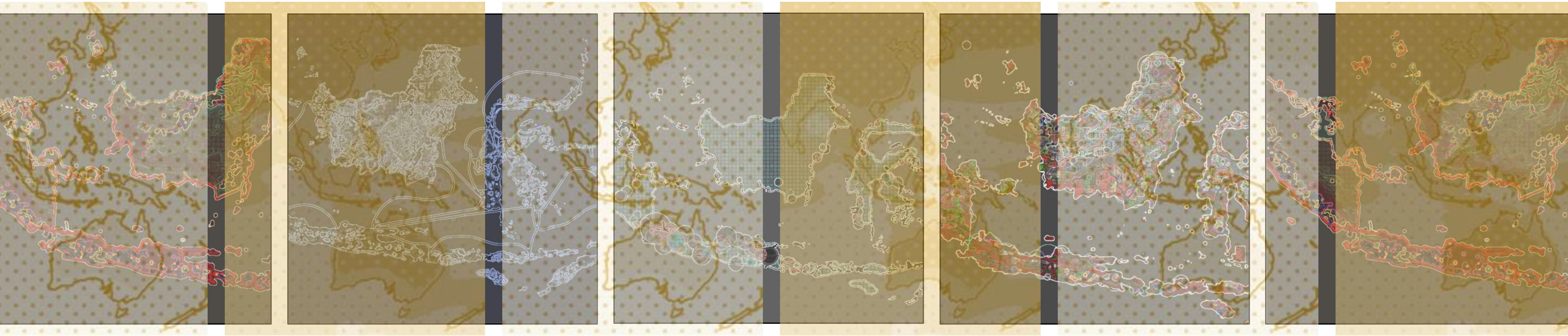

Energy system modelling for regional power sector deep decarbonisation—modelling aspects and challenges

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1. Background
2. Methodology
3. Key aspects to consider in developing a model to assess regional power sector deep-decarbonisation
4. Key challenges in high-resolution energy system modelling of regional complex electricity supply chain system
5. Conclusion

Introduction

- Deep decarbonisation of the power sector plays a key role in reducing total greenhouse gas (GHG) emissions dramatically to meet climate stabilisation goals.
- A common strategy is to avoid, reduce or remove carbon emissions from electricity generation and use low-carbon or carbon-free electricity to help decarbonise residual emissions from other hard-to-reduce sectors (transportation, building, industry).
- Charting a path towards power sector deep decarbonisation is a complex task, considering the wide-ranging portfolio of technological solutions and respective challenges.
- A 'good-fit' model is suitable for scenario analysis to help substantiate questions related to systems' capacity deployment and operation, as well as, to provide insights on how the system behave in given condition.

RQ

In assessing pathways of regional power sector's deep decarbonisation…

- What are the aspects of energy system modelling that need to be considered?
- What are the challenges in modelling the complex electricity supply chain?
- How to address these aspects and overcome challenges?

Key issues:

- Power sector's deep decarbonisation Protection and conservation vneed to integrate large-share of renewable energy sources (RES) and carbon capture, transport and storage (CCS) technologies.
- There are risks of over-/under-estimating potentials and impacts for not considering the spatial and temporal implications (access quality and costs) of the energy and CCS systems.
  - Most intermittent RES are located a far from demand centers and large-scale integration becomes challenging, due to its variability, uncertainty, and location-specificity.
  - Transportation of feedstock-fuels are influenced by the access quality and costs.
  - CO_2 source-sink matching.
- Protection and conservation values implication towards resource and infrastructure deployment.

Spatiotemporal implications of energy system and infrastructure deployment are critical in influencing the costs and configuration of expanding the electricity supply chain, especially in the case of connecting large untapped population and the integration of wide area RES and CCS technologies.

The aim of this review is to give a comprehensive overview and to discuss the key aspects and challenges of spatial-explicit energy system modelling for regional power sector deep-decarbonisation.

