Advances in European Energy System Modeling

Maike Gnirß, Thomas Schöb, Jann Weinand, Detlef Stolten

m.gnirss@fz-juelich.de

19. Symposium Energieinnovation

11. - 13.02.2026

Jülich Systems Analysis

What is the Purpose of Energy System Modeling?

- Energy system models serve to evaluate performance of potential energy systems[1]
- Energy system models influence energy policy, especially the target setting and strategy planning[2]

European Green Deal[3] and European Climate Law[4]:

- Climate neutral Europe until 2050
- 55 % GHG emissions reduction target by 2030
- 90% GHG emissions reduction target for 2040
- Commitment to negative emissions after 2050
- **Preparation of sector-specific roadmaps**

Scope of this review: Energy system models with

European Scope | **Transformation Pathway** | **Technology Representation** | **Sector Integration**

Sector integration leads to system cost reduction[5]

[1] Fattahi et al. (2020). *A systemic approach to integrated energy system modeling*. RSER, 133, 110195.
[2] Süsser et al. (2021). Model-based policymaking or policy-based modelling?. *Energy Research & Social Science*, 75, 101984
[3] European Commission. (n.d.). *European Green Deal*. Retrieved September 12, 2025.
[4] European Commission. (n.d.). *European Climate Law*. Retrieved September 12, 2025.
[5] Brown et al. (2018). Synergies of sector coupling and transmission reinforcement. Energy, 160, 720–739.

Research Questions

Sector-integrated European energy system models

- Which models are utilized to represent a European energy system with sector integration?

Common characteristics

- What characteristics do these models have in common?

Main challenges

- What are the current challenges limiting modeling approaches?

Potential further advances

- What subsequent developments can be anticipated?

Methodology

- Searching for reviews of energy system models
  - Following PRISMA guideline[1]:
    "TITLE-ABS-KEY ((""energy system*"" OR ""energy-economy-environment"") W/2 (model* OR optimi*)) AND (LIMIT-TO (DOCTYPE , ""re""))“
  - Refining with keywords → 199 results
  - Filtering relevant reviews via title and abstract

➢ No review with focus on European scope

→ Collecting all mentioned energy system models and frameworks

- Latest model for each framework
- 3 inclusion criteria for energy system models: European scope, at least two commodities and certain technical detail

Included	TEMOA-Europe, JRC-EU-TIMES, Balmorel, PyPSA-Eur, Sector-Coupled Euro-Calliope, PRIMES
Non-European scope	LEAP, oemof.solph, GCAM, POLES, TIAM
Power System Model	ELMOD, LIMES-EU+, Urbs-EU, OSEMBE (OSeMOSYS), EMCAS
Integrated Assessment Model	MEDEAS-EU, MESSAGEix

[1] Page, M. J. et al. (2021). The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. *BMJ*, 372, n71.

Sector-Integrated European Energy System Models

Model	Framework	Full Model Name	References
TEMOA-Europe	TEMOA	**T**ools for **E**nergy **M**odel **O**ptimization and **A**nalysis	Lerede et al. (2024). TEMOA-Europe: An open-source and open-data energy system optimization model. Energy.
JRC-EU-TIMES	TIMES	**J**oint **R**esearch **C**entre-**EU**-**T**he **I**ntegrated **M**ARKAL-**E**FOM **S**ystem	Béres et al. (2024). Will hydrogen and synthetic fuels energize our future?. Applied Energy, 375, 124053.
Balmorel	Balmorel		Kountouris et al. (2024). A unified European hydrogen infrastructure planning to support the rapid scale-up of hydrogen production. Nature Communications, 15(1), 5517.
PyPSA-Eur (v0.6.0)	PyPSA	**Py**thon **P**ower **S**ystem **A**nalysis - **Eur**ope	Neumann et al. (2023). The potential role of a hydrogen network in Europe. Joule, 7, 1–25. Victoria et al. (2022). Speed of technological transformations required in Europe to achieve different climate goals. Joule, 6, 1066–1086.
Sector-Coupled Euro-Calliope	Calliope		Pickering et al. (2022). Diversity of options to eliminate fossil fuels and reach carbon neutrality across the entire European energy system. Joule, 6, 1253–1276. Pfenninger & Pickering (2018). Calliope: A multi-scale energy systems modelling framework. Jour. of Open Source Software.
PRIMES	PRIMES	**P**rice-**I**nduced **M**arket **E**quilibrium **S**ystem	Capros et al. (2019). Energy-system modelling of the EU strategy towards climate-neutrality. Energy Policy, 134.

