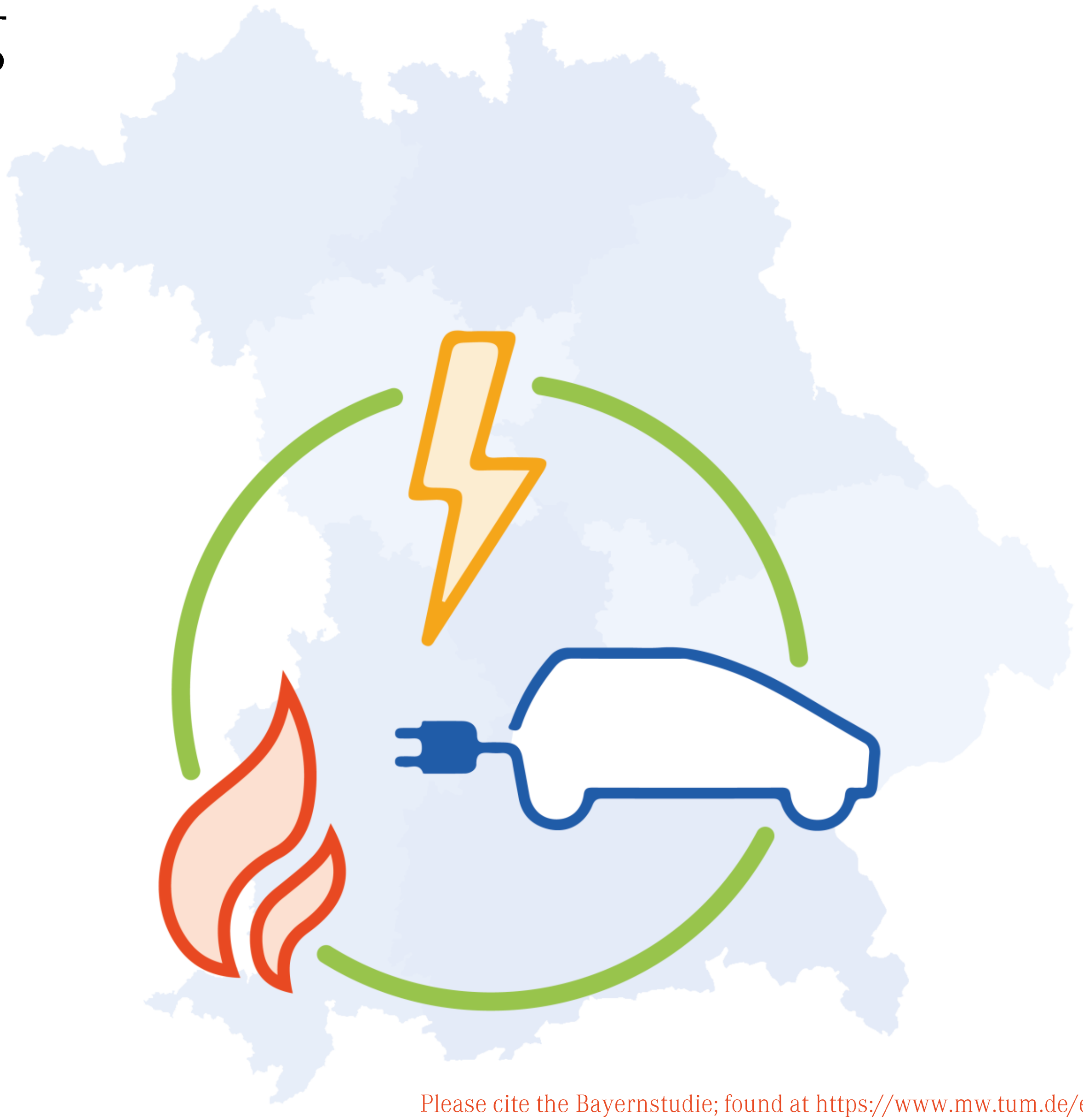


- When electricity production is high, heat is provided electrothermally
- Biomass CHP and SNG CHP provide more flexibility for the power sector
- Heat storage enables increased flexibility in the heat load of a type area

