ENERDAY 2018 - 12th International Conference on Energy Economics and Technology

MODELING THE LOW-CARBON TRANSFORMATION IN EUROPE

Developing Paths for the European Energy System until 2050

27.04.2018

Thorsten Burandt, **Konstantin Löffler**, Karlo Hainsch

Technische Universität Berlin, Workgroup for Economic and Infrastructure Policy (WIP)

DIW Berlin, Department Energy Transport and Environment

Agenda

From OSeMOSYS to GENeSYS-MOD

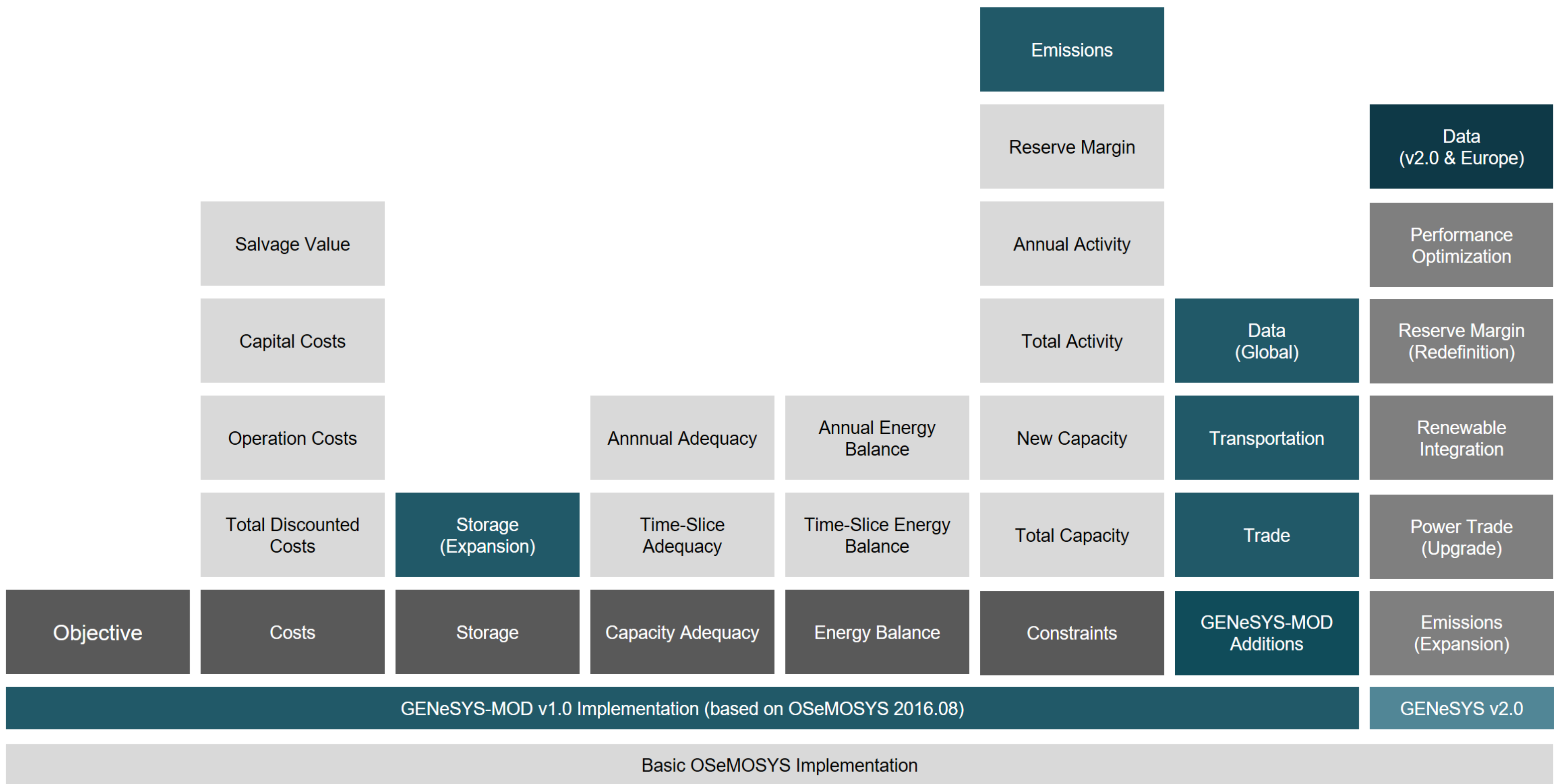
OSeMOSYS (Open Source Energy Modeling System):

- **Cost-optimizing Linear Program** (LP)
- **Open-source** energy systems model
- Written in GMPL using a free GNU solver
- Mainly developed by KTH in Stockholm
- Available under: http://users.osemosys.org/

GENeSYS-MOD (Global Energy System Model)…

- …offers a fully translated **GAMS version of OSeMOSYS**.
- …enhances the OSeMOSYS framework with multiple **additional features**.
- …is being made **publicly available** to the community with both code and model data.
- For further information on GENeSYS-Mod see: Löffler et al. (2017): https://www.diw.de/documents/publikationen/73/diw_01.c.563040.de/dp1678.pdf
- Also published in the journal *Energies 10(10)*

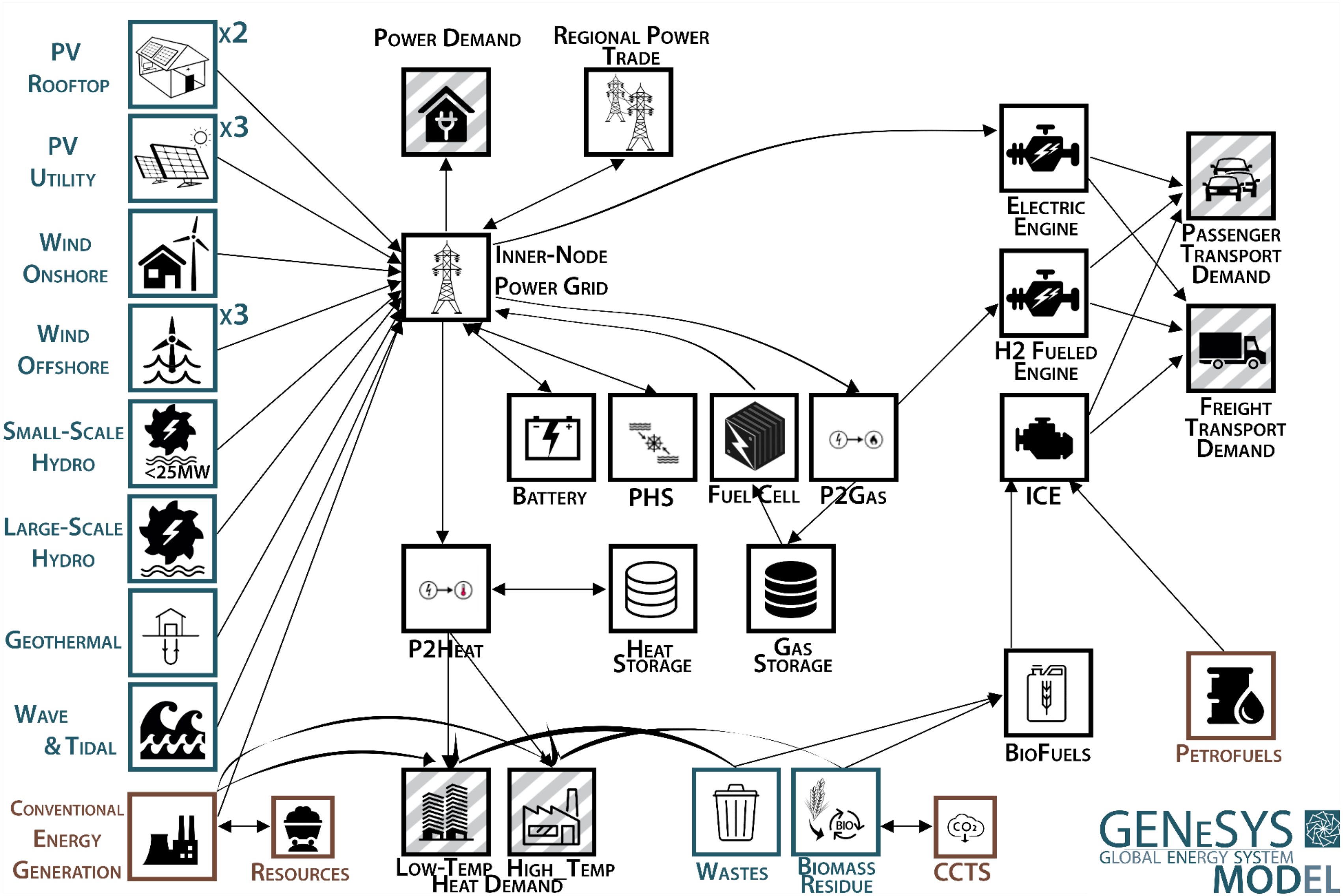
GENeSYS-MOD v2.0: Blocks of Functionality



Agenda

1) Introduction
2) Model Setup and Key Assumptions
3) Results

Model Design & Technologies



Model Setup: Key Assumptions and Disaggregation

Key Data and Constraints

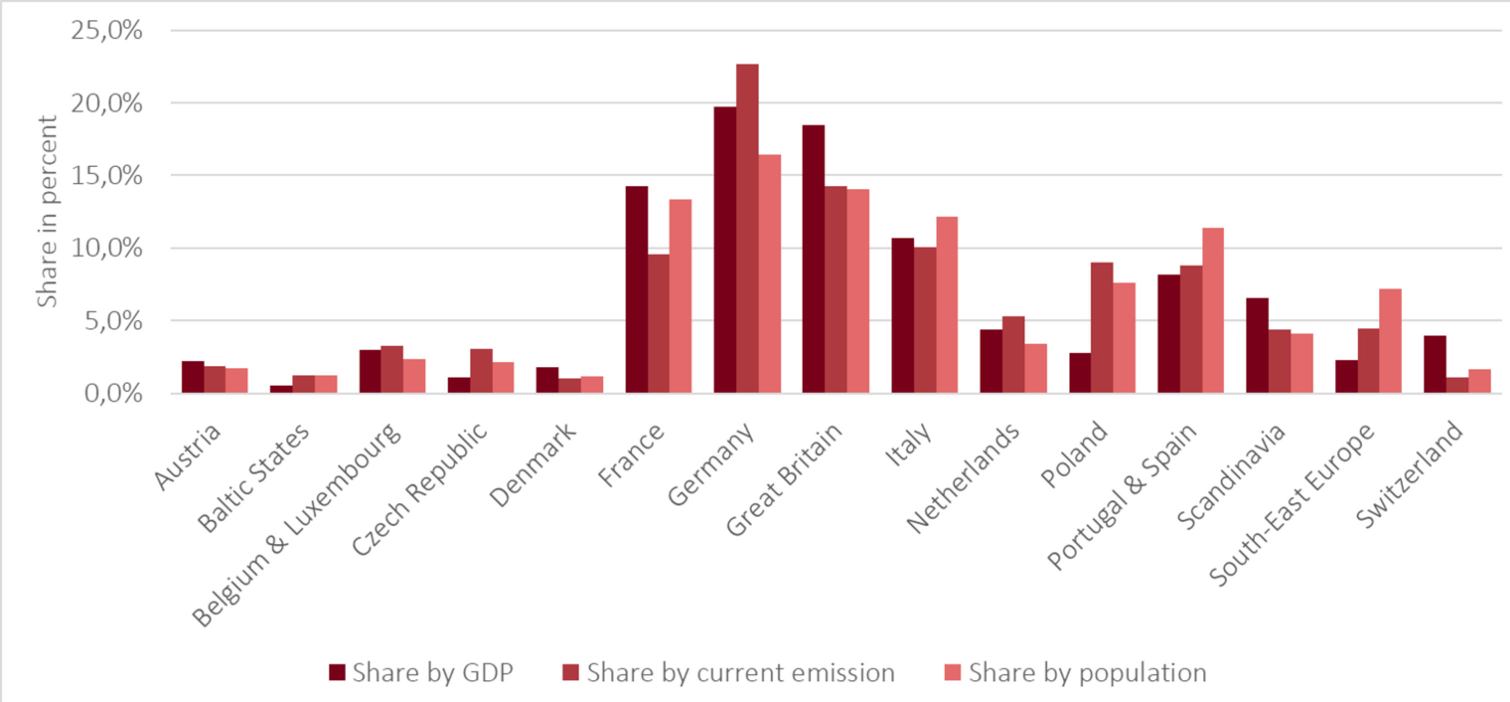
- **15 regions** are considered.
- The years 2020 - 2050 are modeled in **5-year steps**, with 2015 as a baseline.
- The model considers **16 time slices** in total: four seasons, each with four daily time slices.
- A carbon price based on the World Energy Outlook 2016 is included.
- Electricity demand based on the EU Reference Scenario (PRIMES, EUREF).
- Heat and transport demands (2015) based on recent literature and data.
- Demand development and fossil fuel prices are fixed and based on the IEA 450ppm scenario datasets (World Energy Outlook 2016).
- Residual capacities for supply technologies are taken from Farfan and Breyer (2017).
- CO_2 storage potential taken from Oei et al. (2014).