Publication	Focus
(Kriechbaum, Scheiber, and Kienberger 2018) “Grid-based multi-energy systems—modelling, assessment, open source modelling frameworks and challenges” (Mancarella 2014) “(multi-energy systems): An overview of concepts and evaluation models” (Lopes et al. 2016) “Modelling of integrated multi-energy systems: drivers, requirements, and opportunities”	**Grid-based multi-energy system concepts and modelling**
(Nunes, Causer, and Ciolkosz 2020) “Biomass for energy: A review on supply chain management models”	**Biomass supply chain model**
(Krishnan et al. 2016) “Co-optimization of electricity transmission and generation resources for planning and policy analysis: review of concepts and modeling approaches” (Syranidis, Robinius, and Stolten 2018) “Control techniques and the modeling of electrical power flow across transmission networks” (Samsatli and Samsatli 2015) “A general spatio-temporal model of energy systems with a detailed account of transport and storage”	**Generation and transmission co-optimisation model**
(Kuby, Bielicki, and Middleton 2011) “Optimal Spatial Deployment of CO_2 Capture and Storage Given a Price on Carbon” (Middleton and Bielicki 2009) “A scalable infrastructure model for carbon capture and storage: SimCCS”	**Carbon capture, (transport) and storage (CCS) infrastructure model**
(Kling et al. 2017) “Integrated Assessment Models of the Food, Energy, and Water Nexus: A Review and an Outline of Research Needs” (Grace C. Wu 2020) “Spatial Planning of Low-Carbon Transitions”	**Integrated assessment of energy system externalities**
(Wiese et al. 2018) “A qualitative evaluation approach for energy system modelling frameworks”	**Evaluation of energy system modelling frameworks**

Deep decarbonisation of power sector is achievable through deployment and operation of low-, zero-, negative-carbon electricity supply technologies.

Power sector capacity planning aims to secure adequate, reliable, and cost-effective electricity supplies to the region

Scope: Long-term capacity (investment) planning with considering the short-term dynamics related to operating activities.

Spatial coverage: At least a region (country or multiple neighbouring countries) that comprises of sub-regions interconnected with transport corridors.

Time-horizon: In the context of deep decarbonisation, the time-horizon must cover up to the end of 21st century in line with the targets of the Paris Agreement. This include the net-zero target by early second-half of the century. In general, long-term capacity investment planning ranges about 30-50 years.

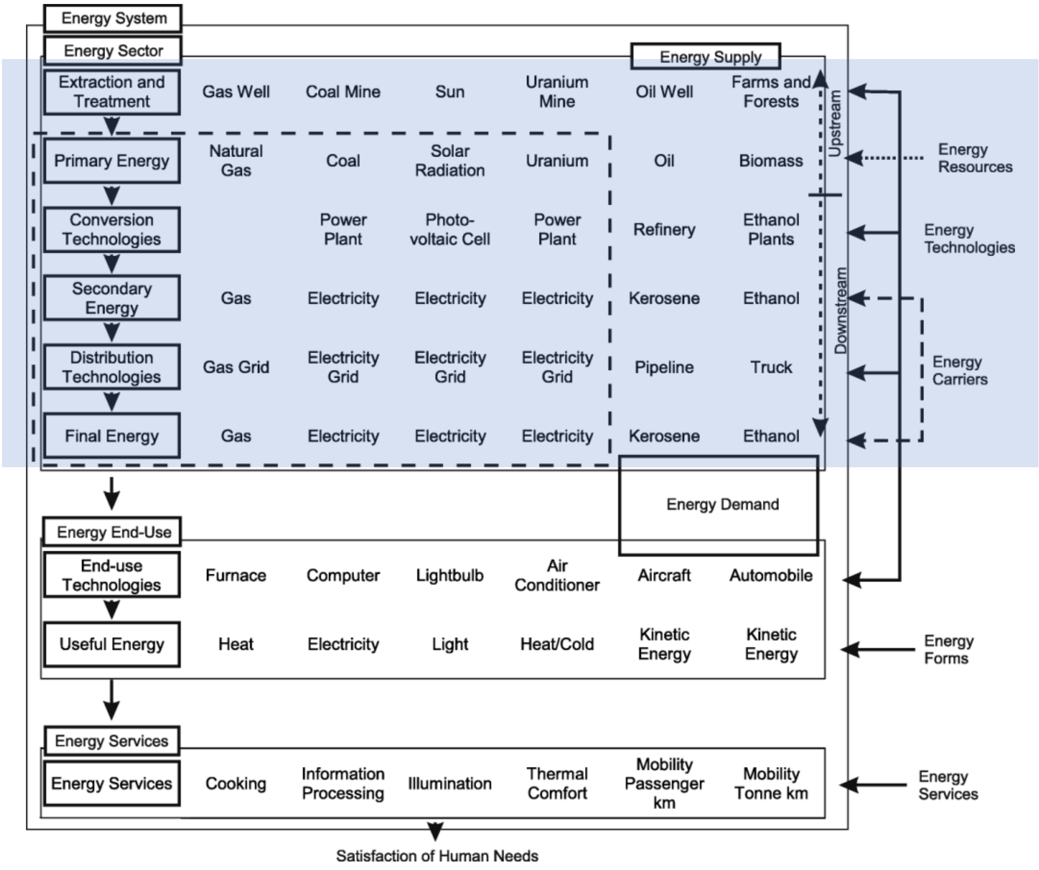
Investment
(size-sitting and feasibility)