Sector-Integrated Energy System Models

Model		
TEMOA-Europe		
JRC-EU-TIMES		
Balmorel		
PyPSA-Eur (v0.6.0)		
Sector-Coupled Euro-Calliope		
PRIMES		

Sector-Integrated Energy System Models

Model	Approach	Theoretical Framework	License
TEMOA-Europe	Bottom-up	Optimization & Partial Equilibrium	open-source (AGPL-3.0)
JRC-EU-TIMES	Bottom-up	Optimization & Partial Equilibrium	commercial (free demo version)
Balmorel	Bottom-up	Deterministic Partial Equilibrium	open-source (ISC License)
PyPSA-Eur (v0.6.0)	Bottom-Up	Optimization	open-source (MIT)
Sector-Coupled Euro-Calliope	Bottom-up (own assessment)	Optimization	open-source (Apache 2.0)
PRIMES	Hybrid, Agent-based, Sub-models	Partial Equilibrium	non-free

Research Questions

Sector-integrated European energy system models

- PRIMES
- Balmorel
- PyPSA-Eur (v0.6.0)
- TEMOA-Europe
- JRC-EU-TIMES
- Sector-Coupled Euro-Calliope

Common characteristics

Main challenges

Potential further advances

Methodological Characteristics — Spatial Coverage

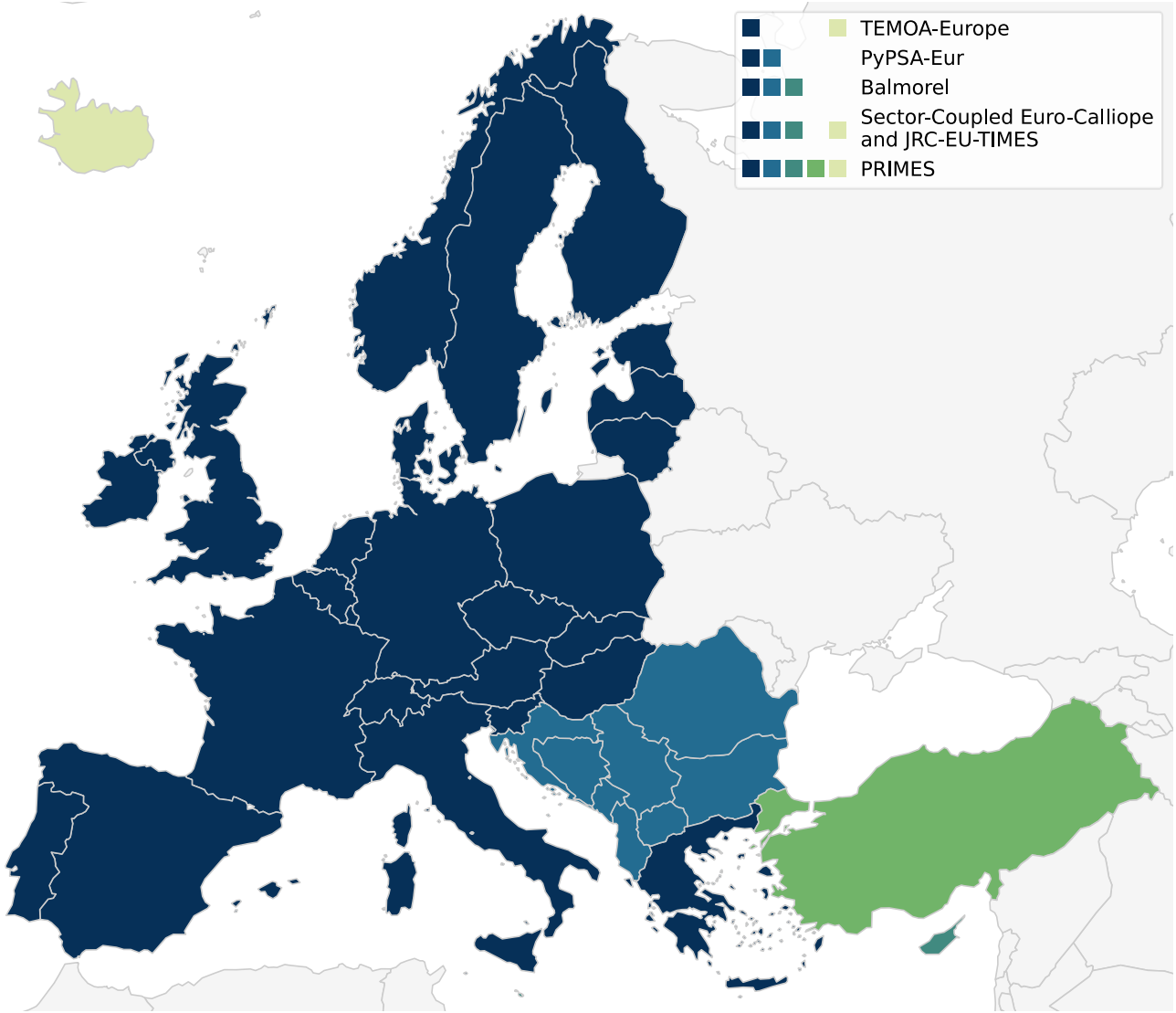


Figure.
Spatial coverage of European Energy System Models