Analyzing multiple pathways…

- **Three** emission pathways (1.5°, 2°, Business as usual (BAU))
- With **four** emission distribution scenarios each
- -> Leads to a total of 12 scenarios being considered

Model Setup: Spatial Resolution

Scenario Definition: Distribution of the Carbon Budget



Analyzing multiple pathways…	…and distributions
• **1.5°:** Limit of 24 $GtCO_2$ • **2°:** Limit of 49 $GtCO_2$ • **Business as usual (BAU)**: 137 $GtCO_2$	• **Free Distribution** • **Share by GDP** • **Share by current emissions** • **Share by population**

Agenda

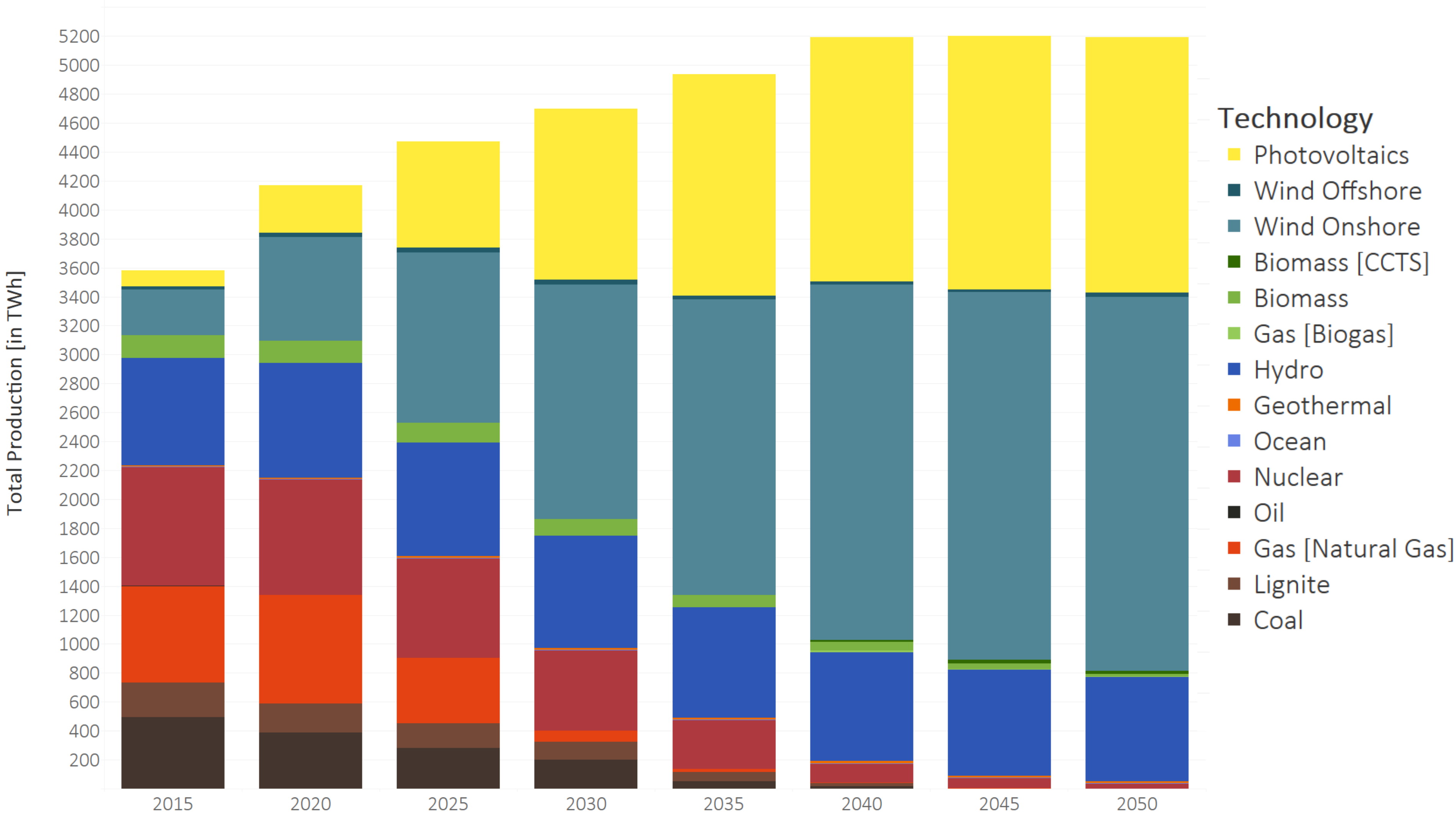
1) Introduction

2) Model Setup and Key Assumptions

3) Results

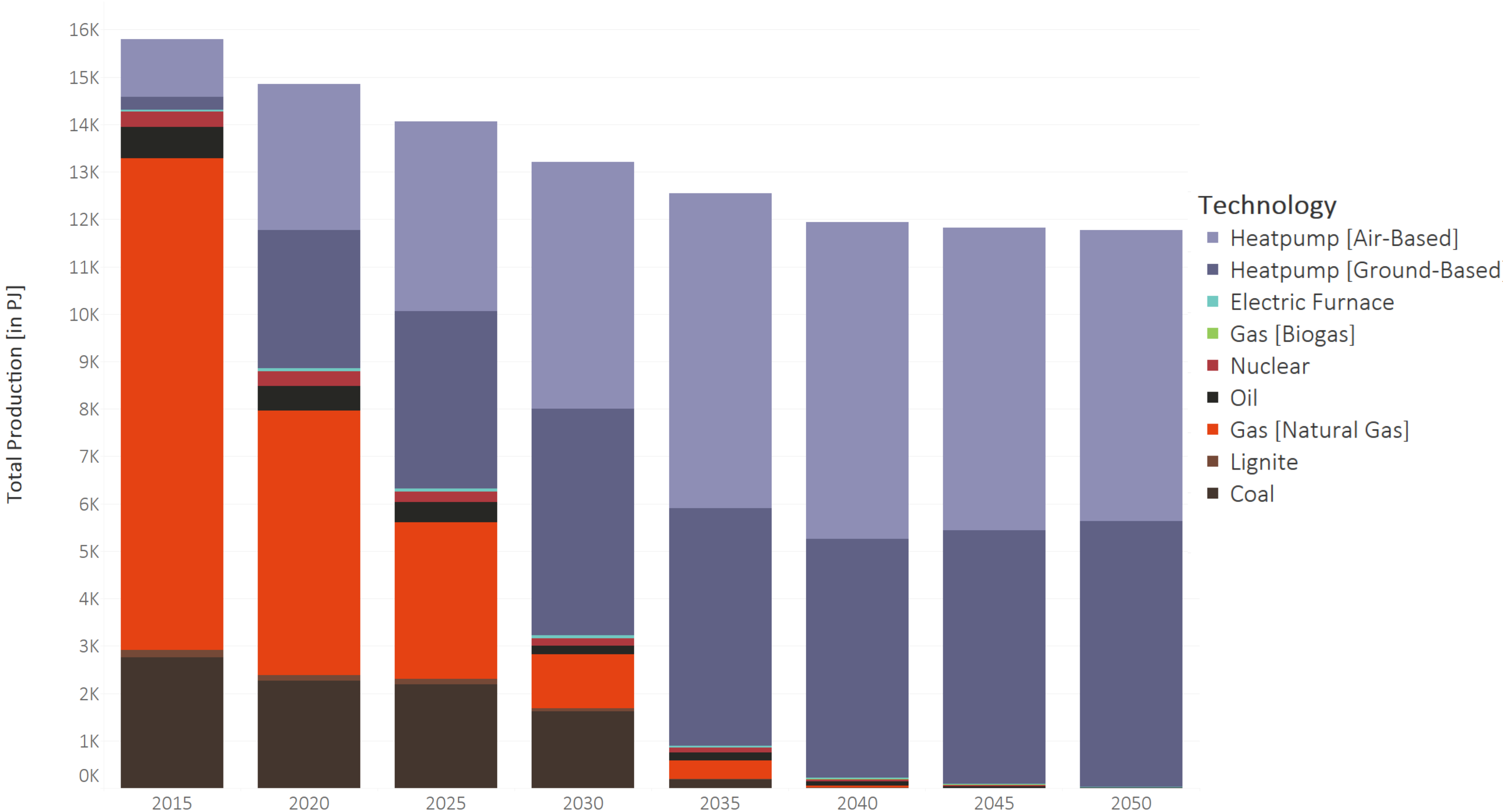
Base Scenario (2°, Free Distribution)