→ indirect effect on the power sector

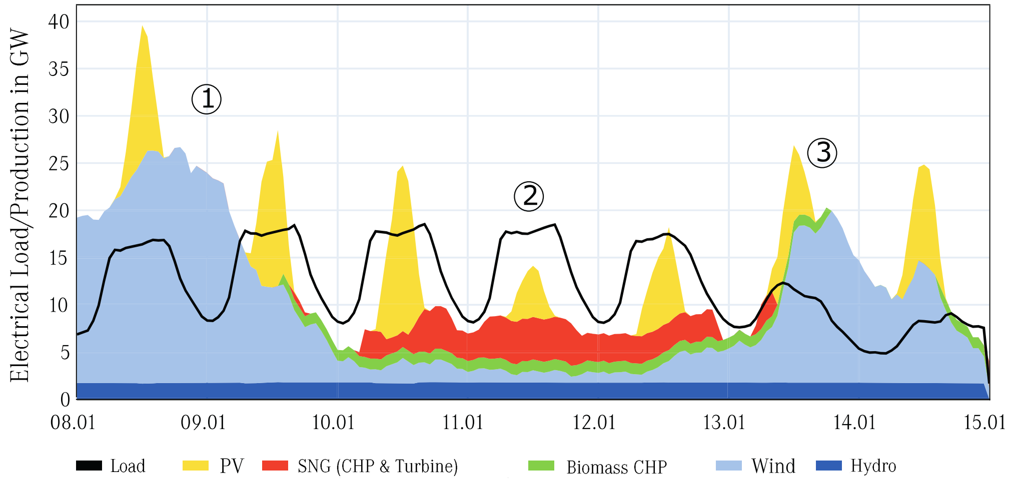
Please cite the Bayernstudie; found at https://www.mw.tum.de/es/publikationen/bayernstudie

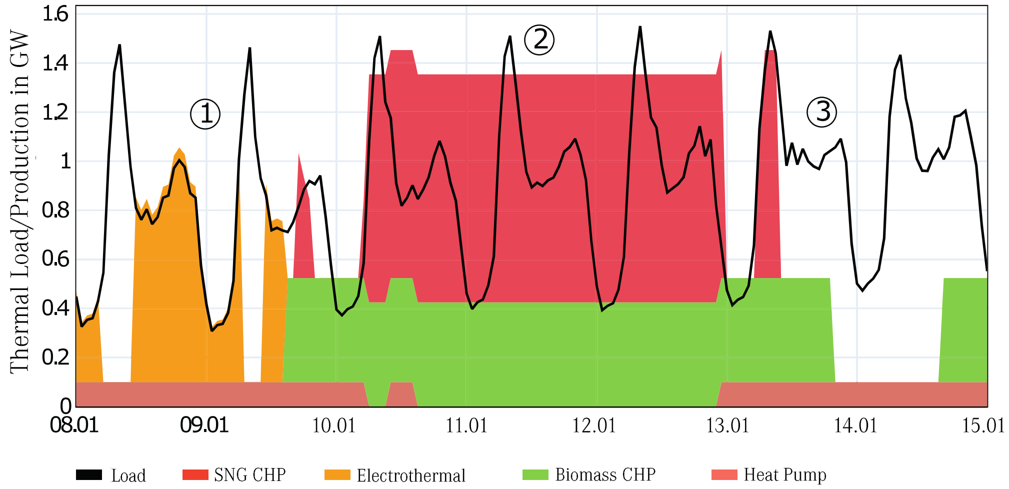
Sector Coupling



Please cite the Bayernstudie; found at https://www.mw.tum.de/es/publikationen/bayernstudie

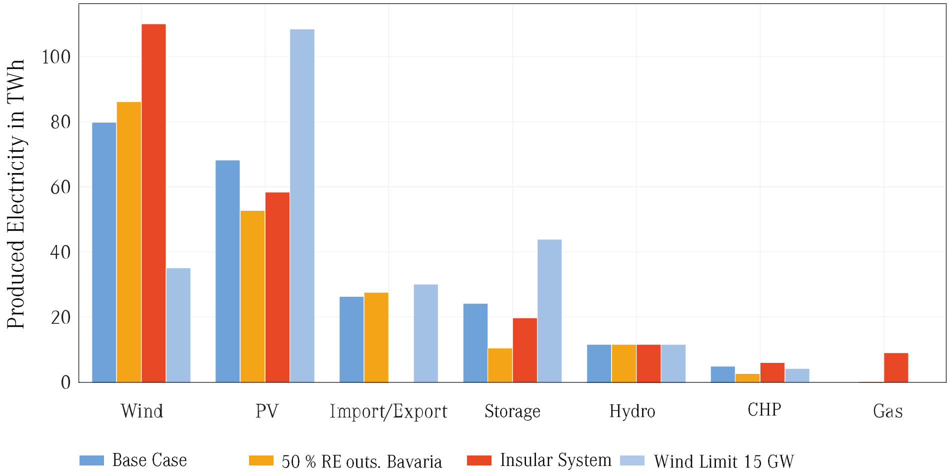
Flexibility during Low Wind and PV Production