Methodological Characteristics

Model	Spatial Resolution	Time Horizon	Temporal Resolution	Transformation Pathway	Foresight	Energy Vectors
TEMOA-Europe						
JRC-EU-TIMES						
Balmorel						
PyPSA-Eur (v0.6.0)						
Sector-Coupled Euro-Calliope						
PRIMES						

[1] a little finer with 37 nodes for 33 countries
[2] NUTS-1
[3] calibrated on the years 2010 to 2020
[4] hourly for New Fuels and PRIMES/IEM sub-model
[5] long term for supply sub-modules, and short for demand sub-modules

Research Questions

Sector-integrated European energy system models

PRIMES

Balmorel

PyPSA-Eur (v0.6.0)

TEMOA-Europe

JRC-EU-TIMES

Sector-Coupled Euro-Calliope

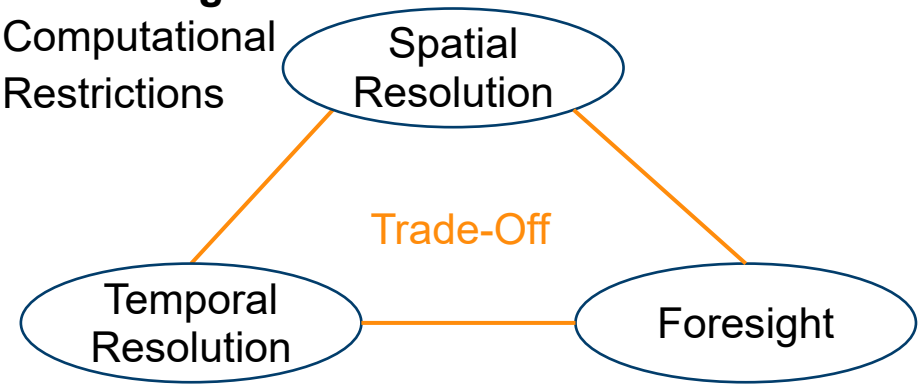
Common characteristics

- Transformation Pathway
- Time Horizon: **2050**
- Spatial Coverage **> EU-27, UK, NO, CH**
- License: **open-source**

Potential further advances

Main challenges

- Computational Restrictions



Research Questions

Sector-integrated European energy system models

PRIMES | Balmorel | PyPSA-Eur (v0.6.0) | TEMOA-Europe | JRC-EU-TIMES | Sector-Coupled Euro-Calliope