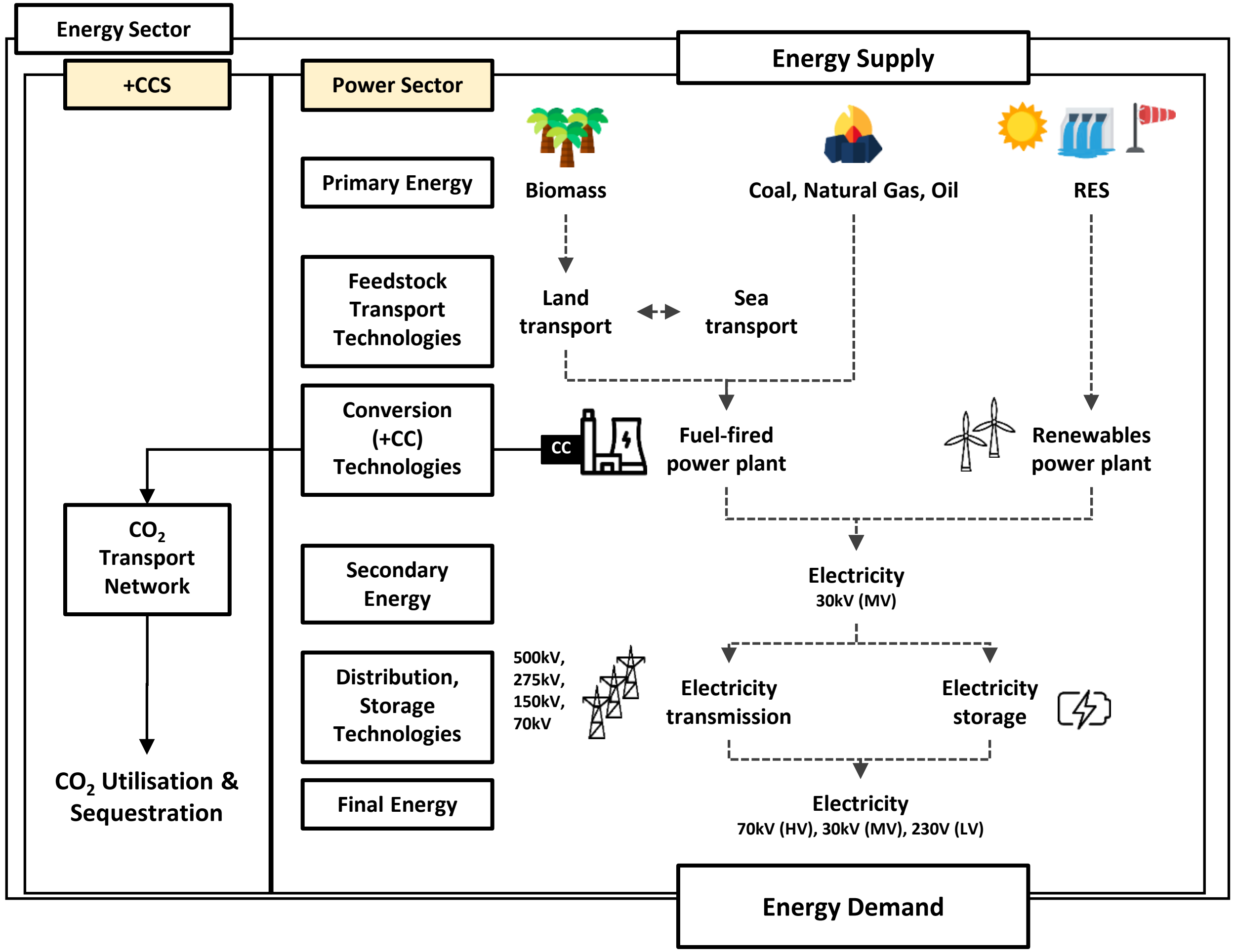
how much, when, where, and what type of electricity generation, storage, distribution, and CCS technologies to deploy?