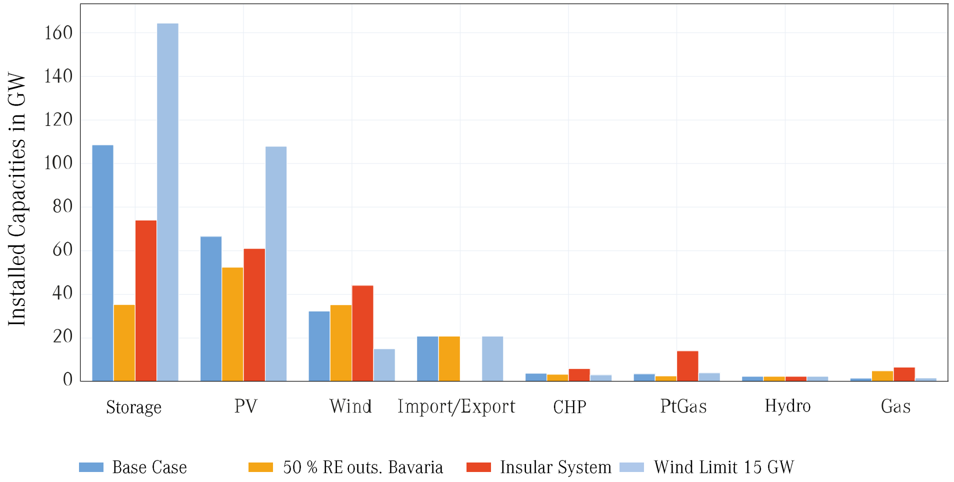




1. Windy Winter Day
   - Wind power greater than electricity demand
   - Charging of electricity storage and electrothermal heat supply
2. Low Wind and PV Production
   - Low wind & PV power output is compensated by storage and CHP electricity
   - Heat supply exceeds demand, heat is stored in district 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

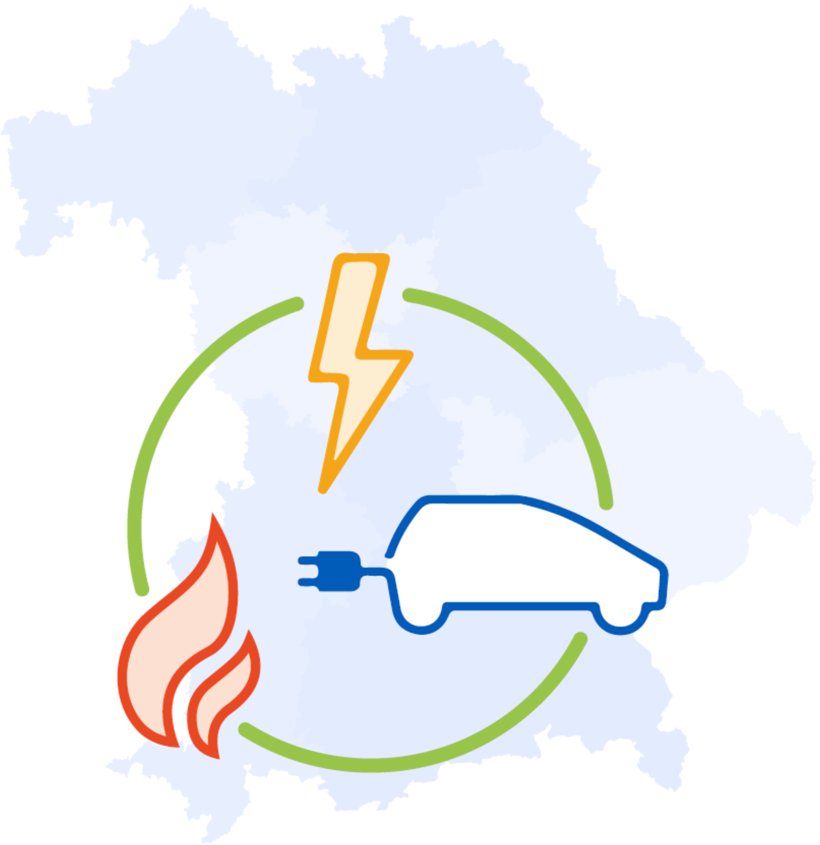
2) Bavaria as an insular system
   - Neighbours provide less flexibility
   - Bavaria needs more flexible generators and storage

