From open to transparent:
Energy system modelling for the next quarter century

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It’s 2025: 25 years left till 2050

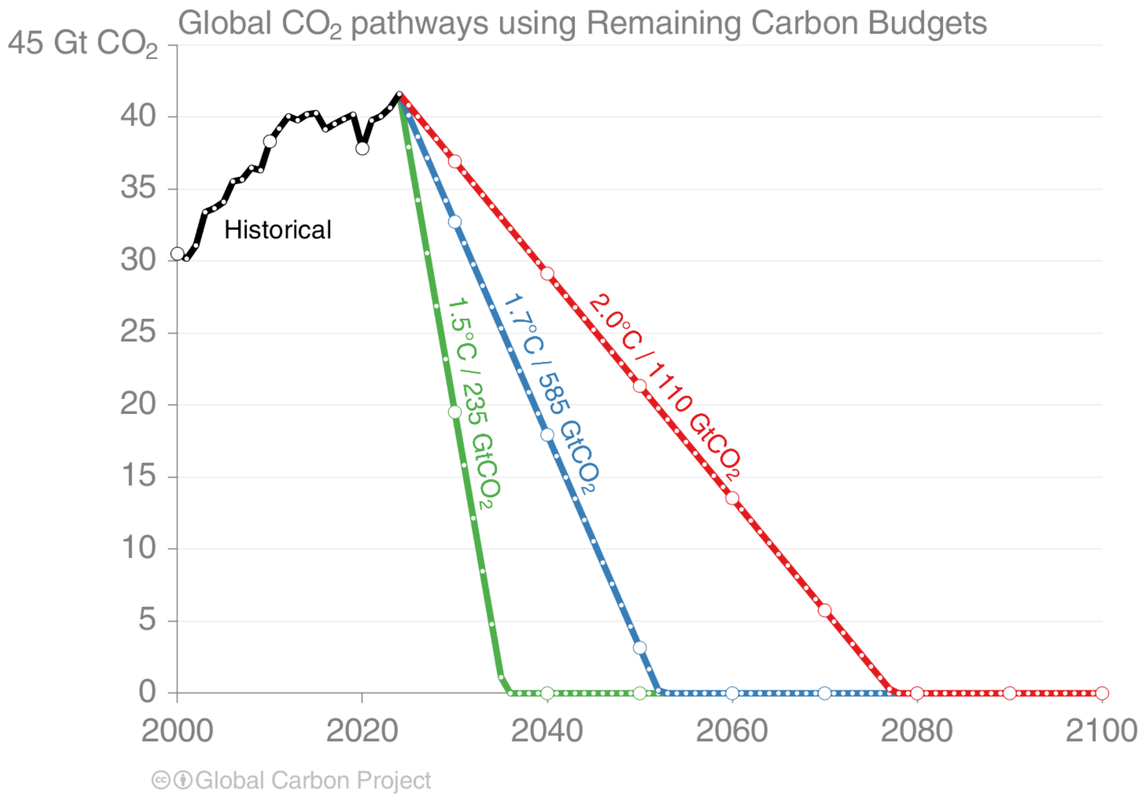
In the first half of 2025:

Global renewable generation has overtaken global coal generation for the first time!

Solar and wind growth together exceeded global demand growth for the first time!

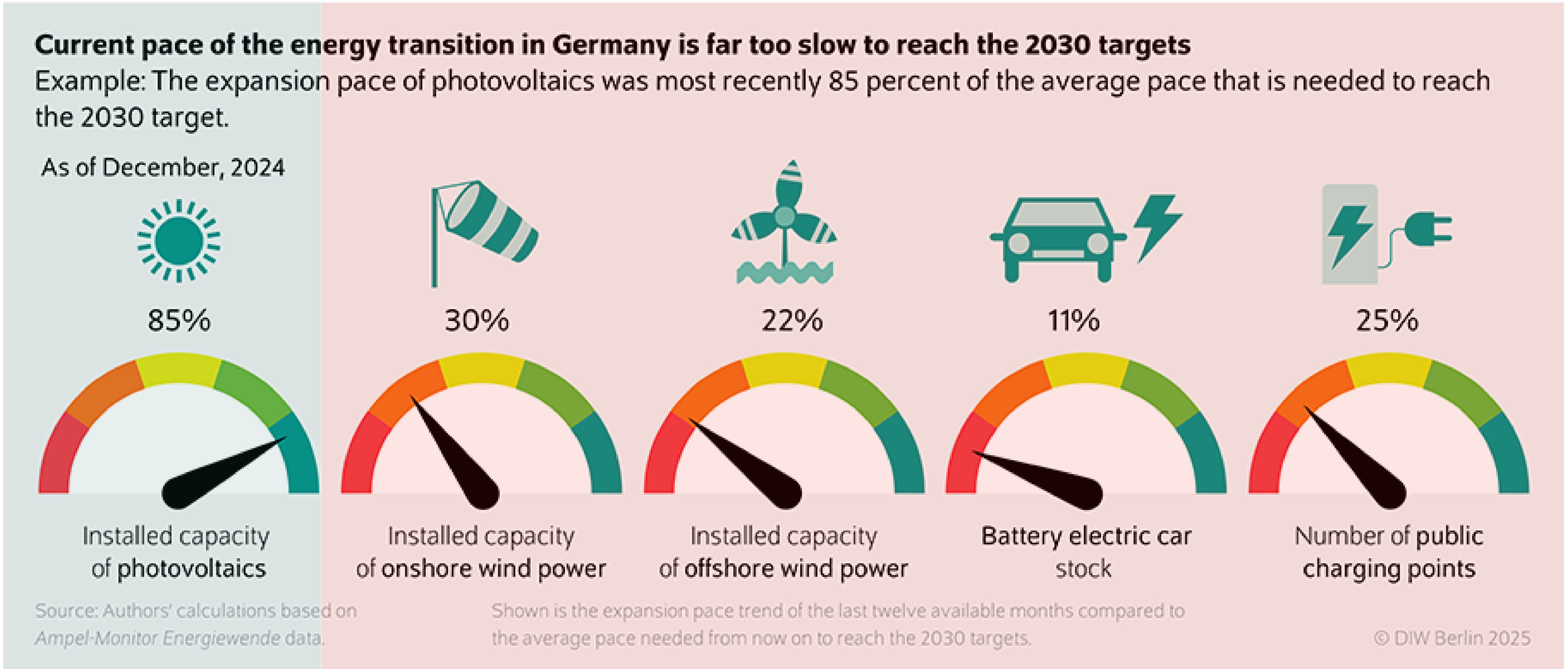
(Ember Energy, 7 October 2025)

Emissions still growing, time running out!



Ember Energy (7 Oct 2025), https://ember-energy.org/latest-insights/global-electricity-mid-year-insights-2025/
Global Carbon Budget (2024), https://globalcarbonbudget.org/gcb-2024/