Development of Power Generation



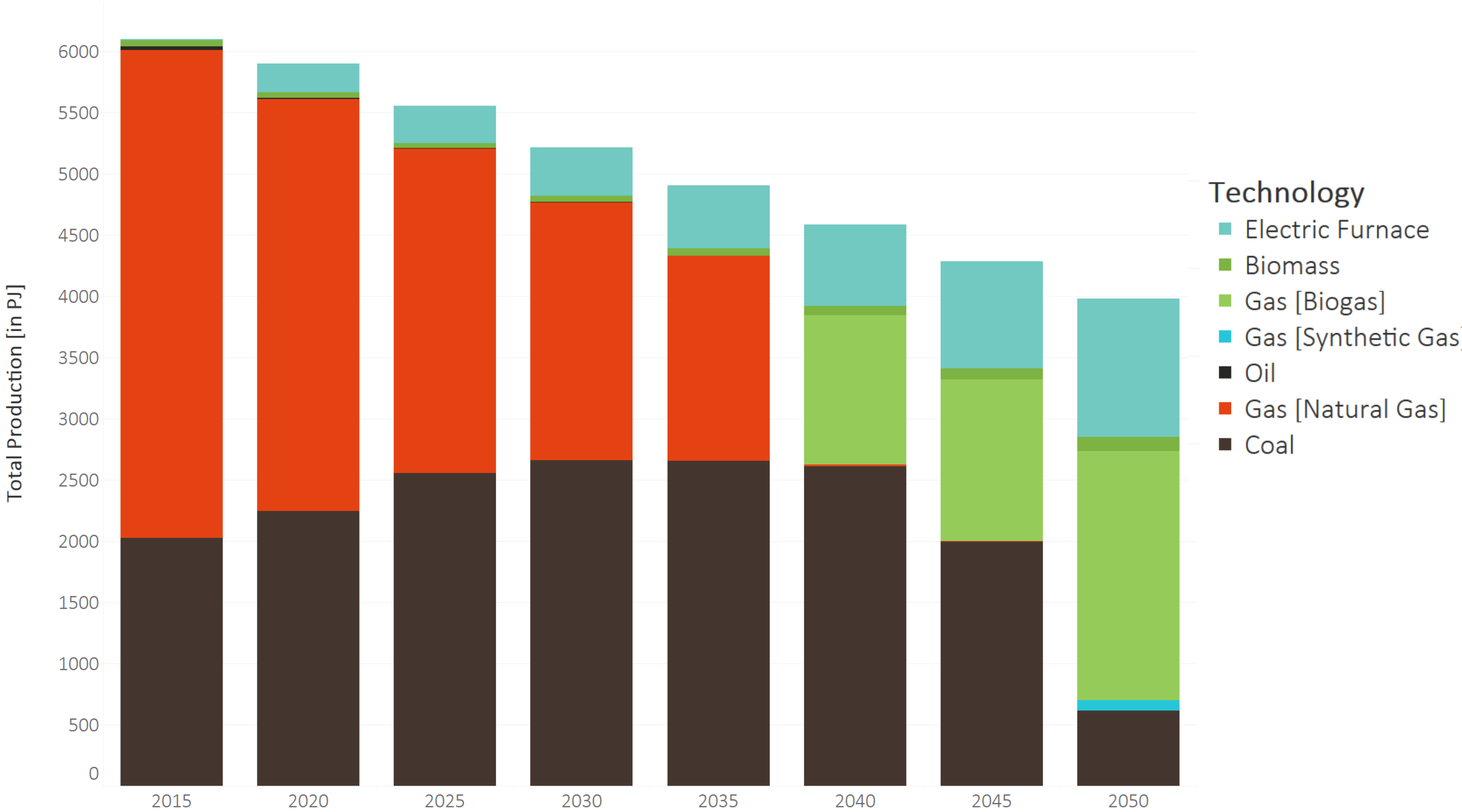
Source: Own Illustration

Development of Low-Temperature Heat Generation



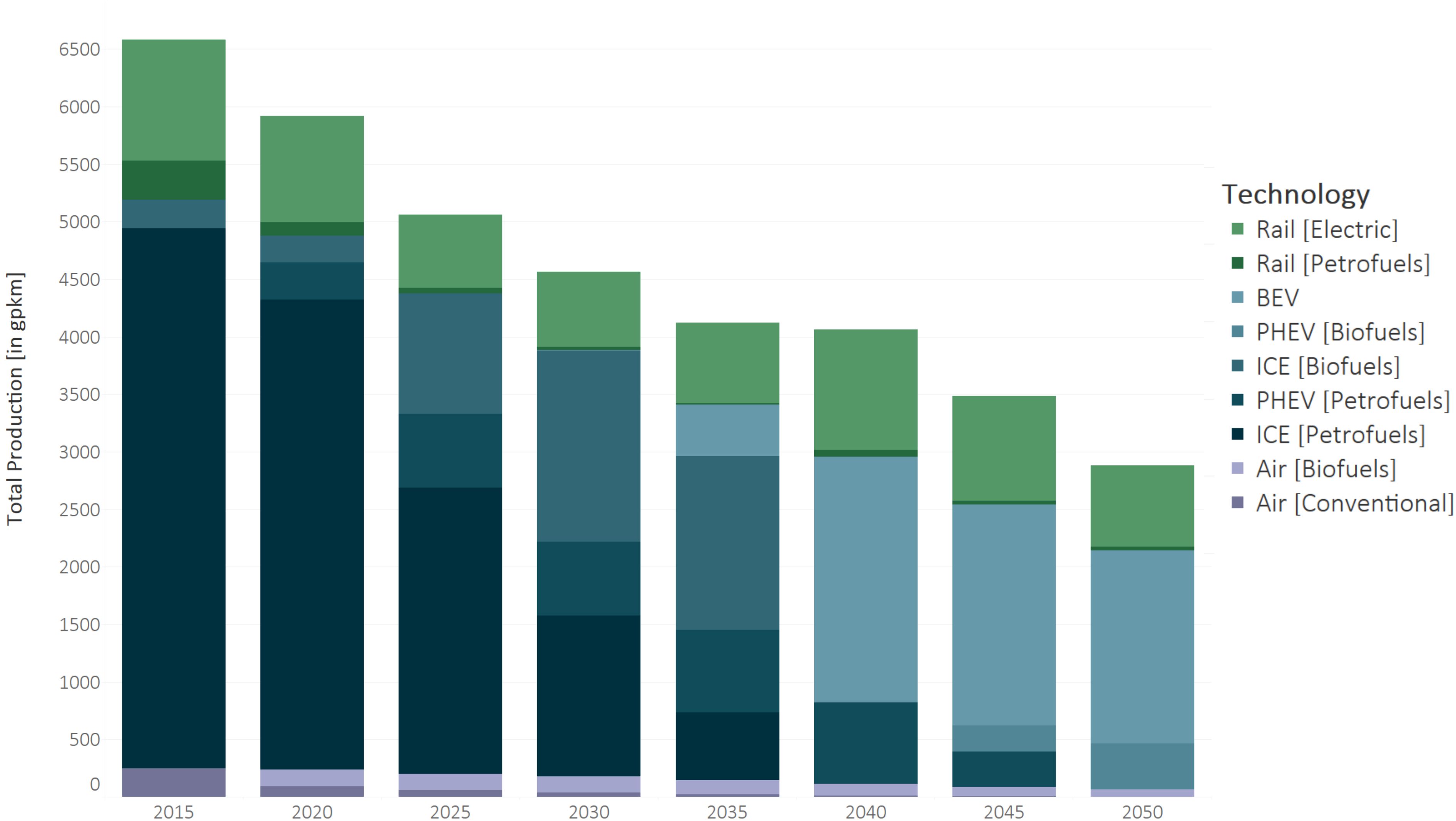
Source: Own Illustration

Development of High-Temperature Heat Generation



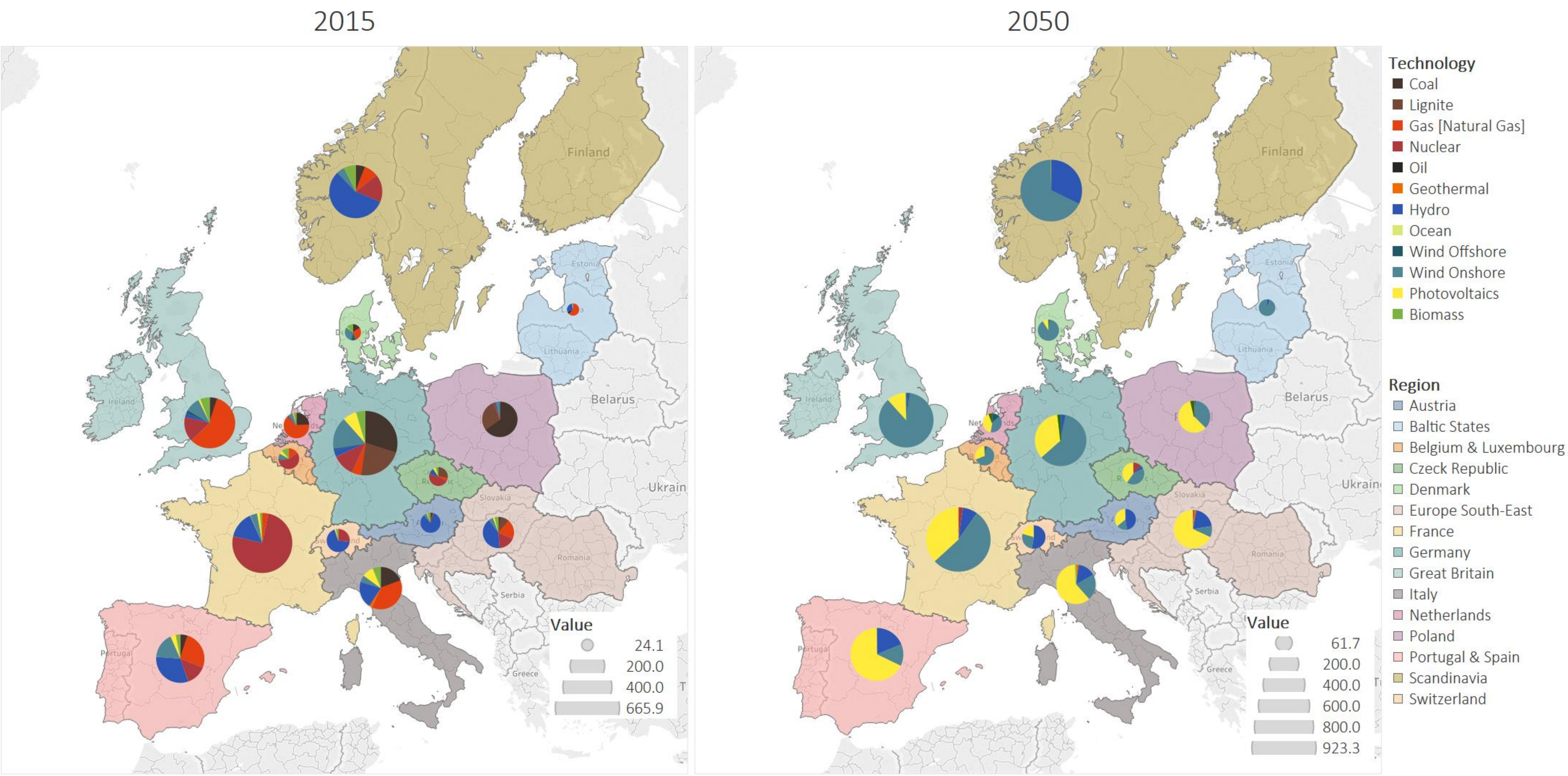
Source: Own Illustration

Development of Passenger Transportation



Source: Own Illustration

Regional Power Generation Profiles 2015 and 2050



Scenario Overview: Cost Comparison

Scenario	Free Distribution	Share by Current Emissions	Share by GDP	Share by Population
1.5° pathway	133,4%	143,6%	Infeasible	152,7%
2° pathway	0,0%	0,3%	1,4%	0,8%
BAU pathway	-1,2%	-1,2%	-1,1%	-1,2%

Conclusion of our Model Results

- Results show that even **ambitious climate targets can be met**, both technically and economically.
- This is due to **renewables becoming more and more competitive**, as well as cheap storages being more available.
- Reaching a climate target of 2° C only nets a cost increase of about 1%, while reducing total emissions by almost 20% compared to the BAU case.
- The distribution of the CO_2 budget **by current emissions** displayed the lowest overall costs relative to the endogenous model optimization.
- The energy transformation in **the power sector is the easiest and cheapest**, and it is thus the first to complete the shift to 100% renewables.
- A **strong sector coupling** between both the heat and transportation sectors with the power sector can be observed.
- The primary energy carriers utilized in 2050 in our model results are: **Wind, solar, hydropower, and biomass** with no further capacity additions of nuclear power plants.
- Flexibility and variability of RES are covered with batteries and long-term storages (e.g. pumped-hydro or compressed air storages).