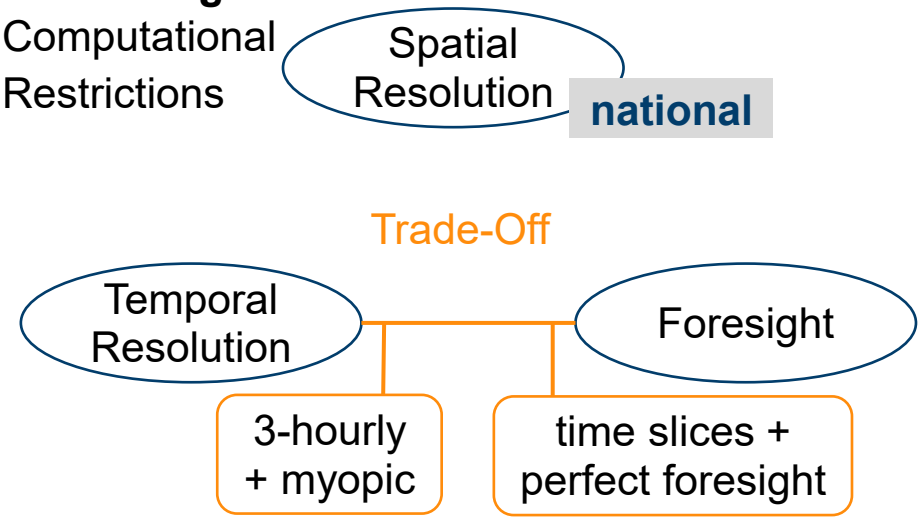
Common characteristics

- Transformation Pathway
- Time Horizon: **2050**
- Spatial Coverage **> EU-27, UK, NO, CH**
- License: **open-source**

Potential further advances

Main challenges

- Computational Restrictions



Research Questions

Sector-integrated European energy system models: PRIMES, Balmorel, PyPSA-Eur (v0.6.0), TEMOA-Europe, JRC-EU-TIMES, Sector-Coupled Euro-Calliope

Common characteristics

- Transformation Pathway
- Time Horizon: **2050**
- Spatial Coverage **> EU-27, UK, NO, CH**
- License: **open-source**

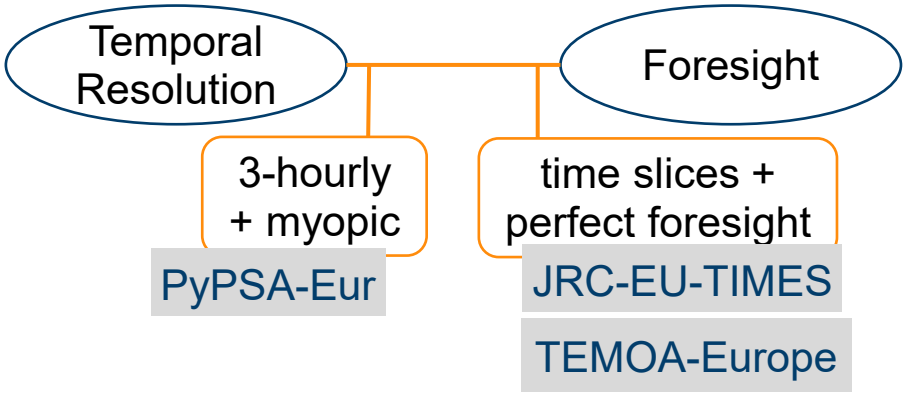
Potential further advances

Main challenges

- Computational Restrictions

Spatial Resolution: **national**

Trade-Off



Research Questions

Sector-integrated European energy system models

PRIMES | Balmorel | PyPSA-Eur (v0.6.0) | TEMOA-Europe | JRC-EU-TIMES | Sector-Coupled Euro-Calliope