Some parts of transition faster than needed, many still slower



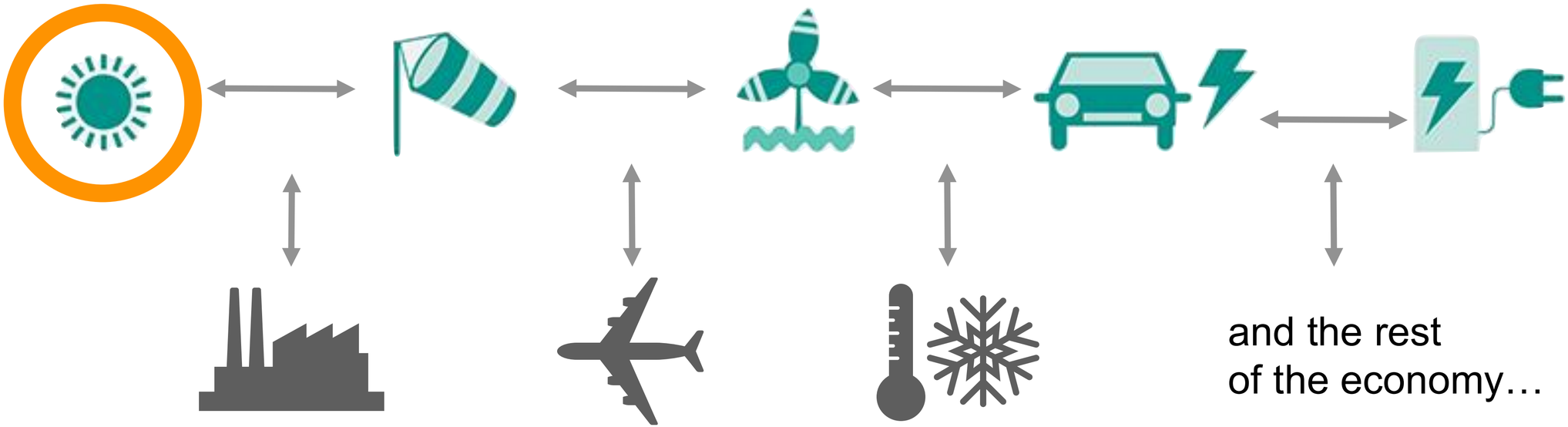
Few: faster

Most: slower than needed

DIW (Dec 2024), https://www.diw.de/ampel-monitor

Energy system models

In theory, (energy) system models* should help plan system integration and balance the speed of a well-planned transition across all system components



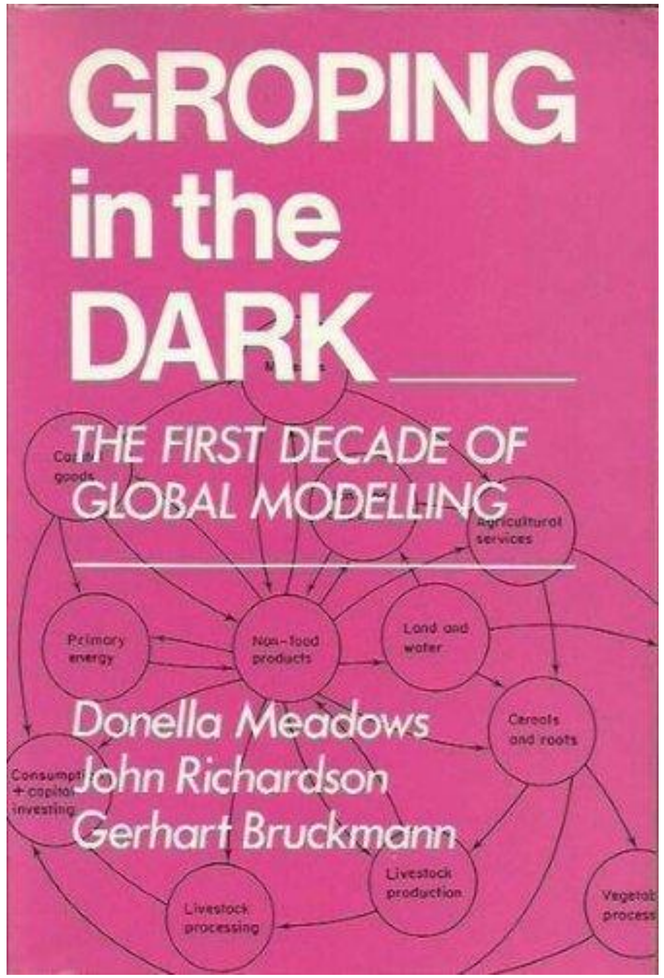
* I am mostly talking about energy system models that typically use mathematical optimisation methods to plan and/or operate an energy system at scales from cities to continents, typically minimising cost or maximising social welfare.

Meanwhile,
back in the 80s…

https://en.wikipedia.org/wiki/The_Terminator

Meanwhile, back in the 80s…

Conference Proceedings of the Sixth IIASA Symposium on Global Modeling (1978)



11 areas of disagreement

…

3. Should models be normative or descriptive?

…

6. Should models be big or small?

…

Meadows et al. (1982), http://archive.org/details/gropingindarkfir0000mead
(Conference Proceedings of the Sixth IIASA Symposium on Global Modeling, 17-20 October 1978)

Meanwhile, back in the 80s…

13 areas of agreement

5. The most important forces shaping the future are social and political, ***and these forces are the least well represented in the models so far.***

10. Part of the documentation should be so clear and free from jargon that a ***nontechnical audience can understand all the model's assumptions*** and how these assumptions affect the model's conclusions.

11. Modellers should identify their data sources clearly and ***share their data as much as possible***.

12. Model users, if there are any clearly identifiable ones, ***should be involved in the modelling process as directly and frequently as possible***.

Social factors

Transparency

Meadows et al. (1982), http://archive.org/details/gropingindarkfir0000mead
(Conference Proceedings of the Sixth IIASA Symposium on Global Modeling, 17-20 October 1978)

Challenges for energy system modelling (as of 2014)

Resolving time and space

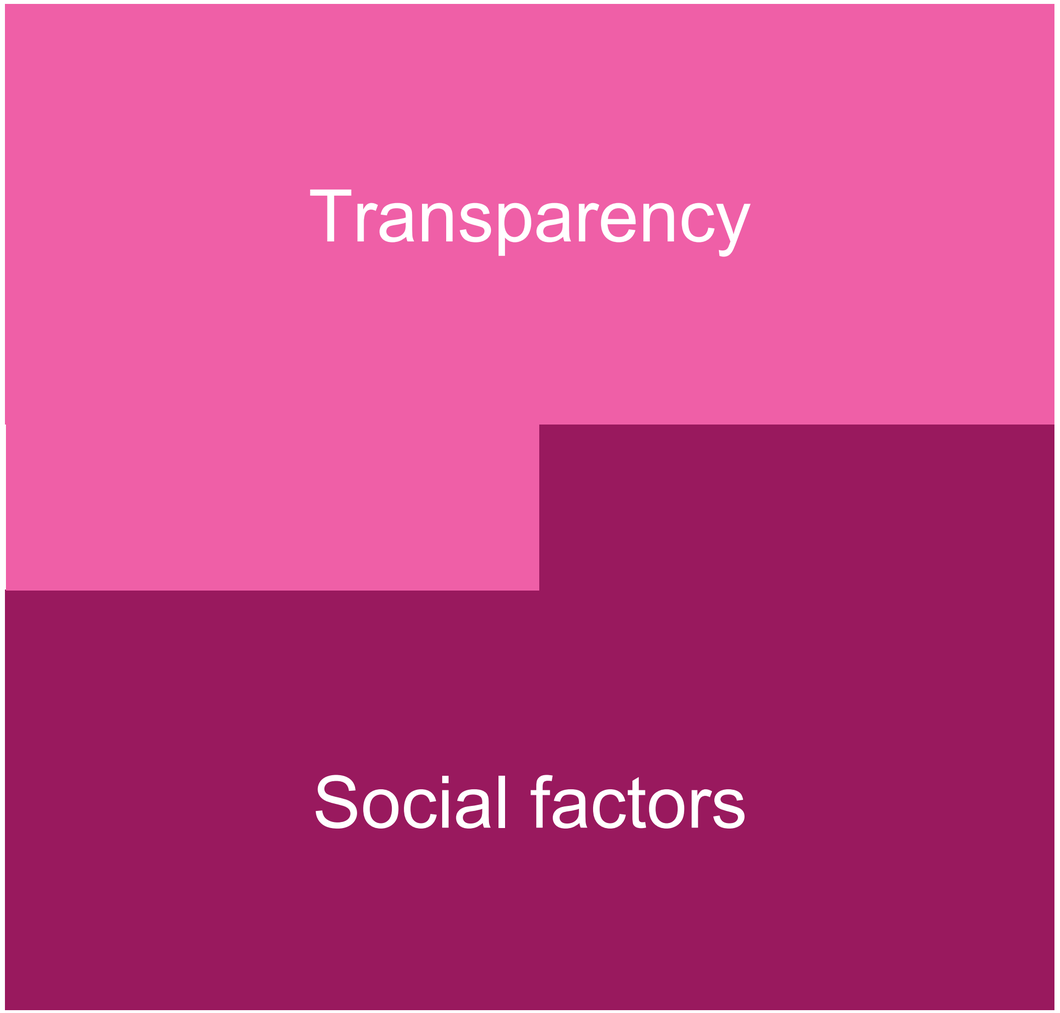
Addressing the growing complexity of the energy system

Balancing uncertainty and transparency

Integrating human behavior and social risks and opportunities

Pfenninger et al. (2014). https://doi.org/f526xf

Today, we will focus on:



Can we address both of these simultaneously?