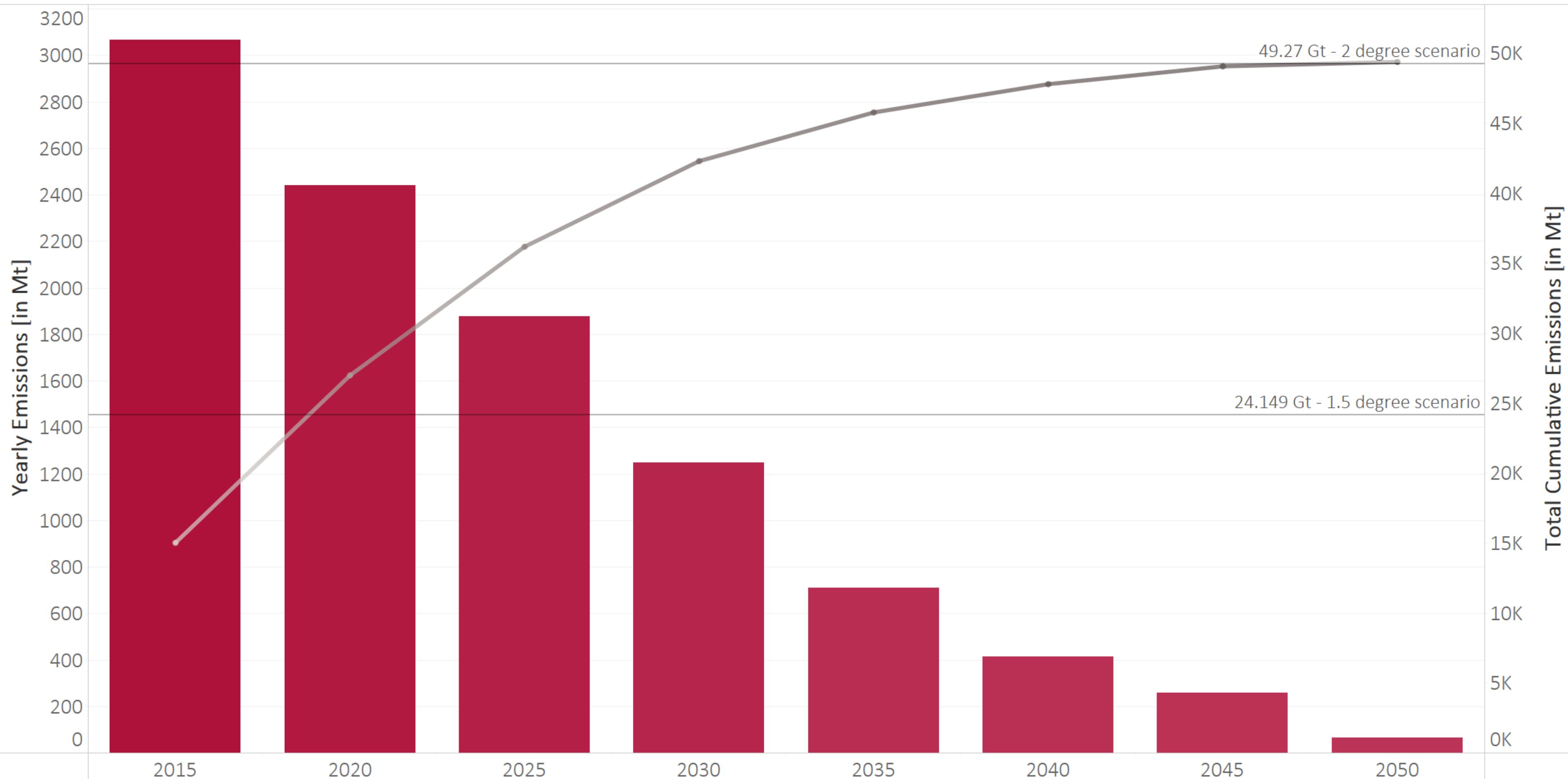
Thank you for your Attention!

© pixabay

Konstantin Löffler
kl@wip.tu-berlin.de

Back-Up Slides

Emissions



3200
3000
2800
2600
2400
2200
2000
1800
1600
1400
1200
1000
800
600
400
200
0
Yearly Emissions [in Mt]
49.27 Gt - 2 degree scenario
24.149 Gt - 1.5 degree scenario
50K
45K
40K
35K
30K
25K
20K
15K
10K
5K
0K
Total Cumulative Emissions [in Mt]
2015
2020
2025
2030
2035
2040
2045
2050

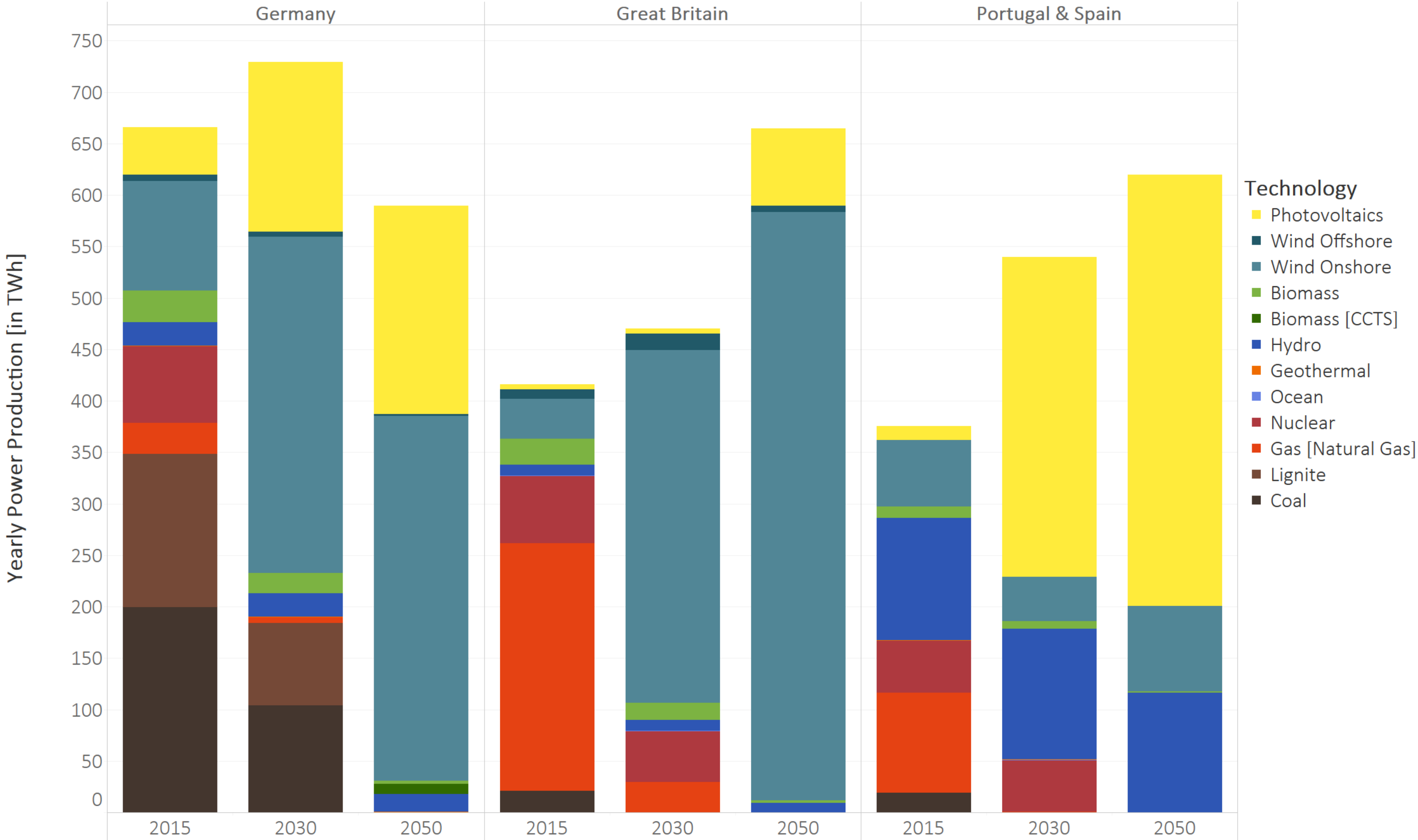
Further Research Plans and Outlook

Further Research and Outlook

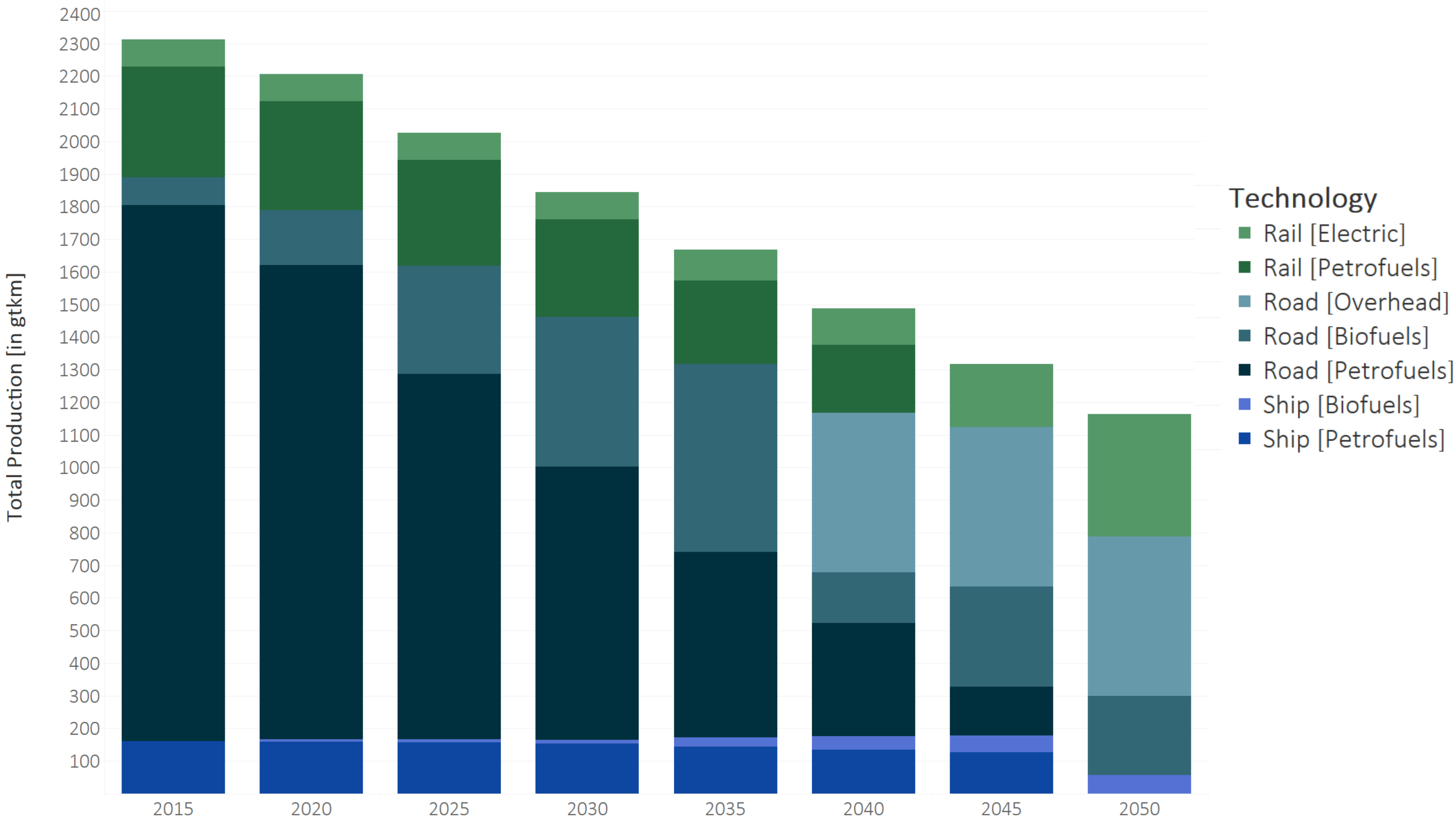
- Analysis of the European energy system with further scenarios (e.g. SetNAV, entso-e, etc).
- Better inclusion of local public transport in the transportation sector.
- Refinement of spatial resolution (including the Balkan countries, divide some regions).
- Implementing Direct Air Capture and other possible CO_2 mitigation technologies.
- Incorporating a better representation of the industrial sector with special focus on steel, aluminium and cement production.
- Investigation of the stranded asset problem in Europe.