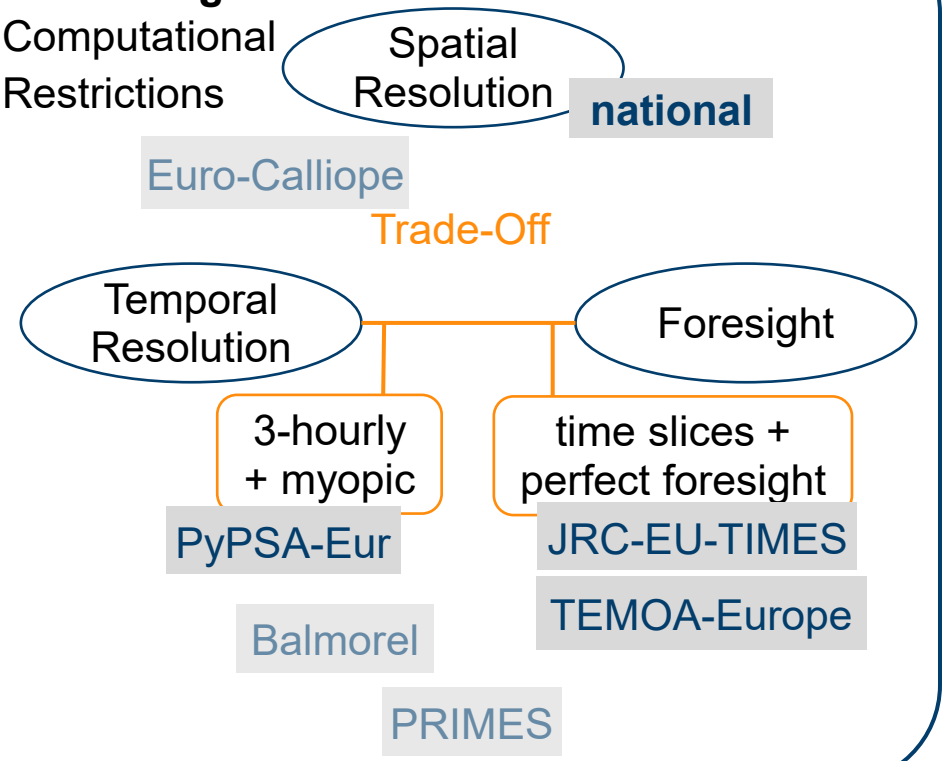
Common characteristics

- Transformation Pathway
- Time Horizon: **2050**
- Spatial Coverage **> EU-27, UK, NO, CH**
- License: **open-source**

Potential further advances

Main challenges

- Computational Restrictions



Sectoral Resolution

+	several competing technologies
●	limited technologies
–	single technology or aggregated demand
×	not modelled / not mentioned

Model	Industry	Transport	Building/ Residential
TEMOA-Europe	+	+	?
JRC-EU-TIMES	+	●	+
Balmorel	–	–	–
PyPSA-Eur (v0.6.0)	●[2]	●	●[3]
Sector-Coupled Euro-Calliope	–	●	–
PRIMES	+	+	+

[1] Land Use and Land Use Change and Forestry
[2] transformation exogenously defined
[3] exogenous building retrofits, and district heating expansion
[4] as CO_2 sink

Research Questions

Sector-integrated European energy system models

PRIMES | Balmorel | PyPSA-Eur (v0.6.0) | TEMOA-Europe | JRC-EU-TIMES | Sector-Coupled Euro-Calliope

Common characteristics

- Transformation Pathway
- Time Horizon: 2050
- Spatial Coverage > EU-27, GB, N, CH
- License: open-source
- Sectors with competing technologies
- Carbon Capture and Storage

Main challenges

- Computational Restrictions

- Availability of data sources

Potential further advances

- Data centers
- Further Greenhouse Gases
- Outlook beyond 2050
- Competition between major technologies

Summary

Sector-integrated European energy system models

- **PRIMES**
- **Balmorel**
- **PyPSA-Eur (v0.6.0)**
- **TEMOA-Europe**
- **JRC-EU-TIMES**
- **Sector-Coupled Euro-Calliope**

Common characteristics

- Transformation Pathway
- Time Horizon: **2050**
- Spatial Coverage **> EU-27, UK, NO, CH**
- License: **open-source**
- Sectors with competing technologies
- Carbon Capture and Storage

Main challenges

- Computational Restrictions
  - Spatial Resolution: **national**
  - Trade-Off
    - Temporal Resolution: hourly + myopic
    - Foresight: time slices + perfect foresight
- Availability of data sources

Potential further advances

- Data centers
- Further Greenhouse Gases
- Outlook beyond 2050
- Competition between major technologies

Thank you for your attention!

Profile
go.fzj.de/
JuelichSystemsAnalysis

Publications
go.fzj.de/ice2_publications

GHG net zero scenario
go.fzj.de/ksg45

Project DacStorE
go.fzj.de/dacstore

H2 Atlas Africa
go.fzj.de/h2africa

Project Resur
go.fzj.de/resur

LinkedIn
go.fzj.de/linkedin-ice-2

For further questions, please contact:

Maike Gnirß
+49 160 92252891
m.gnirss@fz-juelich.de

Prof. Dr. Jochen Linßen
+49(0)1751495243
j.linssen@fz-juelich.de