1. Introduction

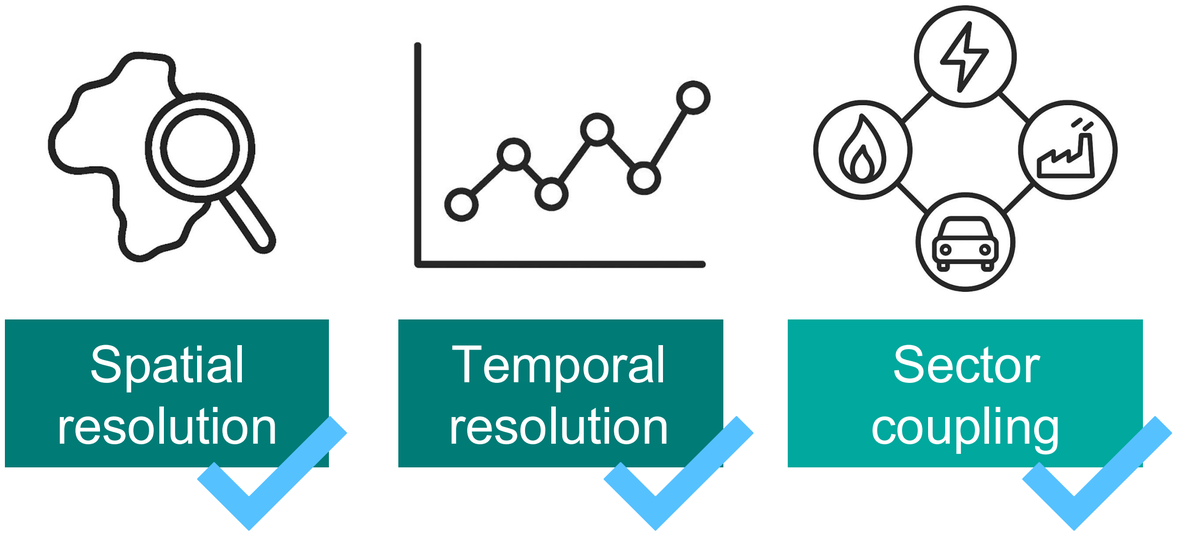
2. Progress: resolution + complexity

3. Gaps: transparency + social factors

4. What to do?

5. Conclusion

Resolution and complexity



Status quo reviewed in Chang et al. (2021), and it has only gotten better since.

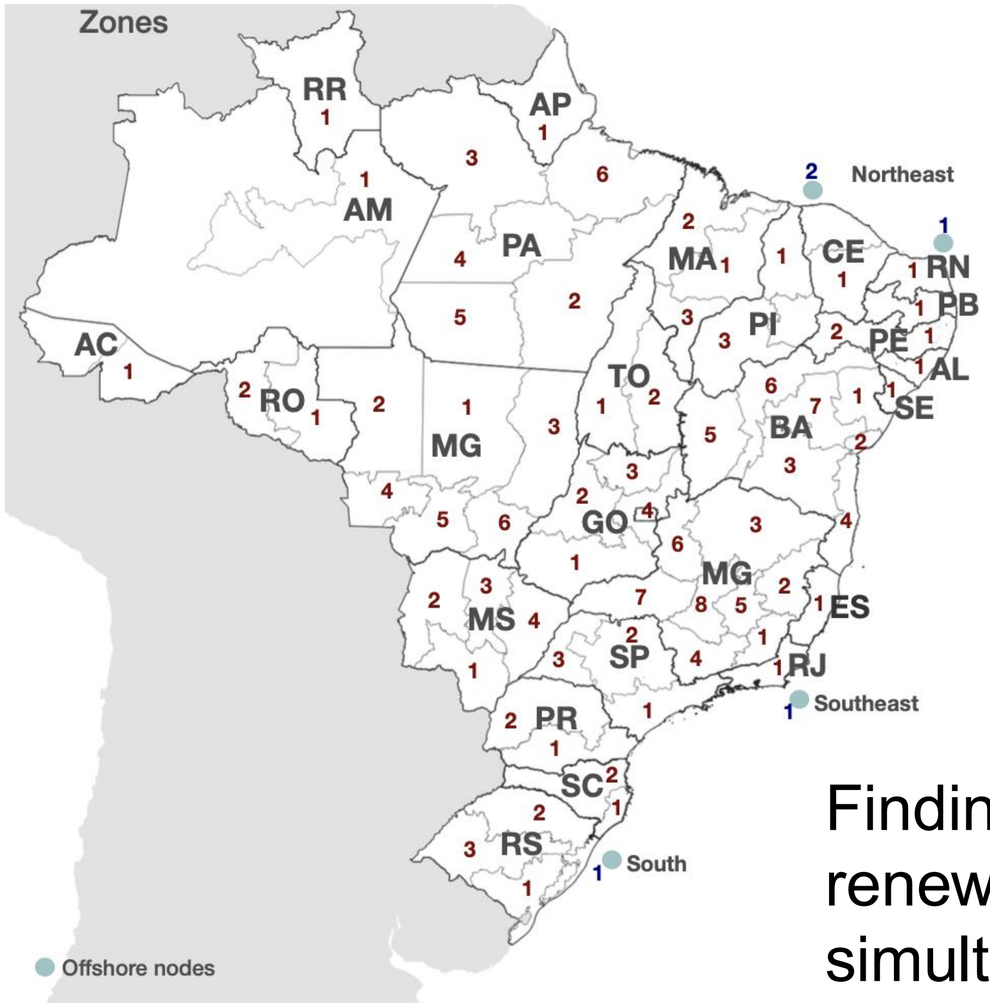
Over the last decade:
Many many examples —
too many to even list here!

Chang et al. (2021), https://doi.org/10.1016/j.apenergy.2021.116731

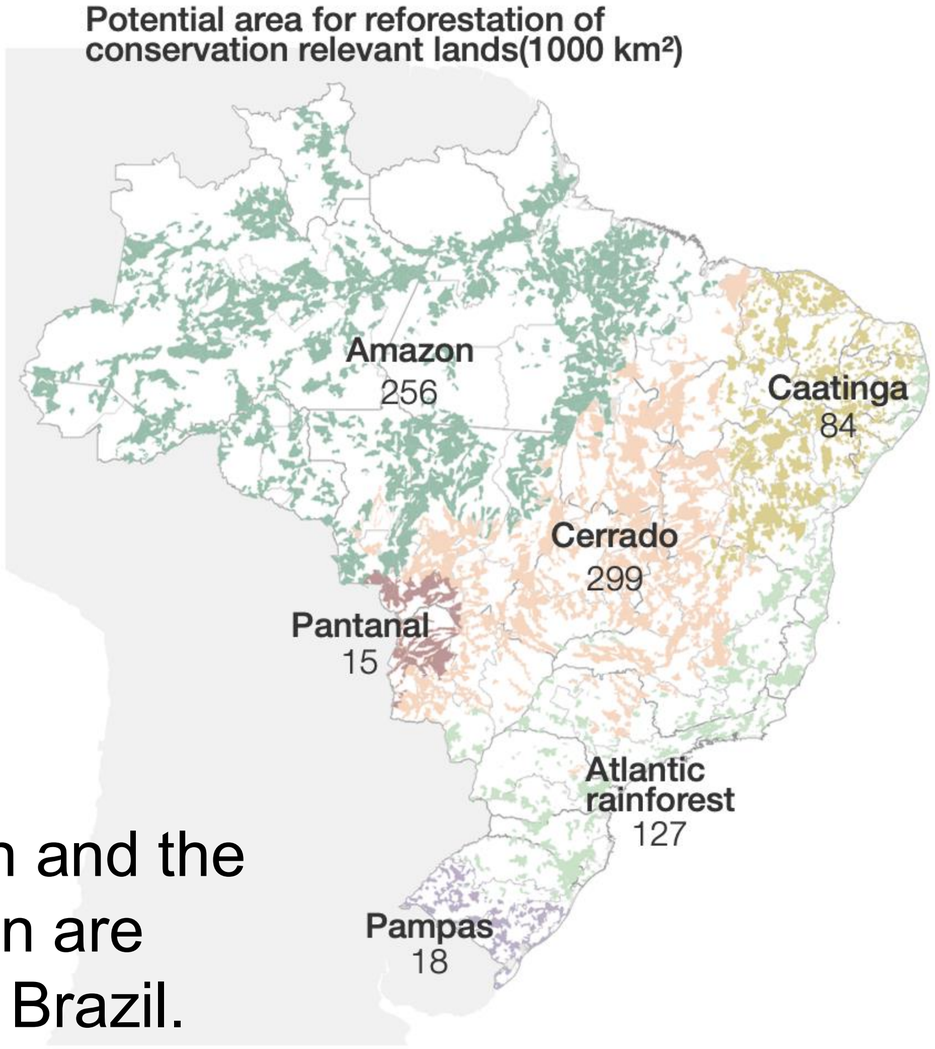
Resolution and complexity also beyond the energy system