Solar Sensitivities

Choosen Country Profiles of Power Generation Capacities

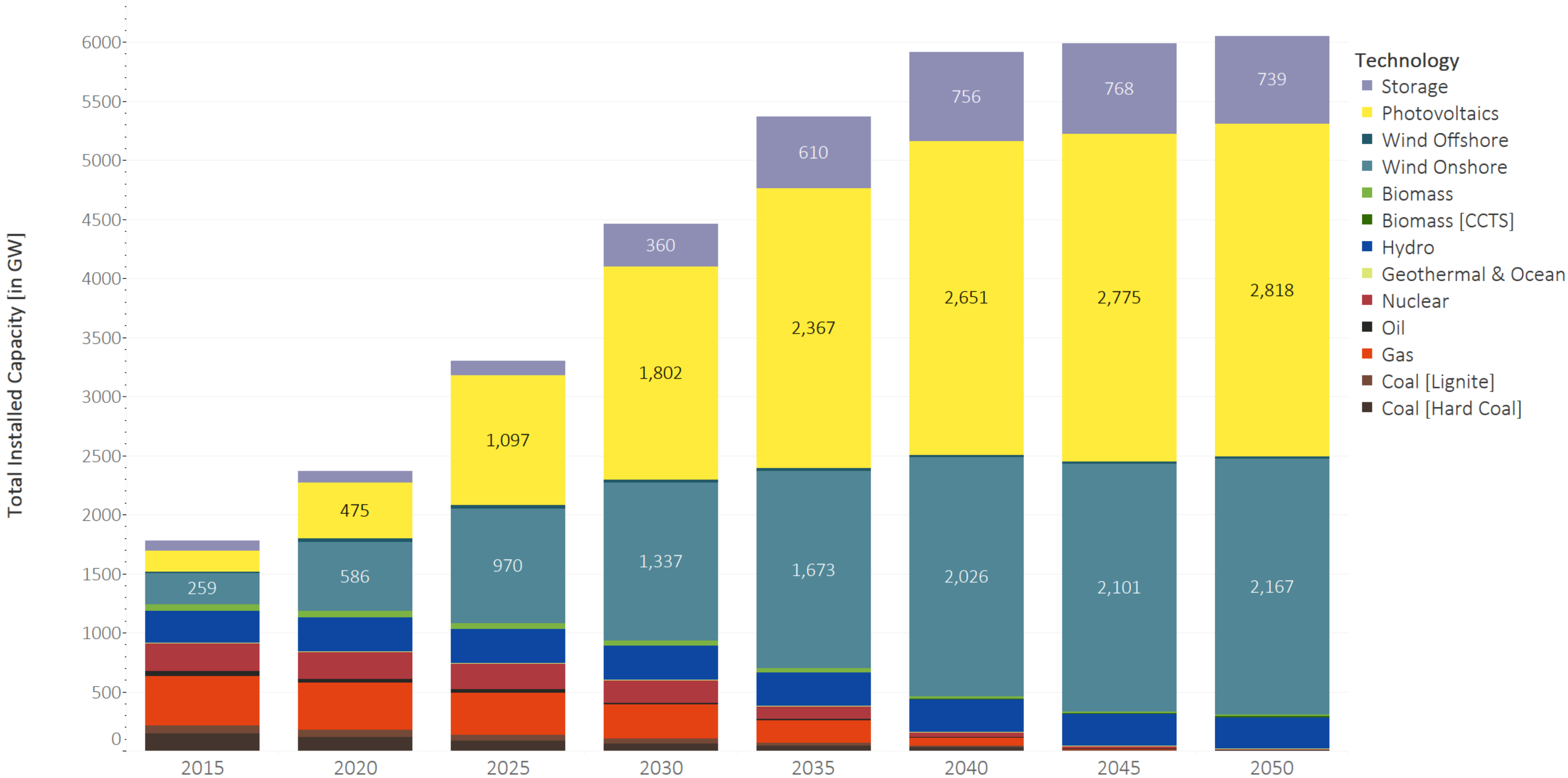


Development of Freight Transportation



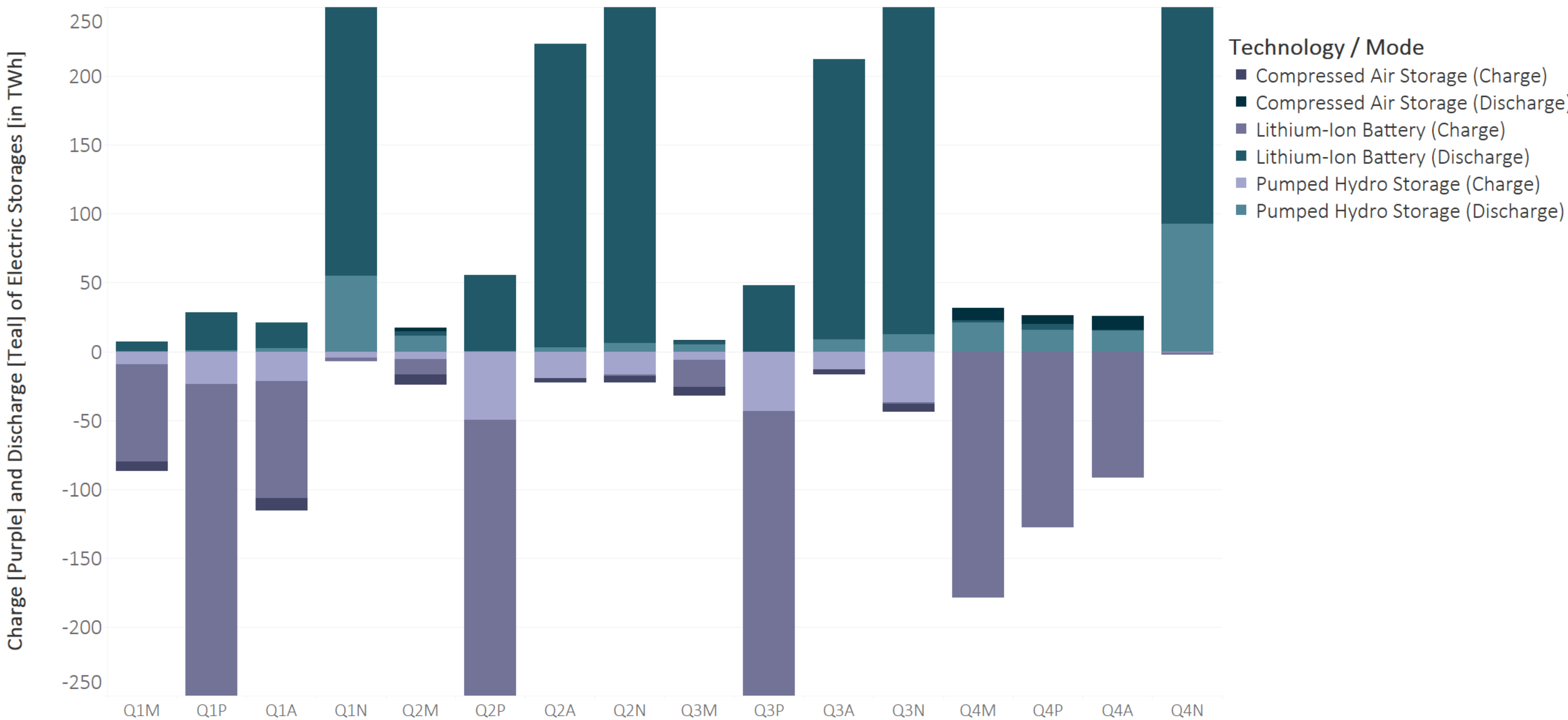
Source: Own Illustration

Capacities



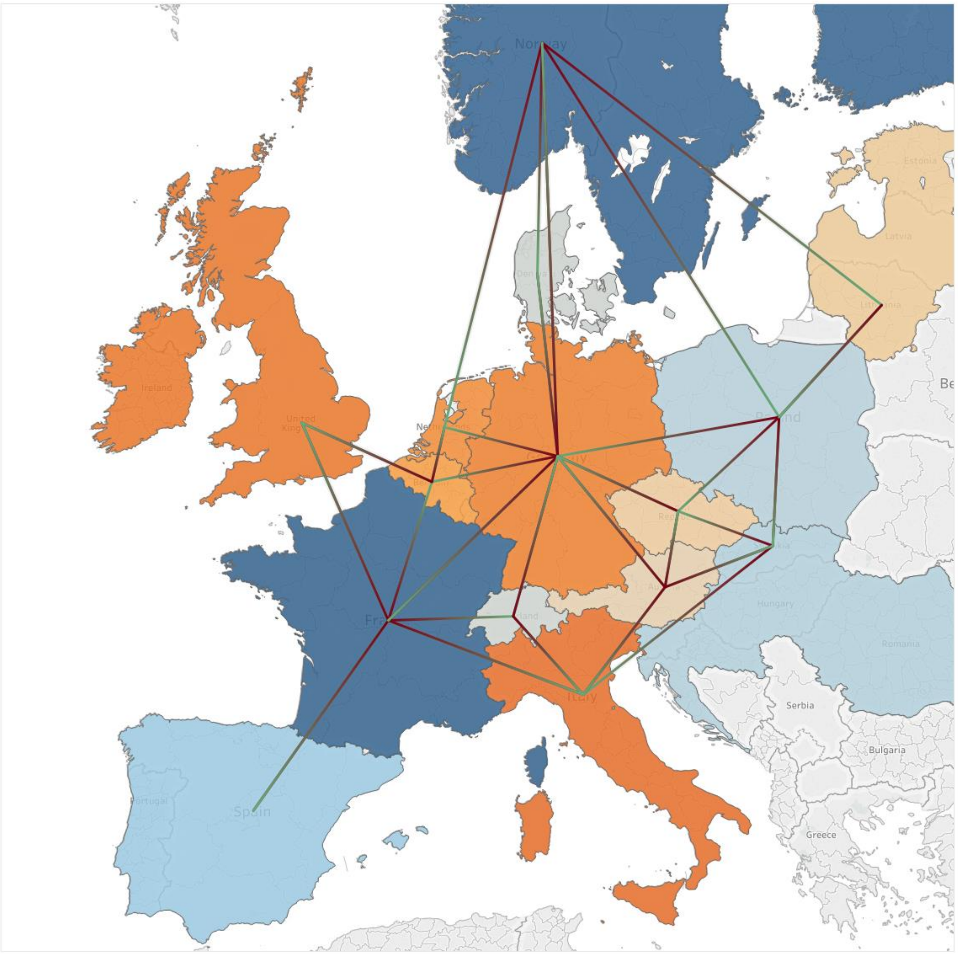
Total Installed Capacity [in GW]
6000
5500
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
2015
2020
2025
2030
2035
2040
2045
2050
259
586
475
970
1,097
1,337
1,802
360
1,673
2,367
610
2,026
2,651
756
2,101
2,775
768
2,167
2,818
739
Technology
Storage
Photovoltaics
Wind Offshore
Wind Onshore
Biomass
Biomass [CCTS]
Hydro
Geothermal & Ocean
Nuclear
Oil
Gas
Coal [Lignite]
Coal [Hard Coal]