Operation
(adequacy and reliability)

how much, when, where, of electricity energy to produce, store or distribute?
(+) … of feedstock and transport for power generation?
(+) … of power generating CO_2 emissions to capture, transport, and inject?

The system boundaries must be carefully defined in order to comprehensively assess the power sector and various deep decarbonisation strategies (low-, zero-, negative-carbon technologies)

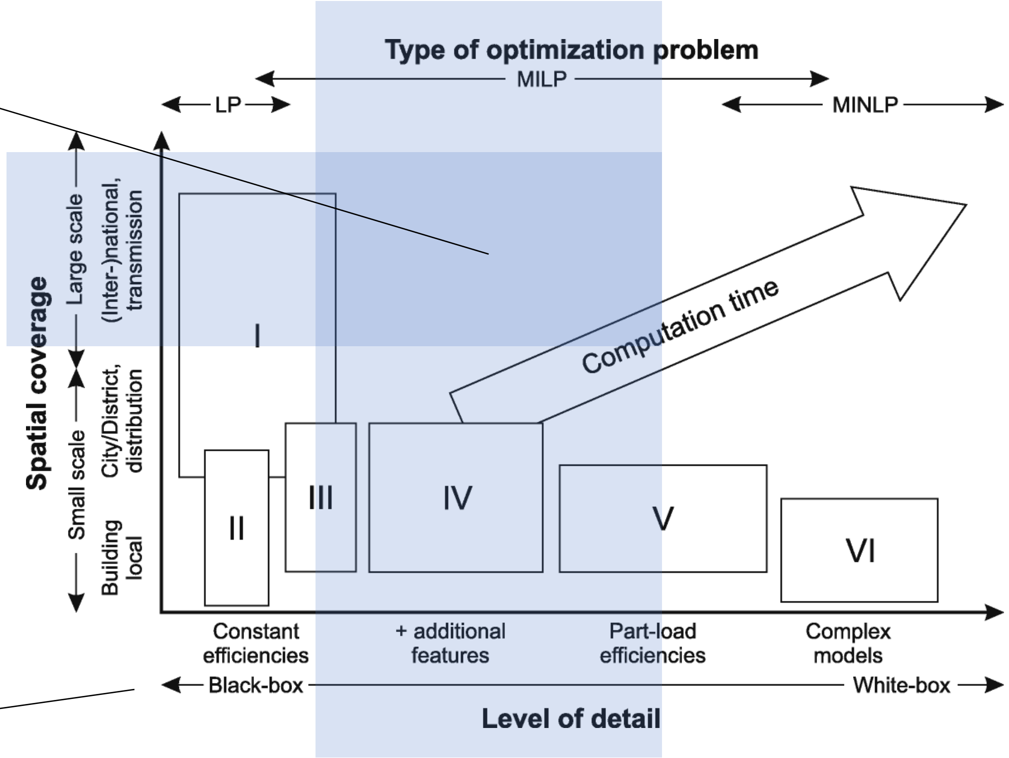




Adapted from:
Global Energy Assessment (GEA). (2012). Cambridge University Press; International Institute for Applied Systems Analysis
Kriechbaum, L., Scheiber, G. & Kienberger, T. Grid-based multi-energy systems—modelling, assessment, open-source modelling frameworks and challenges. *Energy, Sustainability and Society* **8**, 35–35 (2018).

Representation of the physical flows of energy along the electricity supply chain can be described in the modelled system constraints with different levels of detail.

Regional Electricity Supply Chain



Black-box

highly aggregated, databased input-output models without representation of the underlying physical principles