Paula Borba

96-zone model of Brazil



Model land-use constrained renewable expansion.



Finding: Land conservation and the renewable energy transition are simultaneously possible in Brazil.

Borba et al. (accepted in *One Earth*), https://doi.org/10.21203/rs.3.rs-3888976/v1

Challenges for energy system modelling (as of 2014)

Resolution

Complexity

Transparency

Social factors

Pfenninger et al. (2014). https://doi.org/f526xf

1. Introduction

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5. Conclusion

Transparency

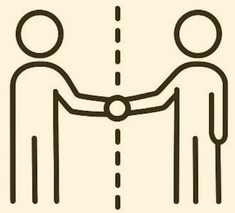
Four reasons for models to be open

(from Pfenninger et al., 2017)

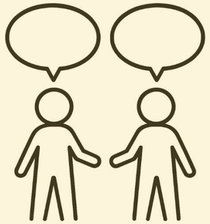
Improved quality of science

Increased productivity through collaborative burden sharing

Internal to research



More effective collaboration across the science-policy boundary



Profound relevance to societal debates

External to research

Transparency and understandability are at the core of all of these.

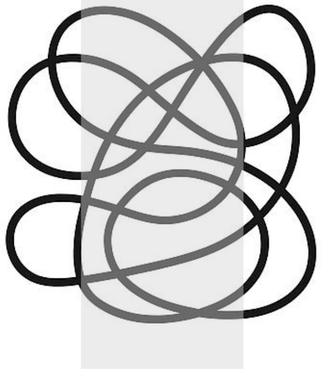
Pfenninger et al. (2017), https://doi.org/10.1016/j.enpol.2016.11.046

Transparency

Isn’t this a solved problem?

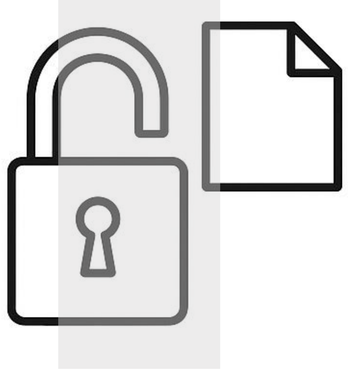
Perhaps not!

Increasing



Complexity and resolution

Increasing



Openness of code and data

Transparency and understandability

PhD candidates rate model usability as lower than senior researchers and often invest **large amounts of effort to get a full picture of the model**.

Scheller et al. (2021)

Chang et al. (2021), https://doi.org/10.1016/j.apenergy.2021.116731
Scheller et al. (2021), https://doi.org/10.1016/j.segy.2021.100057

Social factors

Should social factors be in models?

“[…] the final task is to represent the behaviour of the [social] groups within a model”

Keyser quoted in Meadows et al. (1982)

“We conclude that users want better models regarding the representation of environmental and social factors”

Süsser et al. (2022)

Why do these calls persist over the decades?

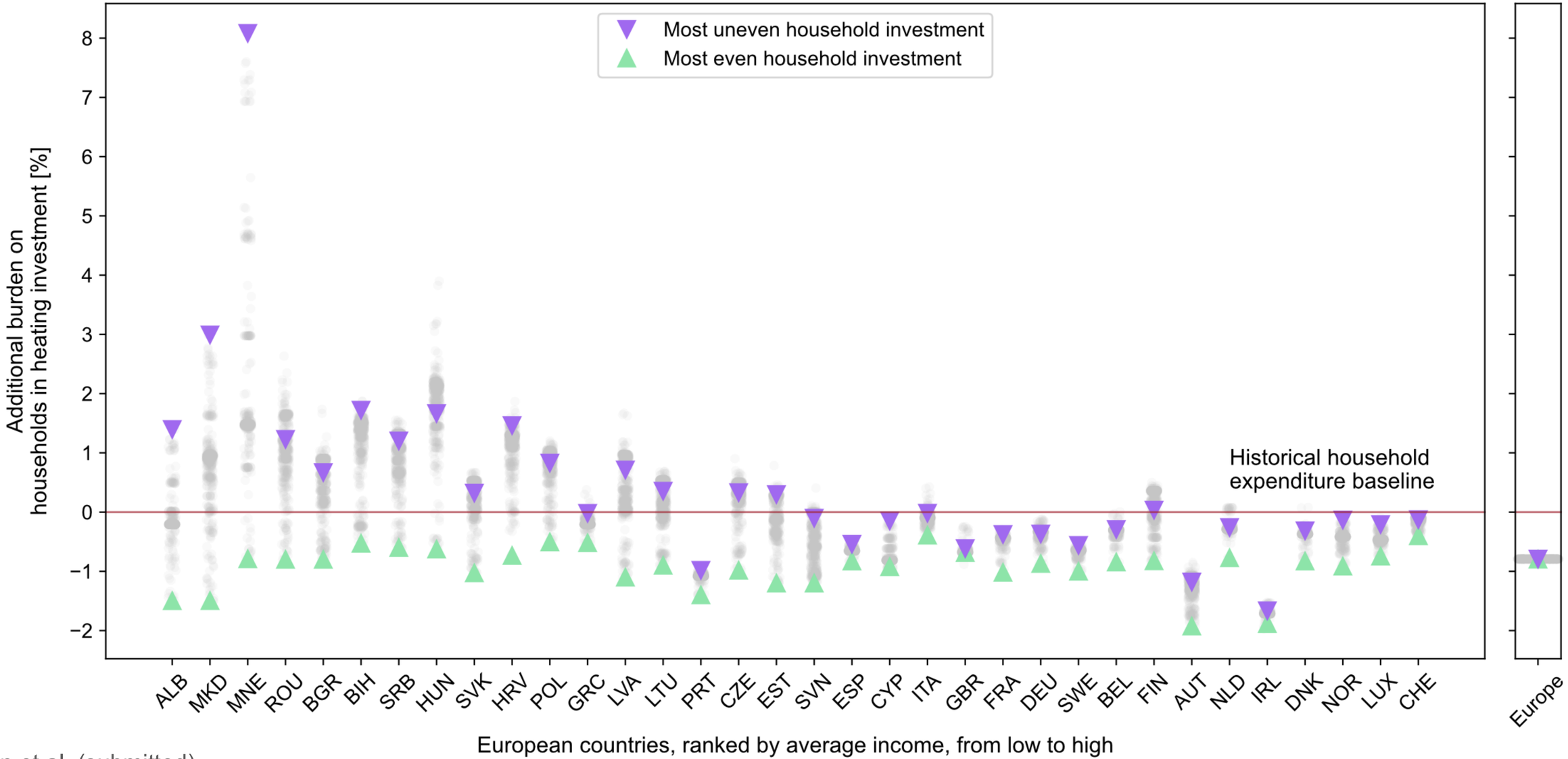
- Progress is being made, but not quickly enough?
- “Social factors” do not suit model paradigms like optimisation?
- …?