Storage Charge and Discharge

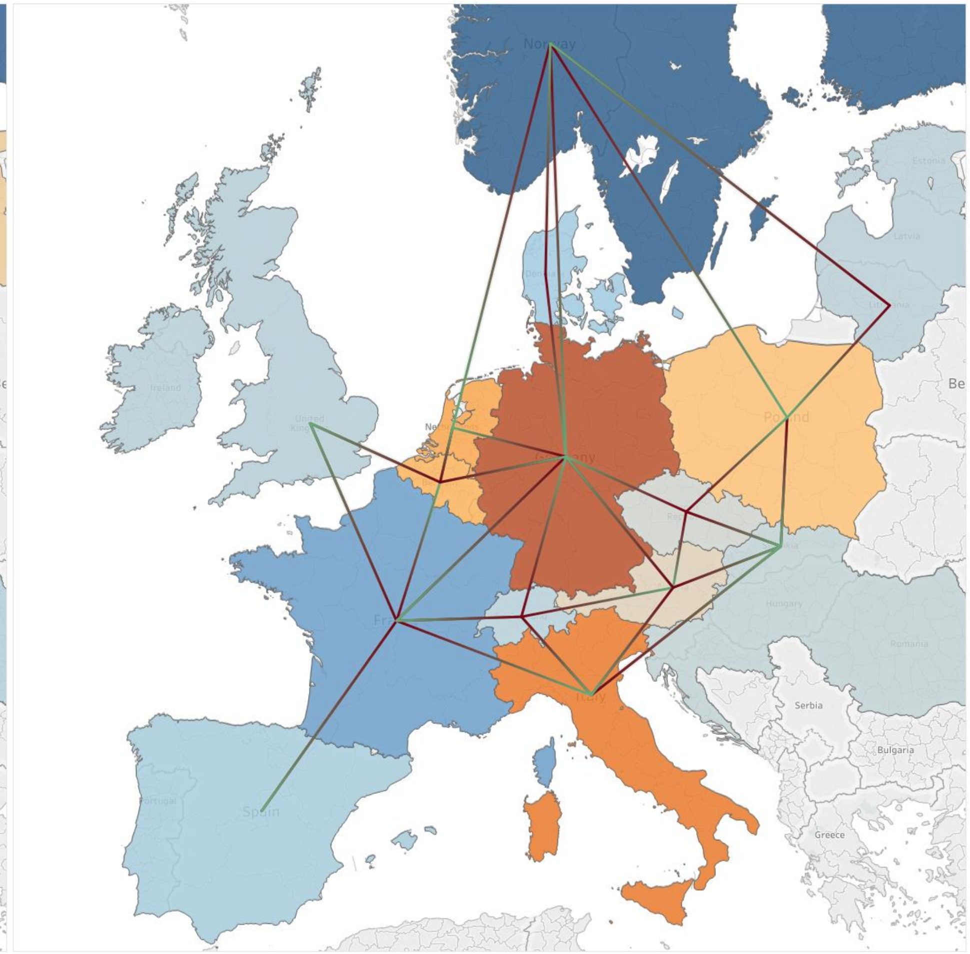


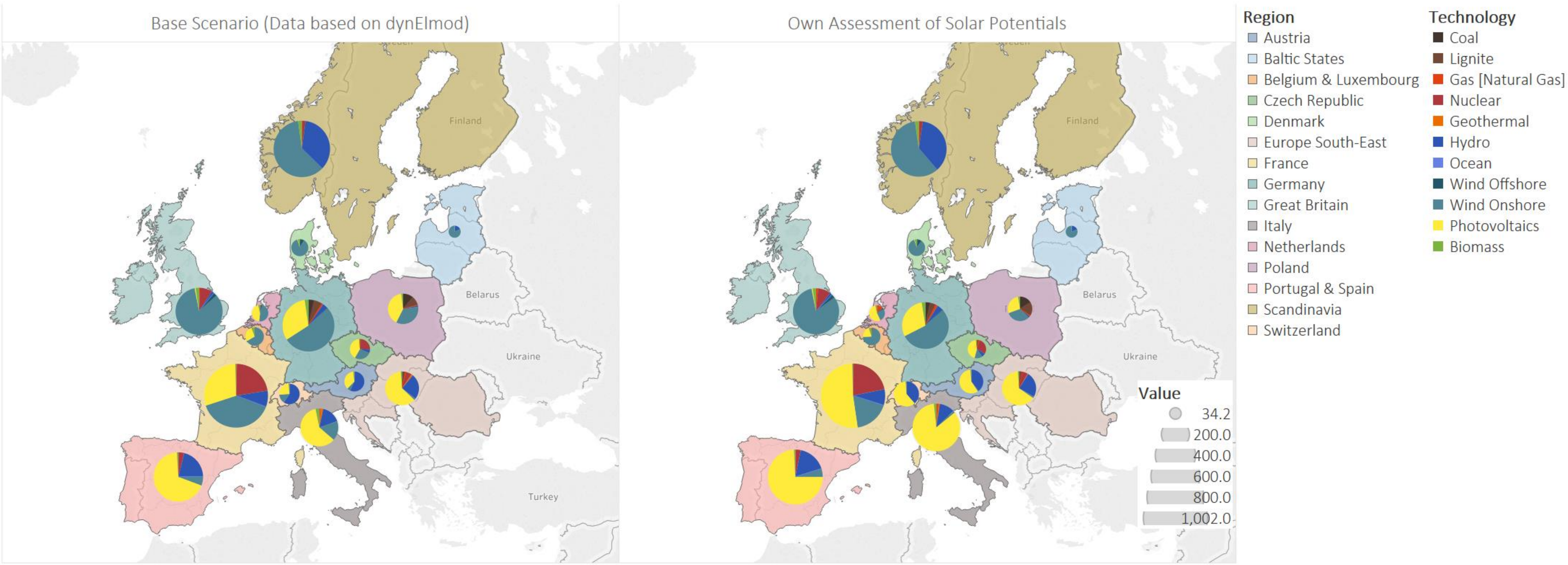
Power Trade

2030



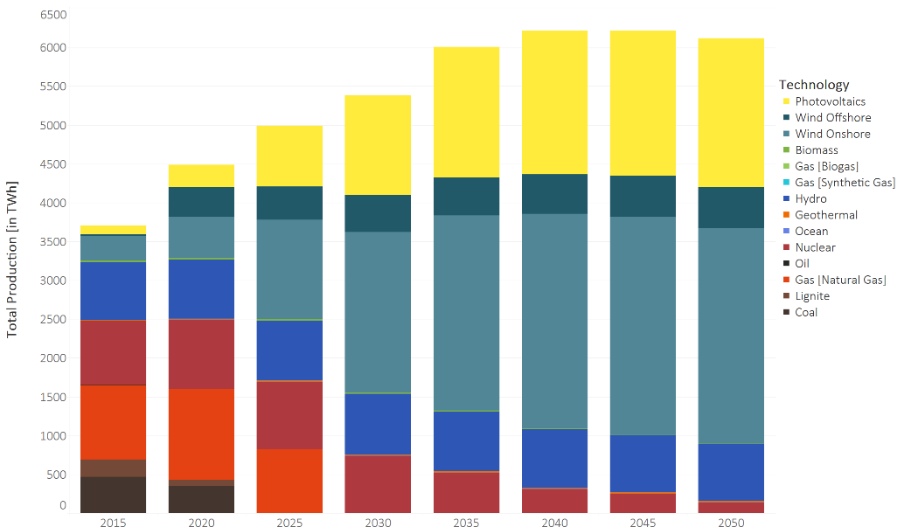
2050

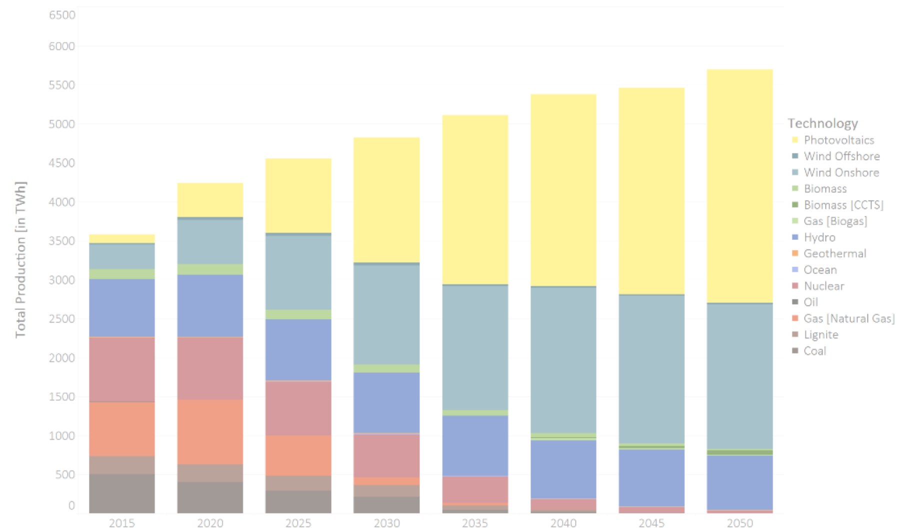


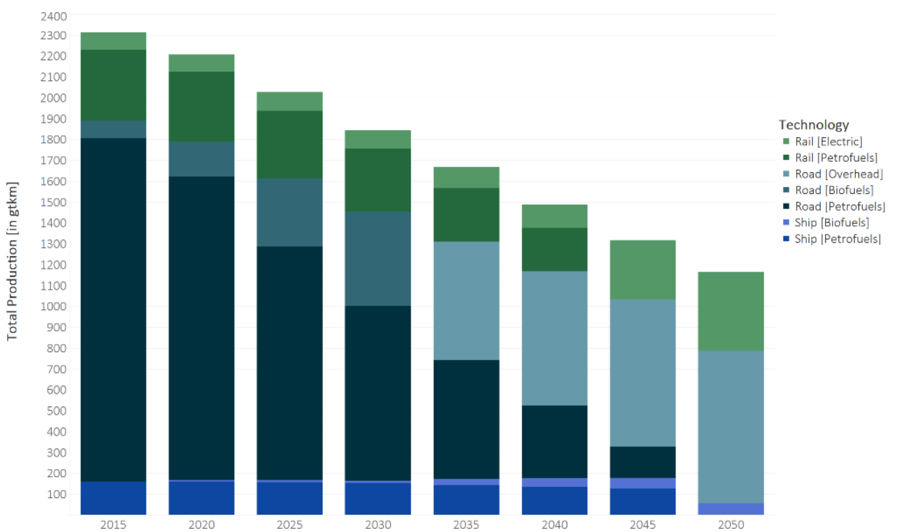

Base Scenario (Data based on dynElmod)
Own Assessment of Solar Potentials
Finland
Belarus
Ukraine
Turkey
Value
34.2
200.0
400.0
600.0
800.0
1,002.0
Region
Austria
Baltic States
Belgium & Luxembourg
Czech Republic
Denmark
Europe South-East
France
Germany
Great Britain
Italy
Netherlands
Poland
Portugal & Spain
Scandinavia
Switzerland
Technology
Coal
Lignite
Gas [Natural Gas]
Nuclear
Geothermal
Hydro
Ocean
Wind Offshore
Wind Onshore
Photovoltaics
Biomass