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

Please cite the Bayernstudie; found at https://www.mw.tum.de/es/publikationen/bayernstudie

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

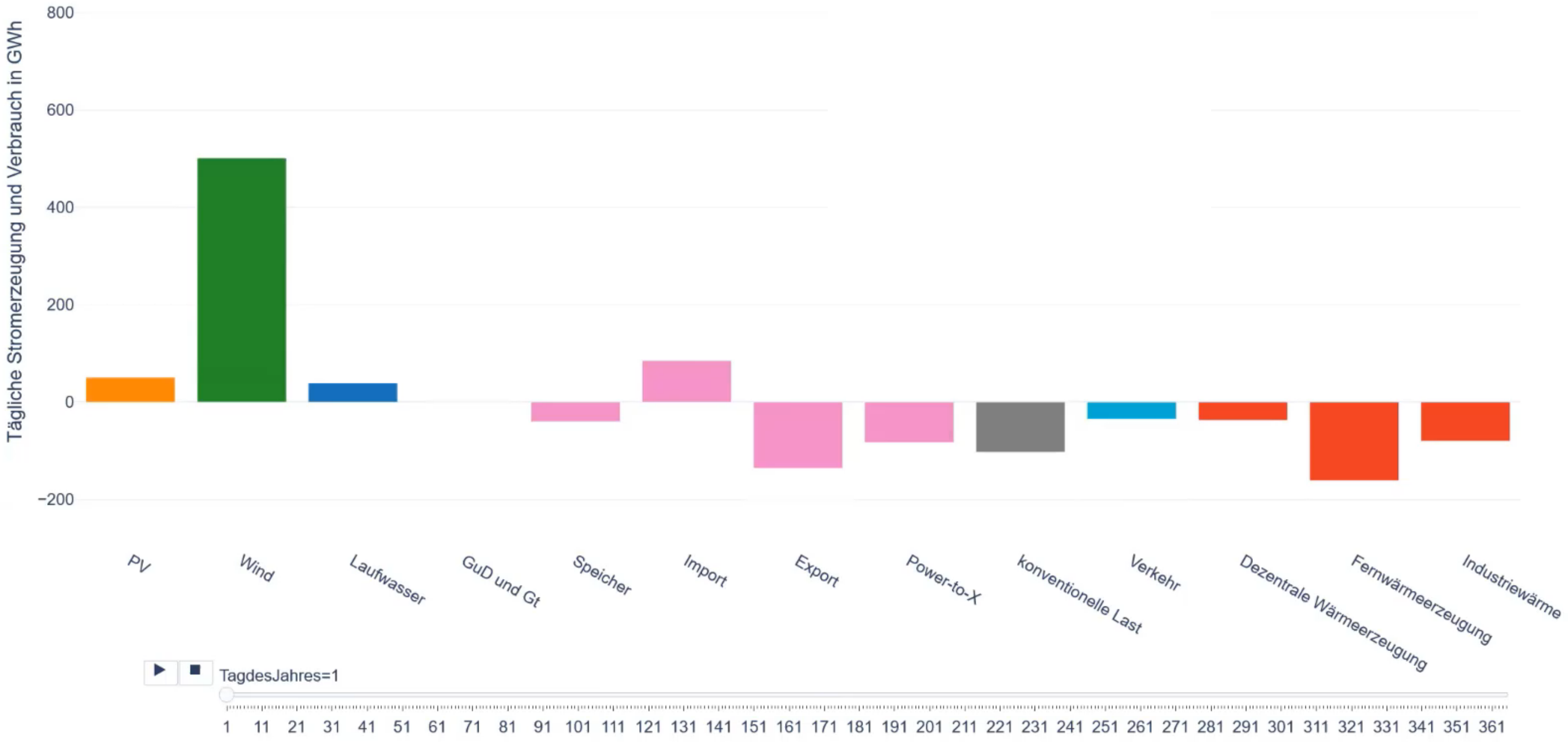
Chair for Energy Systems

Sebastian Miehling*
Benedikt Schweiger*
Wolf Wedel
Andreas Hanel
Hartmut Spliethoff

* shared first authorship

ZAE Bavaria

Jakob Schweiger
Rene Schwermer
Maximilian Blume



Please cite the Bayernstudie; found at https://www.mw.tum.de/es/publikationen/bayernstudie