Grey-box

Simplified physical representations

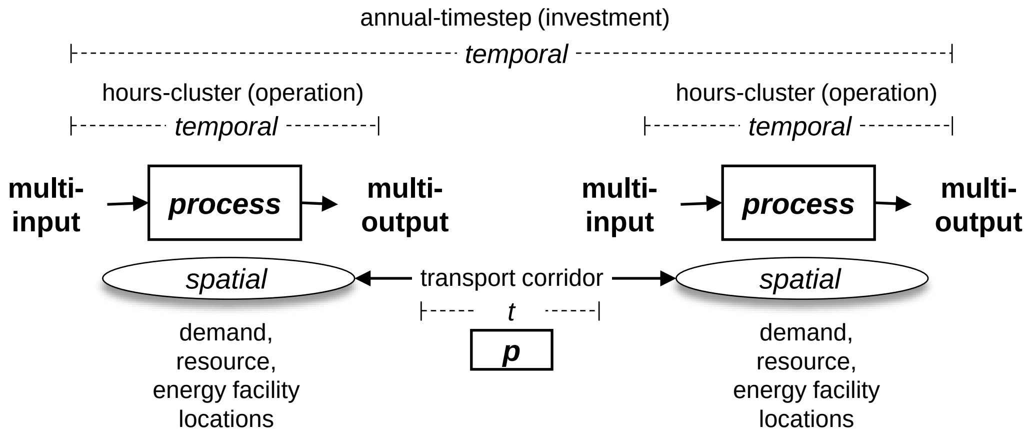
White-box

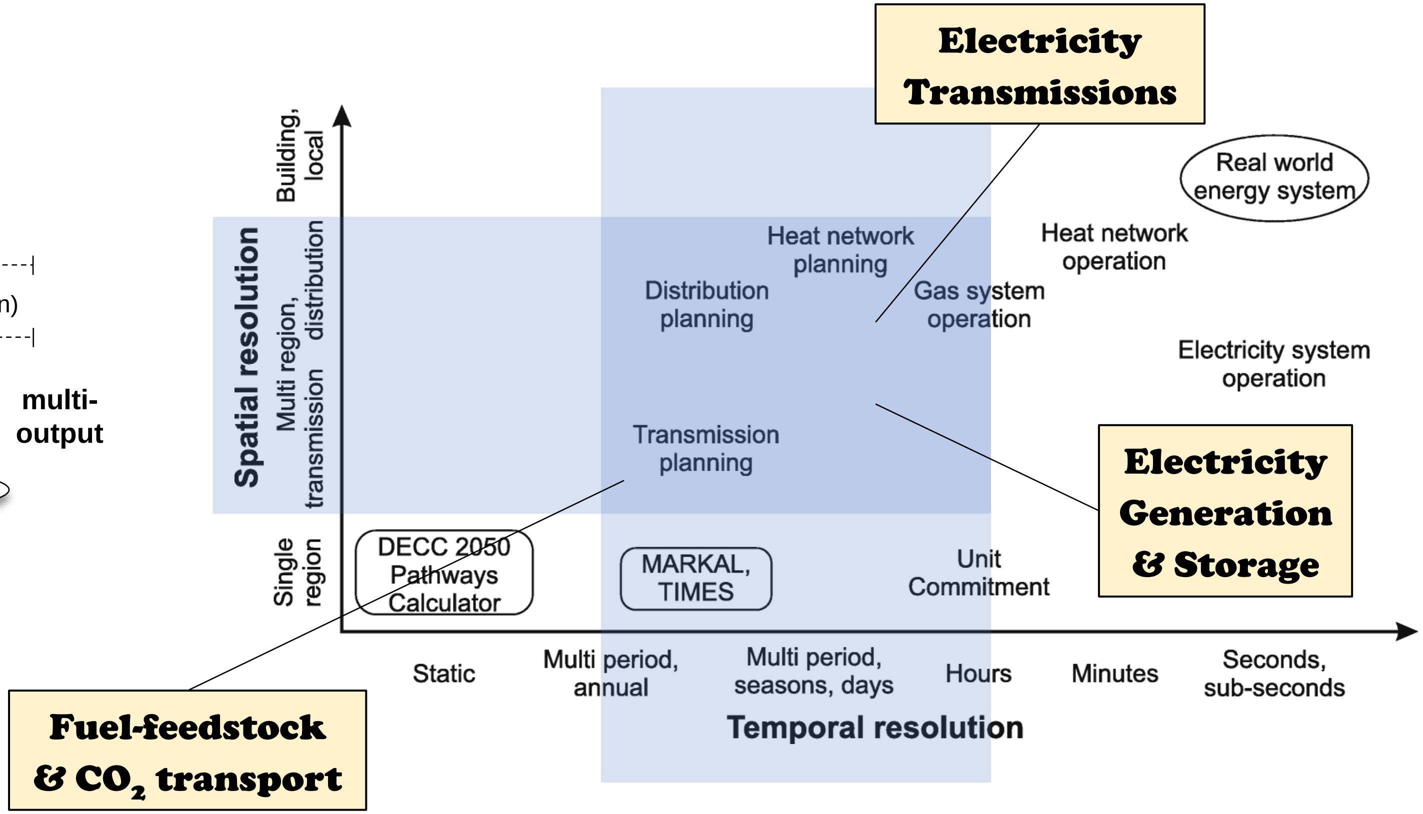
based on physical principles to calculate load flows and conversion efficiencies

Adapted from:
Kriechbaum, L., Scheiber, G. & Kienberger, T. Grid-based multi-energy systems—modelling, assessment, open source modelling frameworks and challenges. *Energy, Sustainability and Society* **8**, 35–35 (2018).