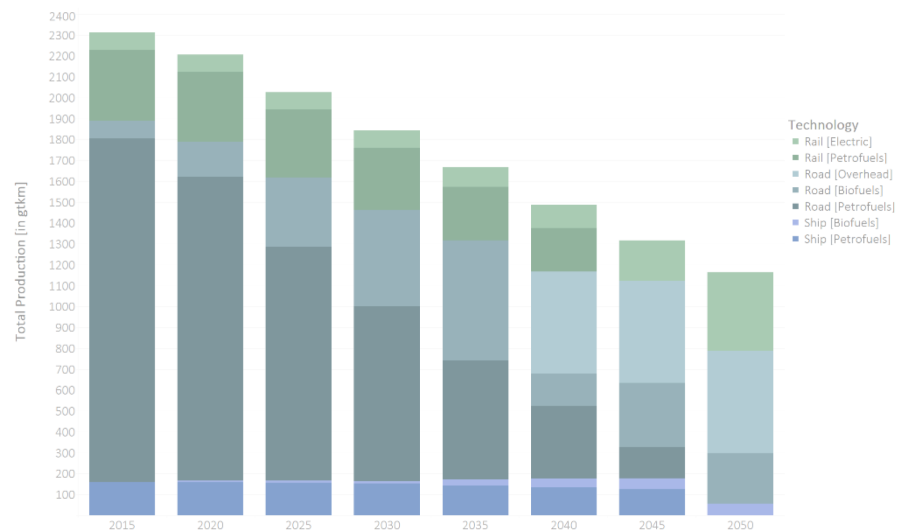
Scenario Comparison

1.5° compared to 2°

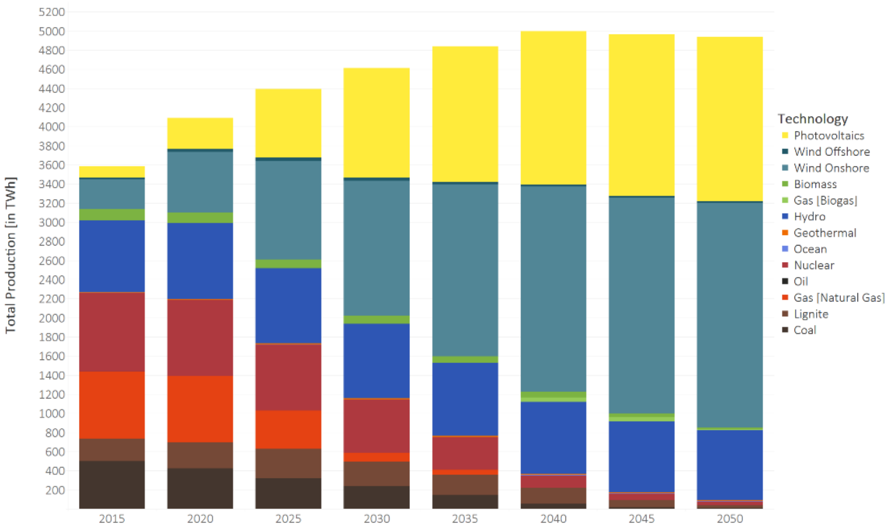


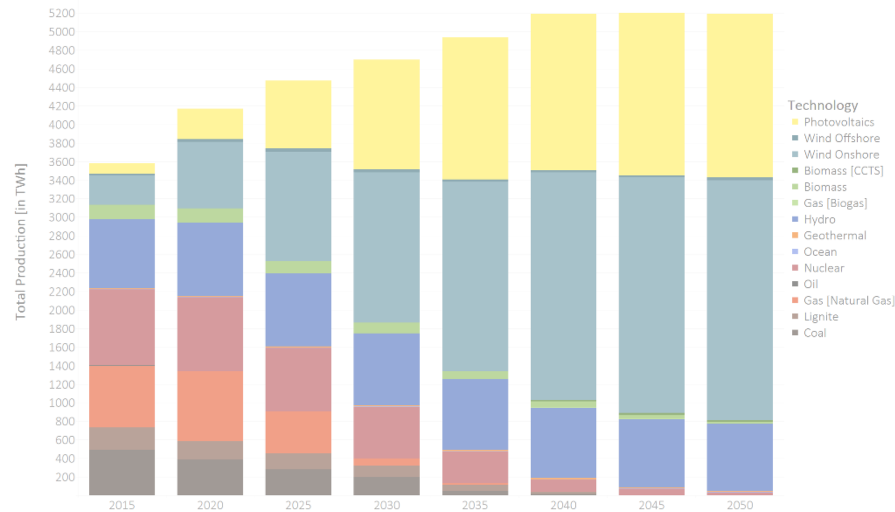


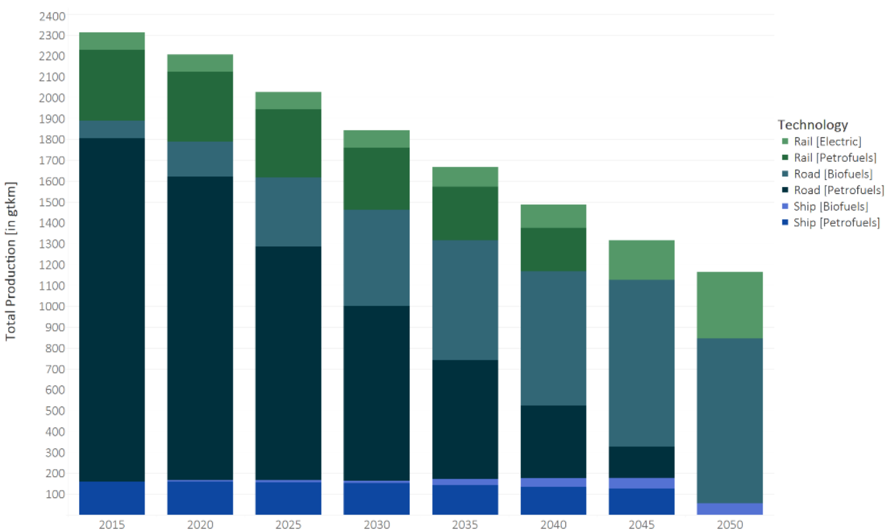


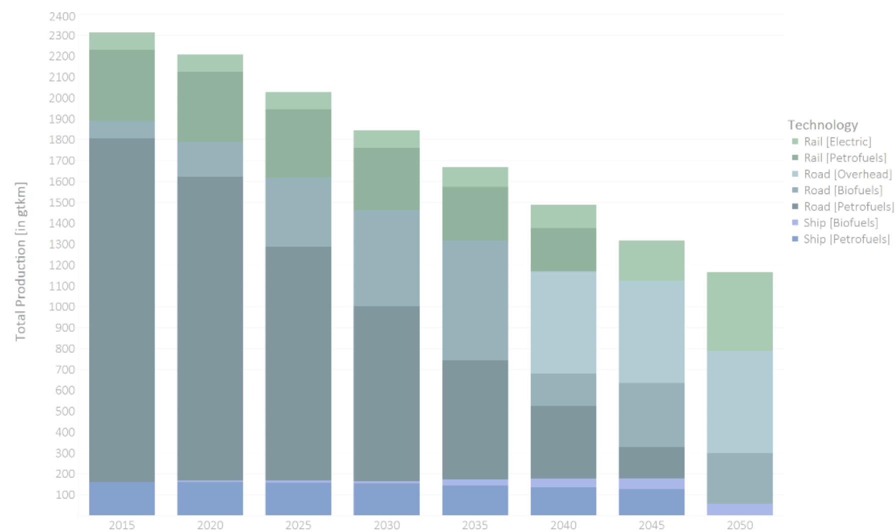


BAU compared to 2°



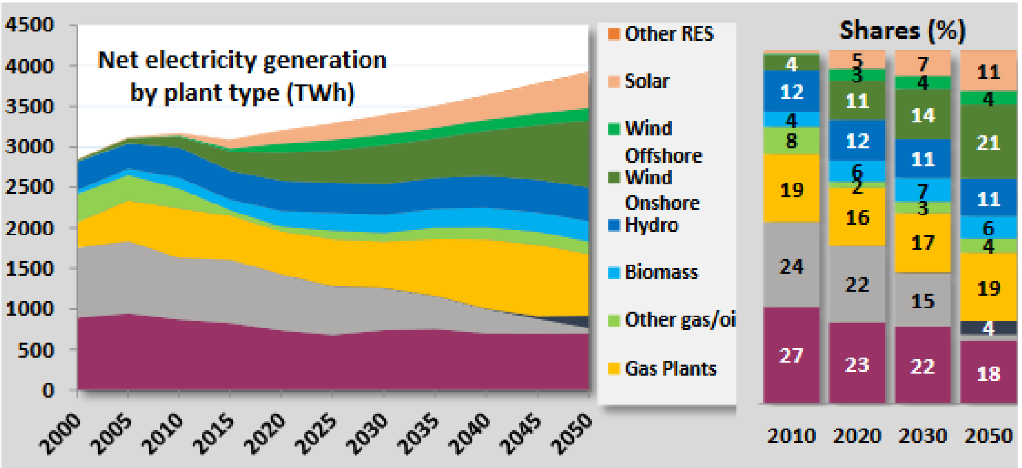






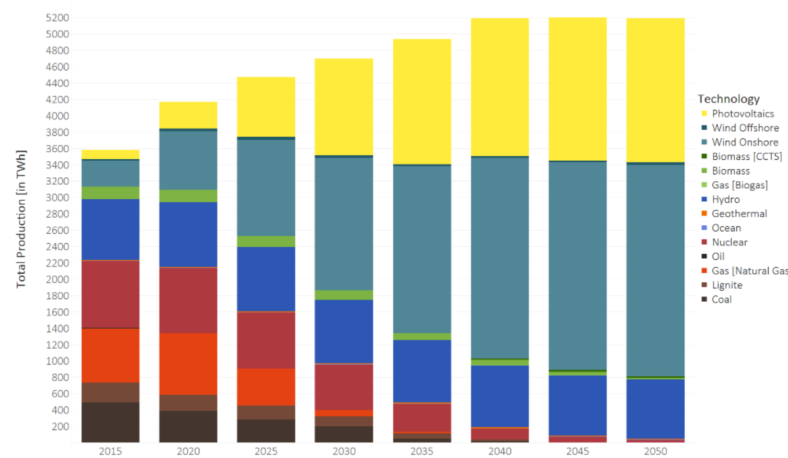
Comparison With the EU Reference Scenario 2016

EU Reference Scenario



Source: European Commission (2013)

GENeSYS-MOD v2.0

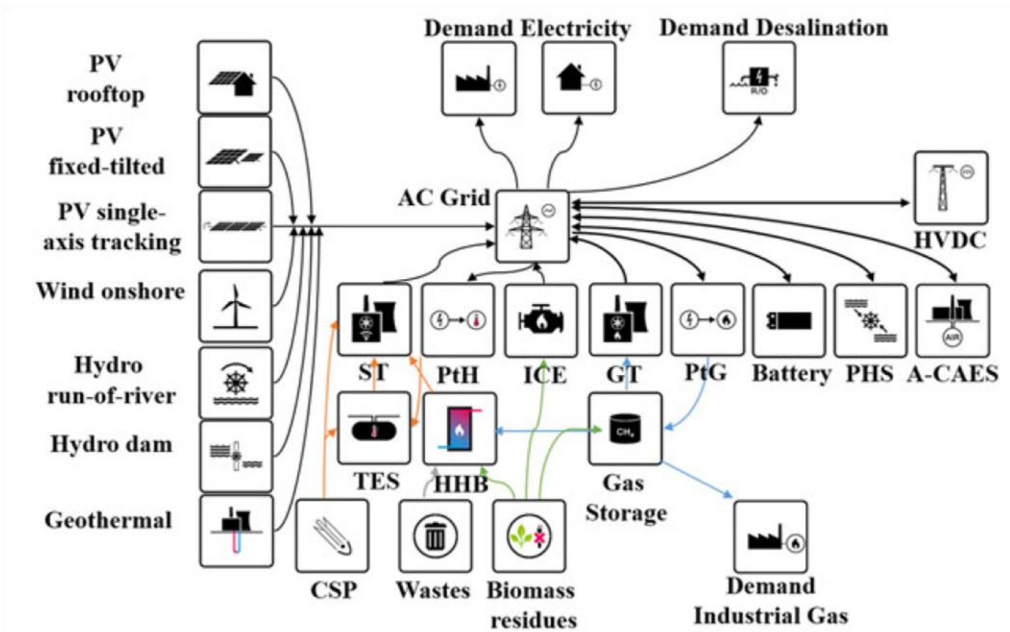


- Much higher shares of solar PV and Onshore Wind.
- Biomass, due to its limited potential, faces only small utilization in the power sector.
- Phase-out of coal and natural gas.
- No lifetime extension or capacity addition of nuclear power plants.
- Higher electricity demand due to sector coupling.