Süsser et al. (2022), https://doi.org/10.1016/j.erss.2022.102775
Meadows et al. (1982), http://archive.org/details/gropingindarkfir0000mead

Social factors

An example of adding social considerations to a cost-minimising model

Meijun Chen



Chen et al. (submitted)

Transparency + social factors: summary so far

Transparency

- More open source and open data
- More complexity and higher resolution
- Transparency and understandability of models: still a challenge

Social factors

- Calls to include them since decades
- Solutions are possible but can be unsatisfactory
- Likely many reasons, including mismatch of optimisation modelling paradigm with “integrating social factors”?

1. Introduction

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What to do? Reminder:

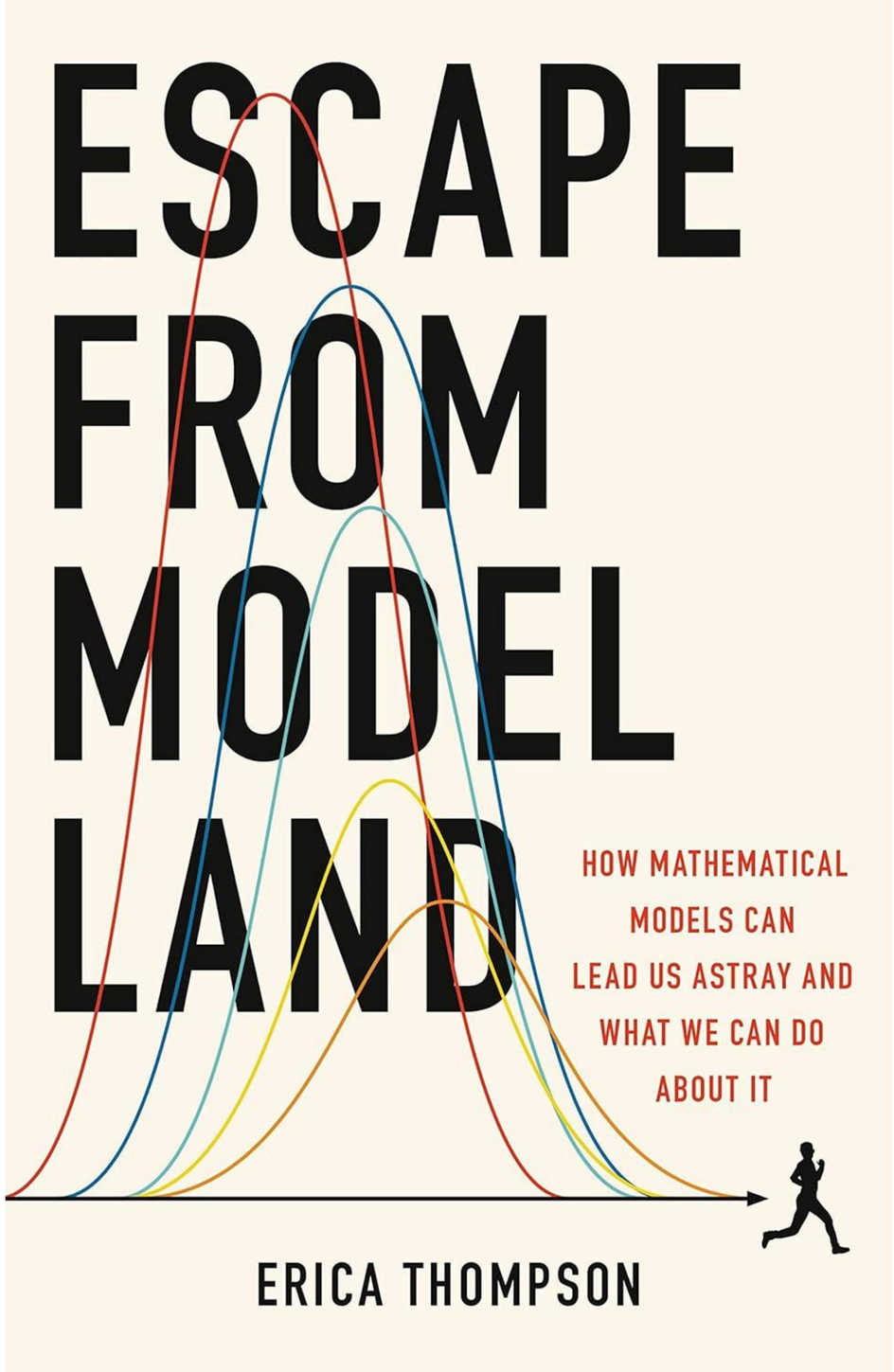
Social factors

Transparency

Can we address both of these simultaneously?

Social factors

The social nature of models



Thompson (2022)

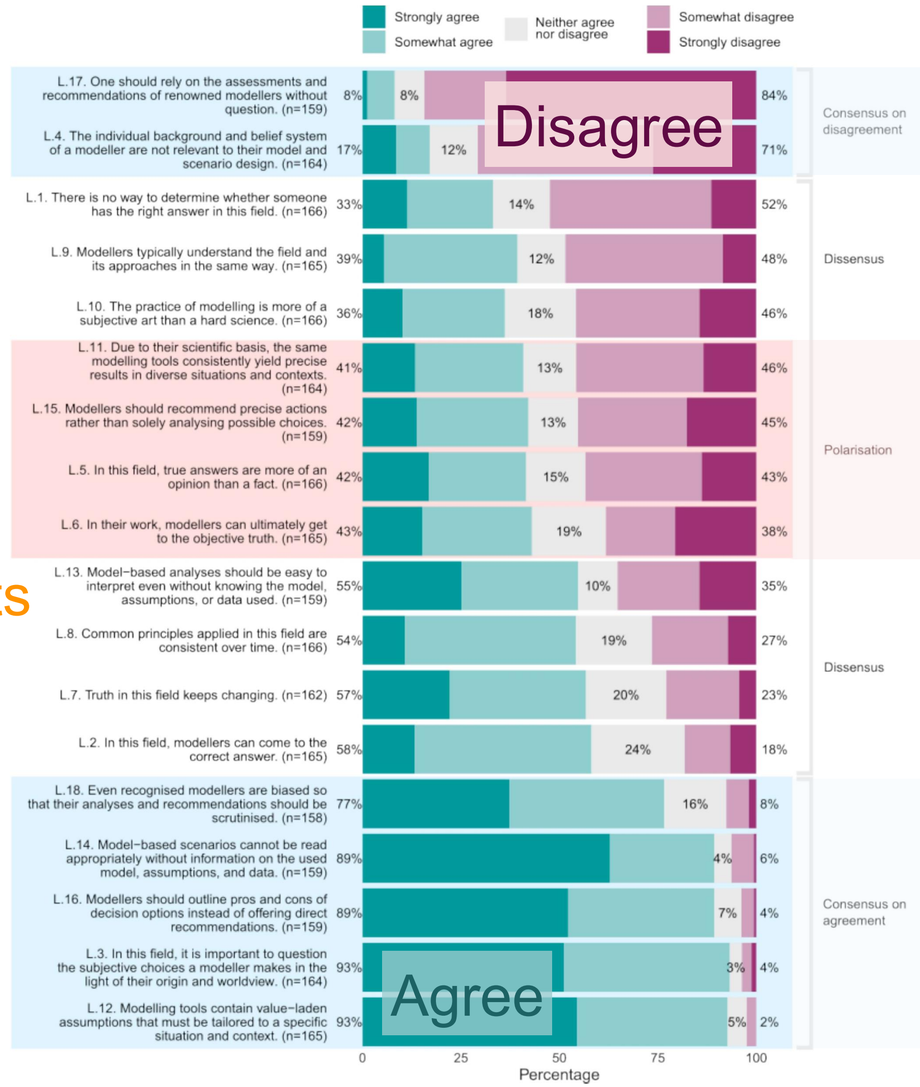
Social factors

What do modellers think?