Energy is not always supplied where and when it is required.→ This imbalance may be compensated by transmissions-grid (spatially) or held by storage to be discharged at a later time (temporally).

Fuel-feedstock and CO_2 source-sink matching also requires detailed spatial analysis for cost-effective transport of resources (energy & CO_2) → influencing the total electricity supply costs.





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Approach to problem

Simulation
| Descriptive |
forecasts how the energy system might evolve.

Optimisation
| Normative |
to provide scenarios of how the energy system could evolve.
- LP
- MILP
- MINLP
- DP

Back-casting
| Reverse-Normative |
to provide scenarios of how the energy system should evolve, given a future state.

Partial-equilibrium
Assessment of policy and technology intervention through the analysis of changes in behaviour of supply, demand, and prices in a whole economy with several or many interacting markets. The interaction of demand and supply will result in an overall general equilibrium.

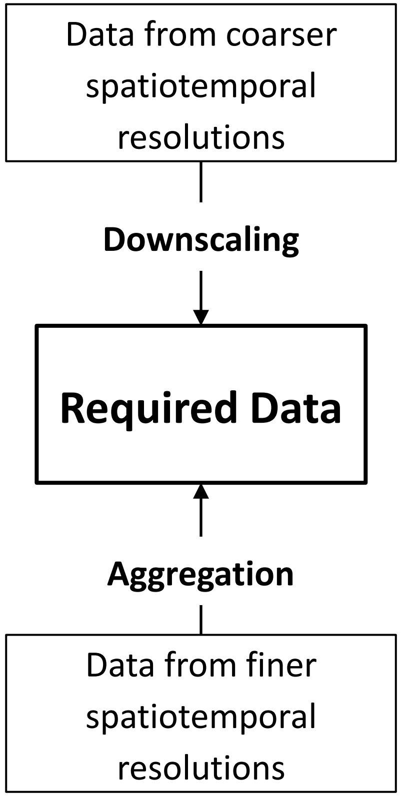
Agent-based
A system is modelled as a collection of autonomous decision-making entities (agents) that individually assesses its own situation and makes decisions based on a set of rules.

Addressing uncertainty

Deterministic
Uses best-estimates for input parameters and not consider the probability distribution, thus model results are straight-forward deterministic.

Stochastic (Probabilistic)
Estimates probability distribution of potential outcomes by allowing random variation in one or more inputs over time.

Finer spatial and temporal resolutions of the model requires appropriate values of both the parameters and independent variables. This vast amount of data required is often not available because it is either not measured, commercially confidential, relates to the future, highly uncertain, or in bad quality. Or is available <u>in different spatiotemporal resolutions</u>.



Choosing the appropriate assessment criterion and indicators are critical to evaluate the power sector development pathways and related deep decarbonisation strategies.

Technical
- Energetic
- Exergetic
- Reliability

Techno-economic
- Costs
- Investment
- Learning rates

Socio-technic
- Acceptability
- Impacts
- Co-benefits

Resource
- Use
- Availability

Environment
- Impacts
- Limits

Climate Change Mitigation (UNFCCC 2015) and Sustainable Development Goals (SDGs) (IAEG-SDGs 2017) provide the integrating framework for assessing the feasibility of energy technology options with considering the integrated multi-dimension of interactions between technology, resources, society, and environment.

These complex interactions influence the extent of energy technology options to be considered as affordable, secure, accessible, acceptable, and sustainable.

Adapted from:
Kriechbaum, L., Scheiber, G. & Kienberger, T. Grid-based multi-energy systems—modelling, assessment, open source modelling frameworks and challenges. *Energy, Sustainability and Society* **8**, 35–35 (2018).

Selection of spatiotemporal resolutions should consider the extremes where decisions may shift. For instance, to consider differences in distance that may significantly change transport routes, or differences in time that may significantly change the loads of supply-demand.