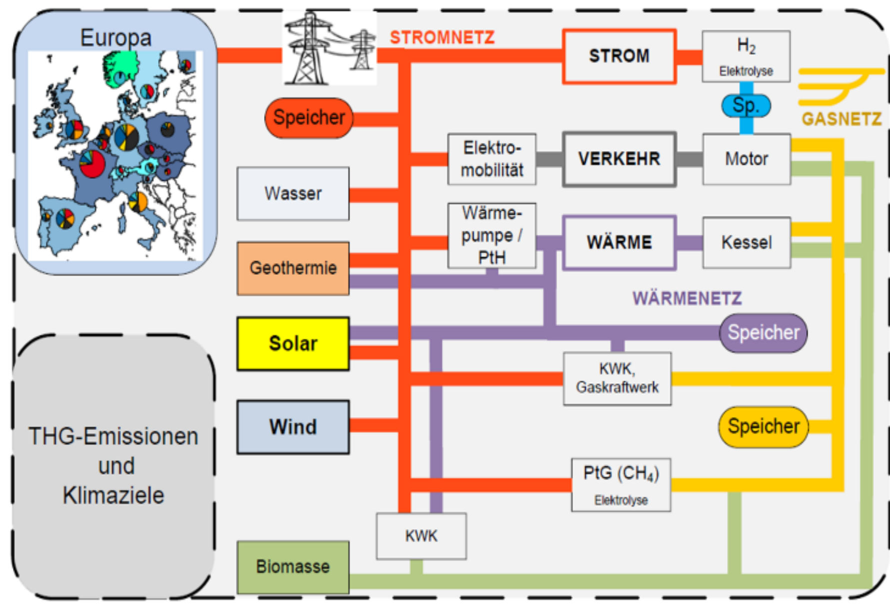
Motivation

Motivation:

- By offering a modeling framework, energy system models pose powerful tools for scientific research, especially considering the growing debate about decarbonization.
- Most current work focuses on either sector-specific decarbonization (e.g. electricity), have a limited time-horizon, or only assume low amounts of decarbonization.



Source: Breyer, et al. (2017)



Source: Fraunhofer, et al. (2015)

Capital Costs

Renewable Potential

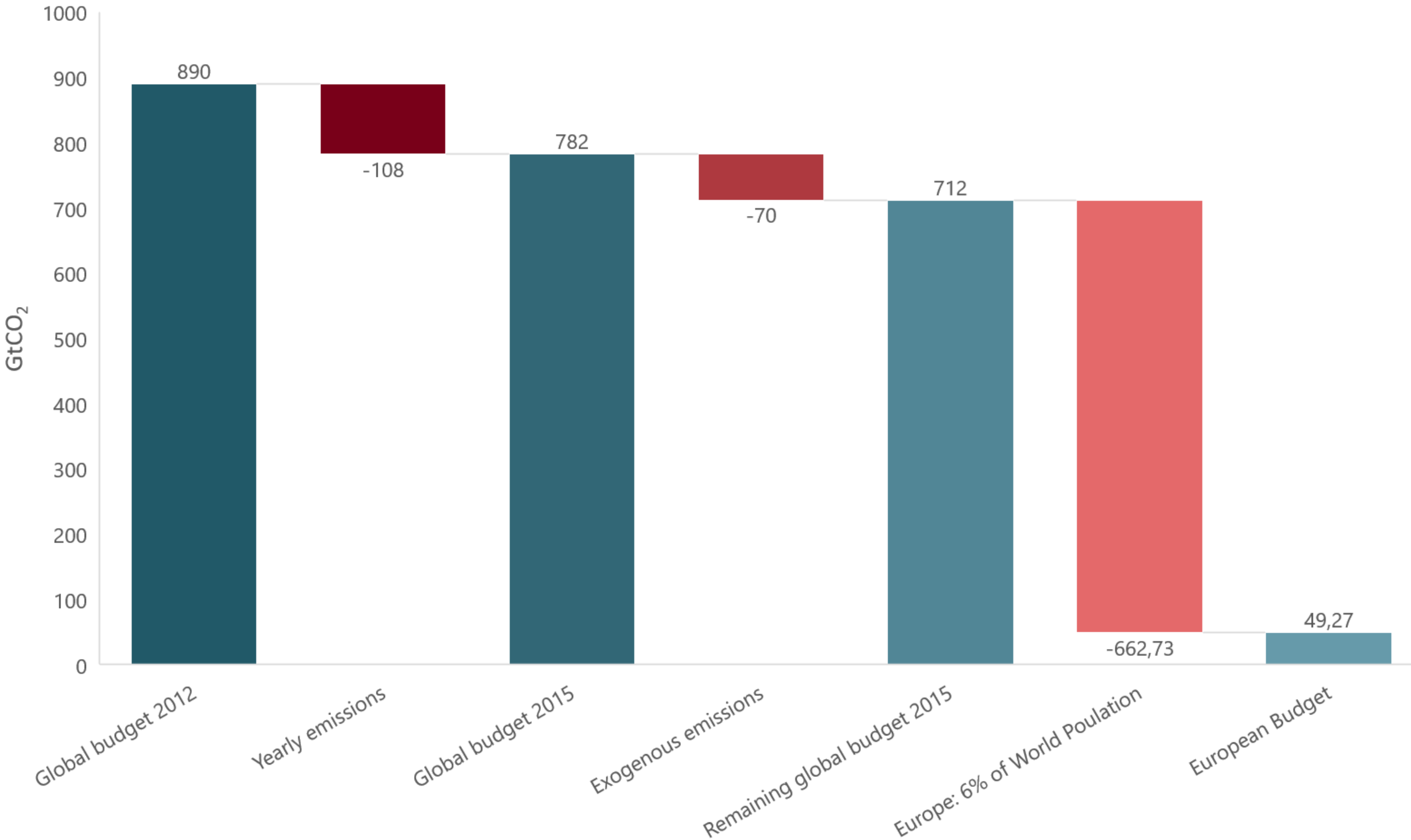
Introducing GENeSYS-MOD v2.0

Major Upgrade from the first version (2016/17):

- Introducing…

- …and more

Carbon Budget



Temporal Disaggregation

N: Night; M: Morning; P: Peak; A: Afternoon

Model Formulation – Objective Function

- **Sets:**

y	*Year*	f	*Fuel*	s	*Storage*
t	*Technology*	m	*Mode of Operation*	e	*Emission*
r	*Region*	l	*Time Slice*		

- **Objective Function**

$$\min costs = \sum_{y}\sum_{t}\sum_{r} TotalDiscountedCost_{y,t,r} + \sum_{y}\sum_{r} TotalDiscountedTradeCosts_{y,r}$$

$$\begin{aligned} TotalDiscountedCost_{y,t,r} &= DiscountedOperatingCost_{y,t,r} \\ &+ DiscountedCapitalInvestment_{y,t,r} \\ &+ DiscountedCapitalInvestmentStorage_{y,s,r} \\ &+ DiscountedTechnologyEmissionsPenalty_{y,t,r} \\ &- DiscountedSalvageValue_{y,t,r} \end{aligned}$$

$$\forall \quad y \in Y, t \in T, r \in R$$

Model Equations

- **Capacity Adequacy**

$$\sum_{m} RateOfActivity_{l,m,r,t,y} = TotalCapacityAnnual_{r,t,y} * CapacityFactor_{l,r,t,y} * AvailabilityFactor_{r,t,y} * CapacityToActivityUnit_{r,t} \quad \forall \; y \in Y, r \in R, l \in L, t \in T$$

$$RateOfProductionByTechnologyByMode_{f,l,m,r,t,y} = RateOfActivity_{l,m,r,t,y} * OuputActivityRatio_{f,m,r,t,y} \quad \forall \; f \in F, l \in L, m \in M \quad \forall \; r \in R, t \in T, y \in Y$$

Model Equations – Investment and Trade Costs

- **Investment Function**

$$TotalCapacityAnnual_{r,t,y} = ResidualCapacity_{r,t,y} + \sum_{yy} NewCapacity_{r,t,yy} \quad \forall \quad r \in R, t \in T, y \in Y$$

$$yy = \{y \in Y : yy > OperationalLife_{r,t} - y \wedge yy \geq y\} \; \forall \, r \in R, t \in T$$

- **Trade Costs**

$$\sum_{f} \sum_{rr \in R} Import_{f,l,r,rr,y} * TradeRoute_{f,r,rr,y} * TradeCosts_{f,r,rr} = TotalTradeCosts_{l,r,y} \quad \forall \quad l \in L, r \in R, y \in Y$$

Selected References

Cleveland, C.J., Morris, C. (Hrsg.) (2013a): Handbook of energy. Vol. 1: Diagrams, charts, and tables; Amsterdam: Elsevier.

Delucchi, M.A., Jacobson, M.Z., Bauer, Z.A.F., Goodman, S., Chapman, W. (2016): 100% wind, water, and solar roadmaps.

EIA (2012): Combined heat and power technology fills an important energy niche - Today in Energy - U.S. Energy Information Administration (EIA); Washington, D.C., USA, last accessed 30.07.2016 at http://www.eia.gov/todayinenergy/detail.cfm?id=8250.

EIA (2016b): International Energy Outlook 2016 - With Projections to 2040; Energy Outlook, Washington, D.C., USA, last accessed 16.07.2016 at www.eia.gov/forecasts/ieo/pdf/0484(2016).pdf.

Fraunhofer ISE (2015): Current and Future Cost of Photovoltaics. Long-term Scenarios for Market Development, System Prices and LCOE of Utility-Scale PV Systems.

Selected References

Hohmeyer, O.H., Bohm, S. (2015): Trends toward 100% renewable electricity supply in Germany and Europe: a paradigm shift in energy policies: Trends toward 100% renewable electricity supply in Germany and Europe; in: Wiley Interdisciplinary Reviews: Energy and Environment, Vol. 4, No. 1, pp. 74–97.

Howells, M., Rogner, H., Strachan, N., Heaps, C., Huntington, H., Kypreos, S., Hughes, A., Silveira, S., DeCarolis, J., Bazillian, M., Roehrl, A. (2011): OSeMOSYS: The Open Source Energy Modeling System: An introduction to its ethos, structure and development; in: Energy Policy, Sustainability of biofuels, Vol. 39, No. 10, pp. 5850–5870.

IEA (2009): Transport, Energy and CO2; Moving Towards Sustainability, Paris, France, last accessed 03.10.2016 at Transport, Energy and CO2.

IPCC (2014a): Climate change 2014: mitigation of climate change: Working Group III contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change; New York, NY: Cambridge University Press.