A survey of 166 energy system modellers

Franziska Bock

18 statements



Consensus (most disagree with statement)

Polarisation

e.g. statement 6: “In their work, modellers can ultimately get to the objective truth.”

Consensus (most agree with statement)

e.g. 18: “Even recognised modellers are biased so that their analyses and recommendations should be scrutinised.”

Bock and Pfenninger-Lee (2025), https://doi.org/10.1016/j.erss.2025.104229

Funding: RE INTEGRATE THINKING INTEGRATED ENERGY STRATEGIES

Social factors

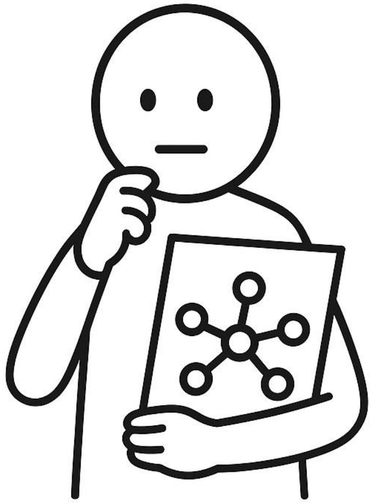
Social science about modellers and modelling

Positivist modeller

Agreement: model-based scenarios cannot be interpreted responsibly without knowledge of the model, assumptions, and data.

Social factors

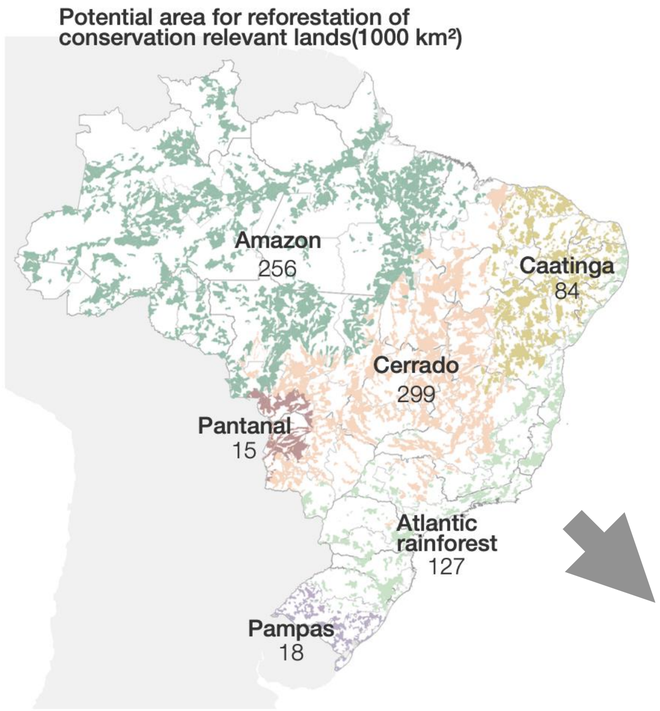
Transparency



Post-positivist modeller

Transparency

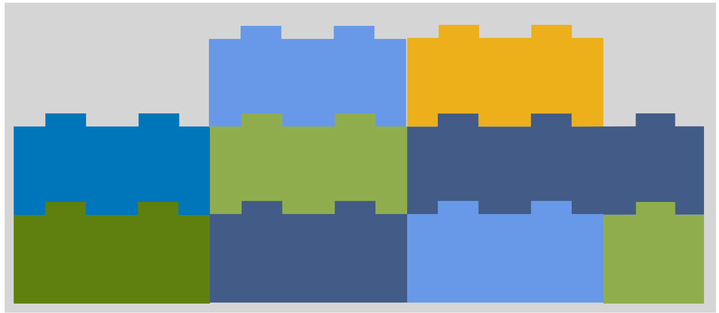
What is inside a model?



Model result

The model

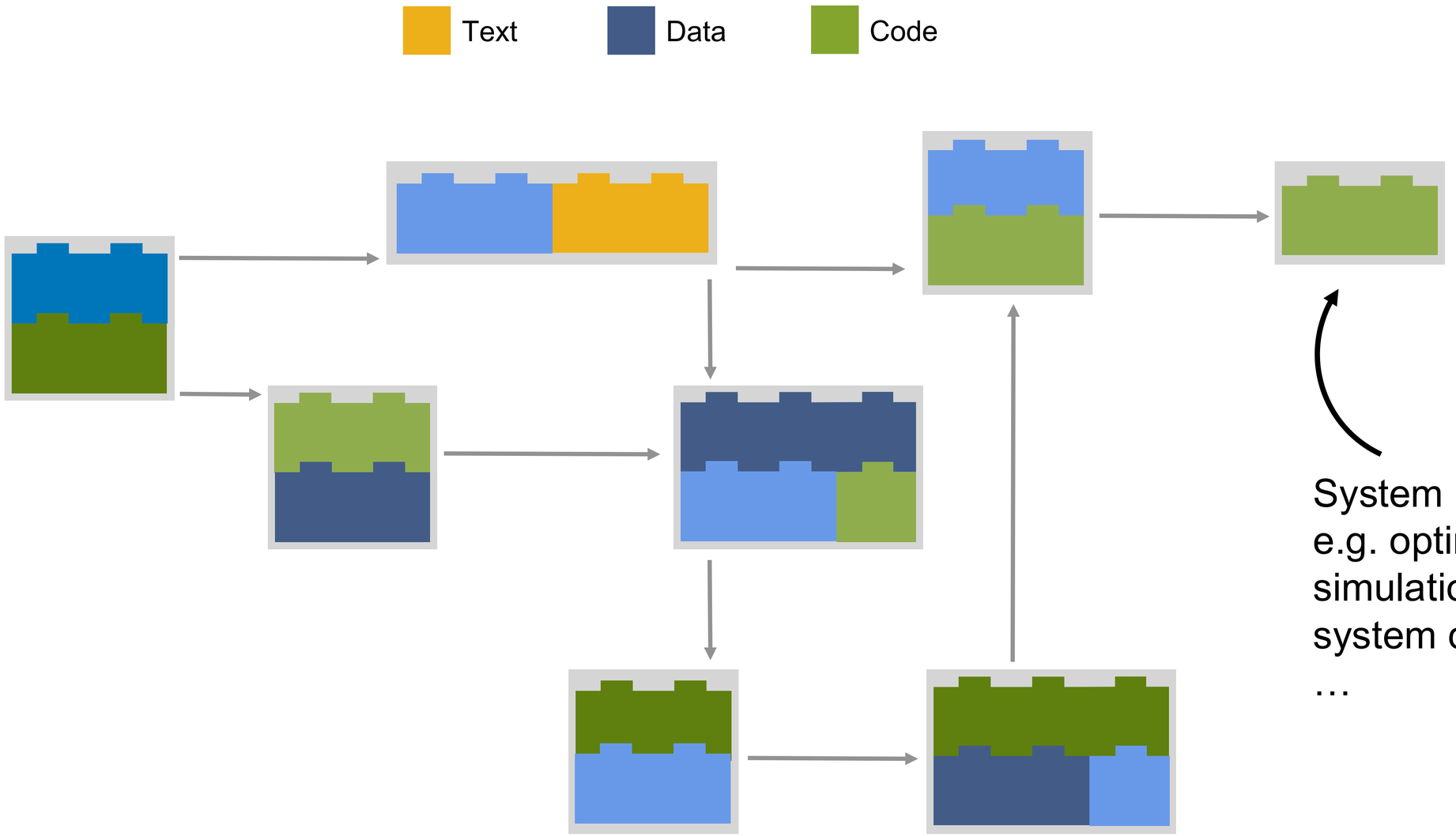
The model is made up of text, data and code