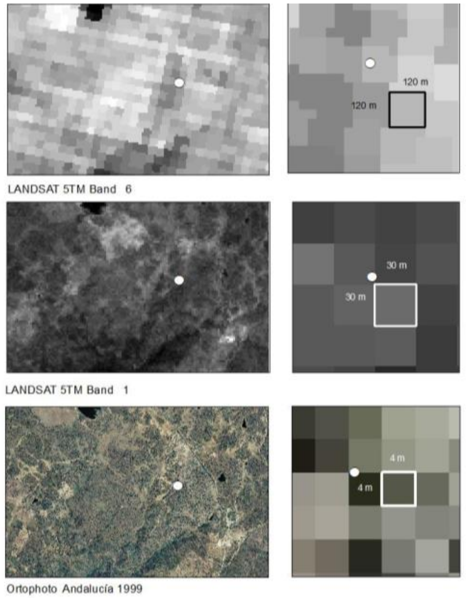
Challenges

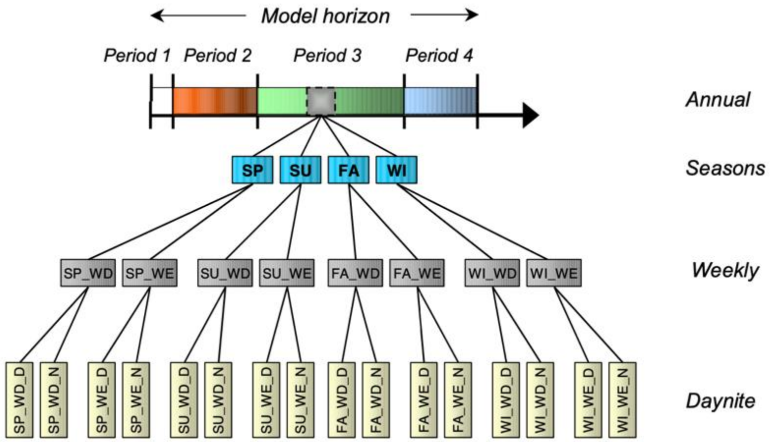
Models with a high degree detail and spatiotemporal resolutions may require too much computational effort to be solved in an acceptable timeframe.

Although a coarse resolution requires less computational effort, it can lead to inaccurate results. This is due its averaging character that may filter out the extreme points when designing the system.

Approach:

- **Spatial clustering of demand, resource, plant sitting locations and transport corridors (e.g. interconnected grid cells as simulation units sized around 10-100 km² of land area).**
- **Temporal clustering of similar-hours (periods) in sub-annual groups.**





Source:
https://www.researchgate.net/publication/260939273_Modelling_surface_energy_fluxes_over_a_dehesa_ecosystem_using_a_two-source_energy_balance_model_and_medium_resolution_satellite_data/figures?lo=1
https://iea-etsap.org/index.php/etsap-tools/model-generators/times

Appropriate assumptions and methodologies are critical in delivering comprehensive results, while minimizing the required computational resources.

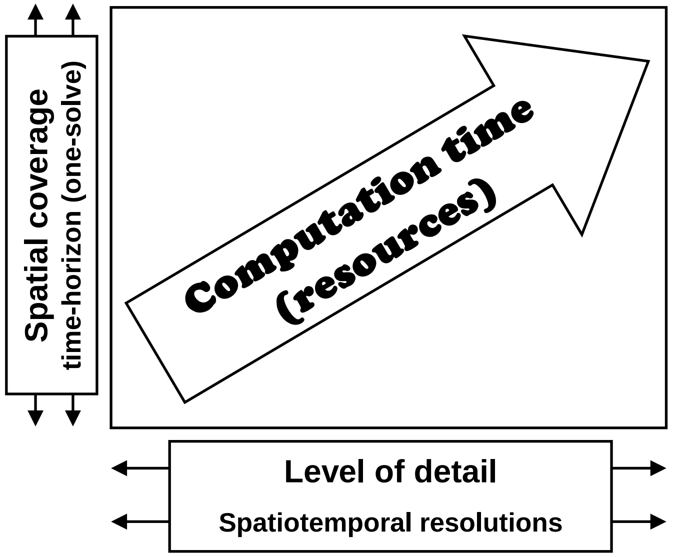
Scale
- **Geospatial coverage**
- **Time-horizon**
- **System boundaries**

Complexity
- **Level of detail**
- **Spatiotemporal resolutions**

Problem simplification
- Reducing scale and complexity
- Using simplistic assumption in describing complex interaction