Pfenninger (2024), https://doi.org/10.1088/2516-1083/ad371e

Transparency

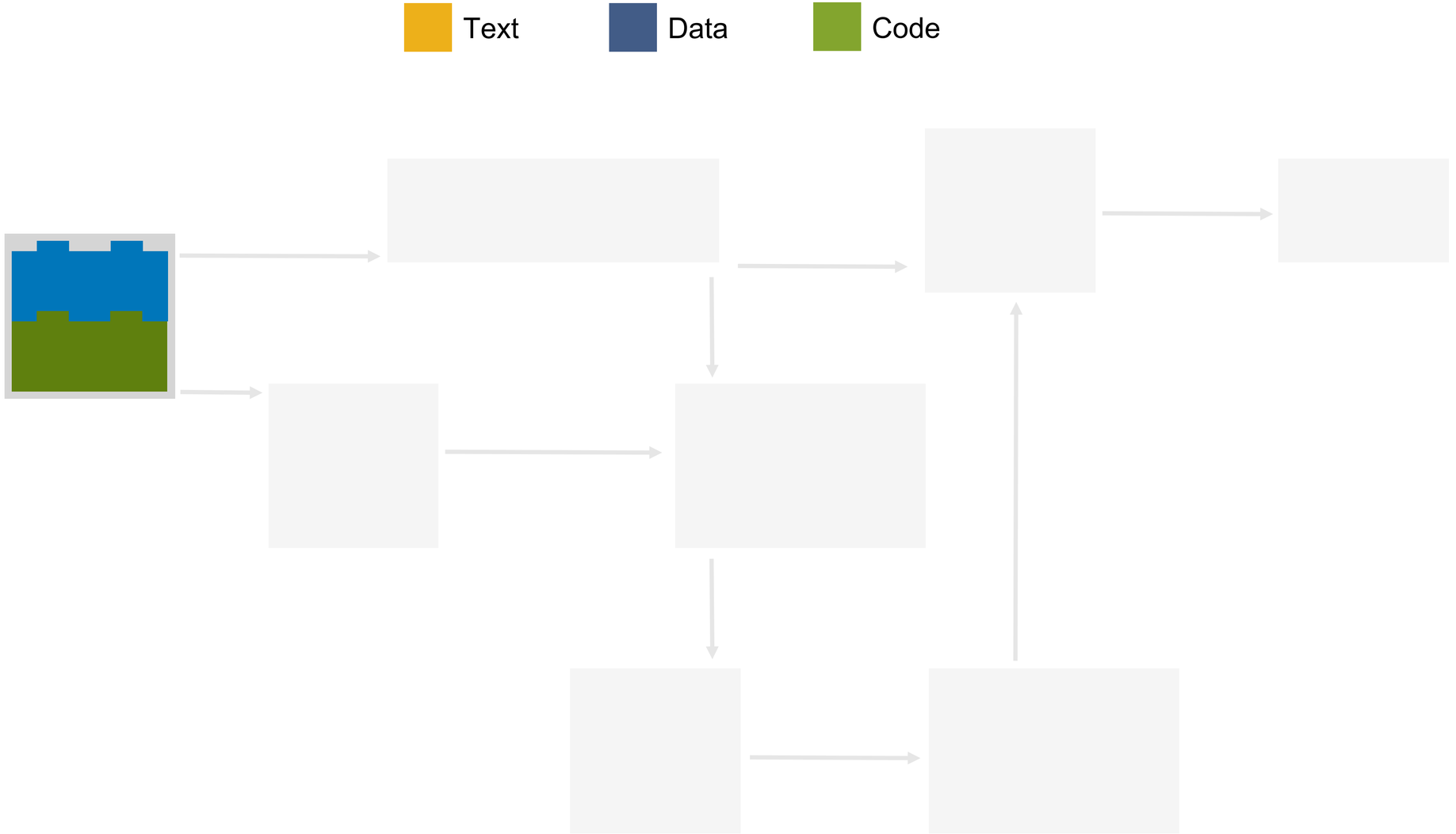
Separation into understandable building blocks



Transparency

Example: land availability

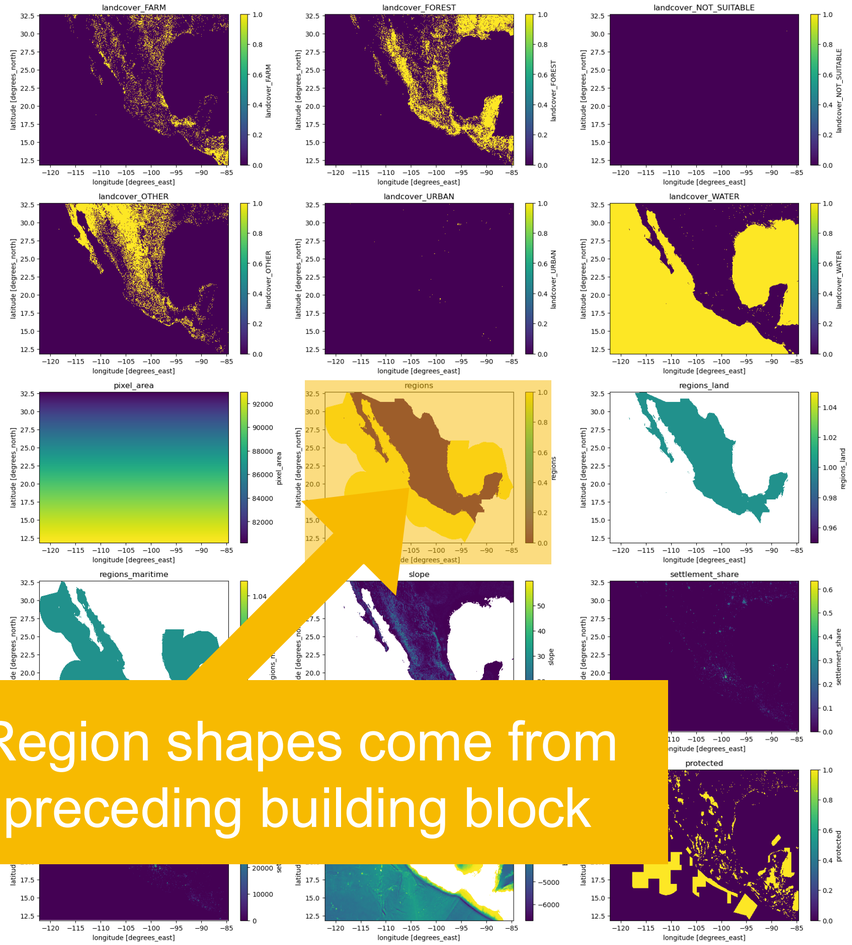
Box:
land availability
for energy system
infrastructure



Transparency

Example: land availability

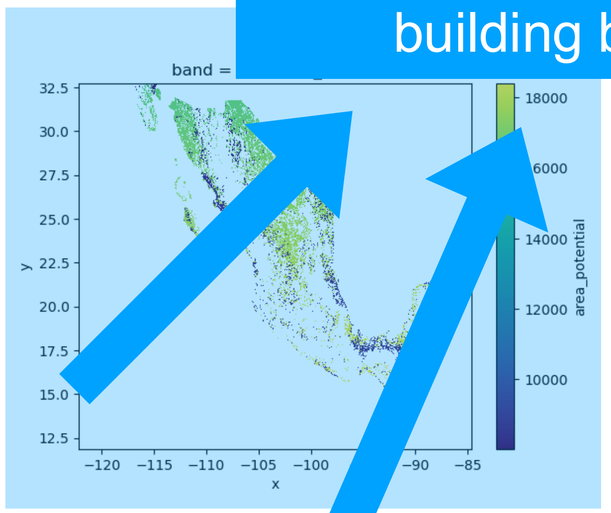
Available areas are passed to a subsequent building block



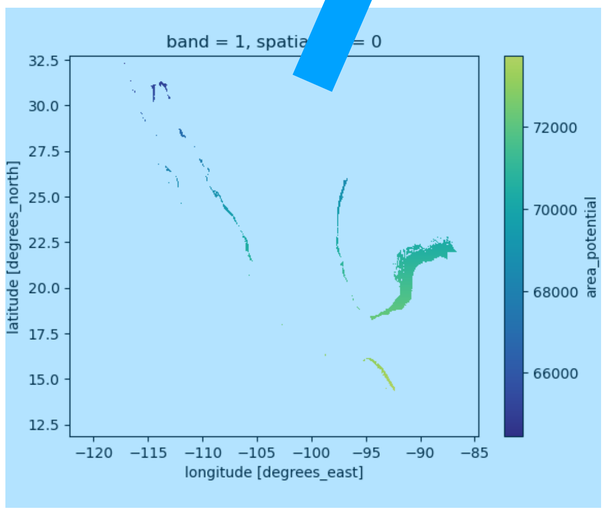
Region shapes come from preceding building block

Configuration

```
pv_open_field:
  initial_area: pixel_area
  continuous_layers:
    slope:
      min: 0
      max: 3
    settlement_share:
      min: 0
      max: 0.01
  binary_layers:
    ...
```



Open-field PV areas



Offshore wind areas

Inputs

Code

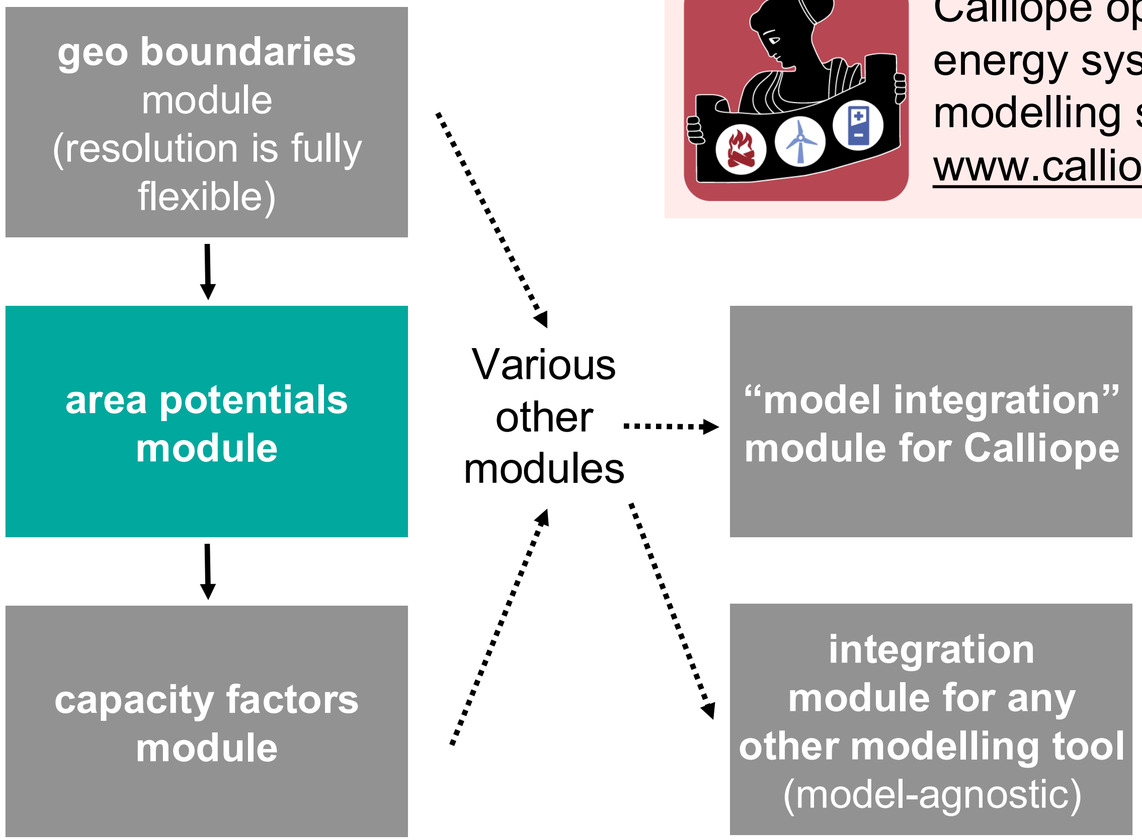
Outputs

Transparency

Clio: a modular “model generator”

Ivan Ruiz Manuel Jann Launer

Calliope open-source energy system modelling software
www.callio.pe



Our aims:

- Run globally, not just Europe
- Understandable and transparent
- Re-use individual modules in different contexts
- Open up new research questions, collaboration with topic experts and wider public
- Shared, model-agnostic effort
- Fully free and open

Social factors (in making models)

⚠ Work in progress

Funding:

Transparency

Lesson learned from Renewables.ninja

Renewables.ninja
solar, wind, demand
and weather simulations
www.renewables.ninja

Collaboratively build more such “building blocks” for models!

1. Introduction

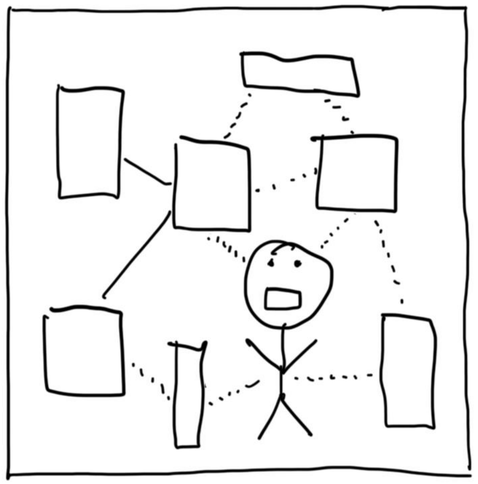
2. Progress: resolution + complexity

3. Gaps: transparency + social/political factors

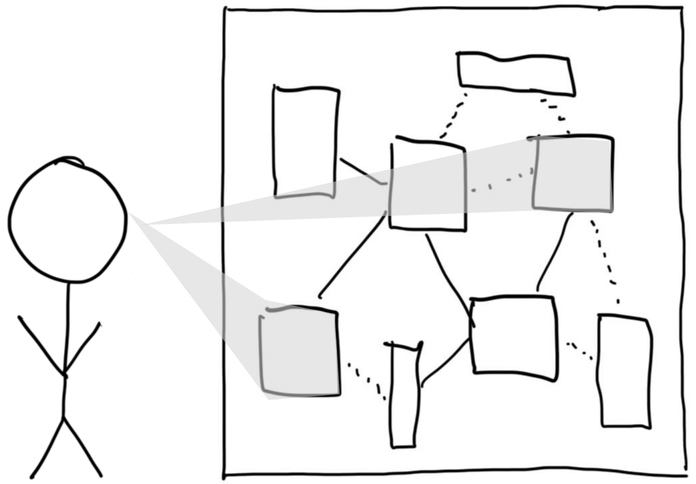
4. What to do?

5. Conclusion

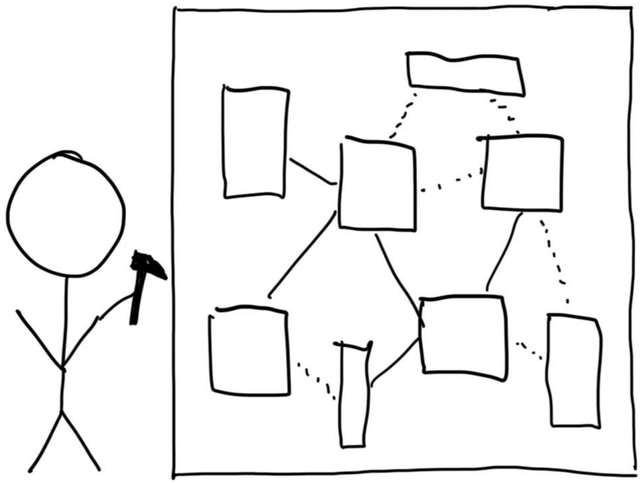
Conclusion



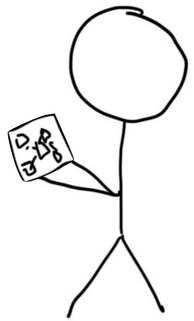
Putting people into models can work, but also consider…



…bringing models to people (in digestible pieces).



… better understanding what goes on inside model builders….



… and users.

Transparency

Social factors

Thanks for listening!

Models to people, not (just) people into models:

1. Let's acknowledge and explore the social dimension of modelling more.

2. Let's collaboratively build models out of smaller, more understandable components.

Get in touch!
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