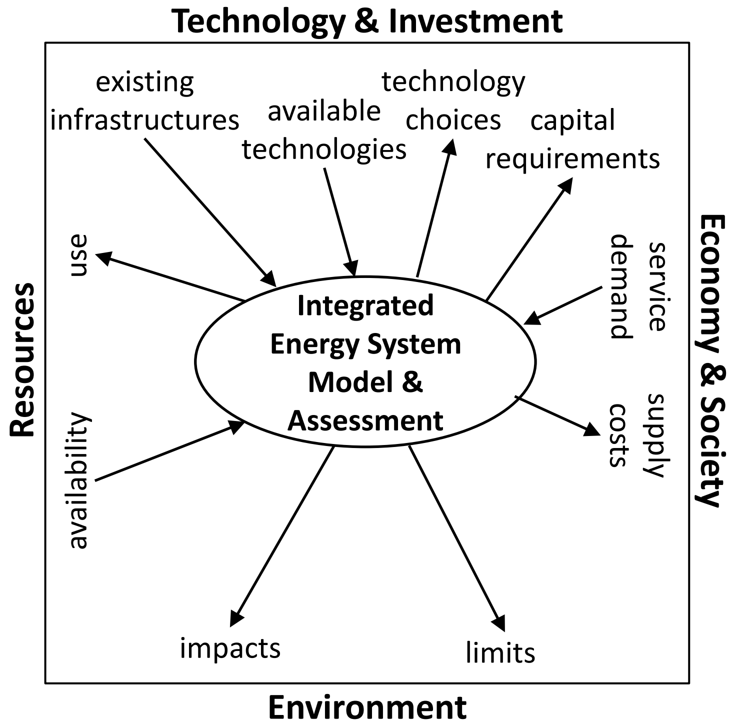
Problem decomposition
- Distributing problems into consecutive solve stages.
- This allows a forward-looking model to analyse the gradual changes impacted by choices made in the previous period

Tractability
| Easy to deal with |



Coupling or linking technology-rich bottom-up models and economy-wide top-down models can integrate large set of externalities to be considered without significantly increase computational effort.

	Politic	Socio-technic	Resources & environment
Country specific	Policy intervention (e.g., subsidies and tax credits) in alignment with non-climate goals and SDGs (e.g., reducing urban air pollution, increasing access to clean energy, jobs retention/creation, reducing fossil fuels imports).	**Cost-effective energy supply chain capacity expansion and operation** in fulfilling society's demand for energy.	**Resource use** (e.g., land, water stresses) and **system impacts on environmental services** (e.g., GHGs emissions and removals).
Dynamic	Increasing political returns to climate change mitigation (decarbonisation) and lowering political constraints over time.	Accelerating international technology diffusion and trade.	Carbon cycle and climate change impacts.



A multi-dimensional feasibility assessment of system deployment

Adapted from:
Kriechbaum, L., Scheiber, G. & Kienberger, T. Grid-based multi-energy systems—modelling, assessment, open source modelling frameworks and challenges. *Energy, Sustainability and Society* **8**, 35–35 (2018).

Data from coarser spatiotemporal resolutions

Downscaling

Required Data

probable / determined

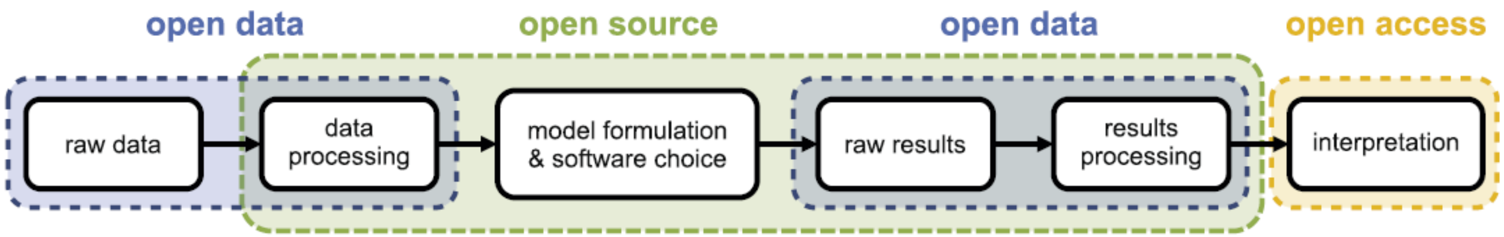
Aggregation

Data from finer spatiotemporal resolutions

Addressing Uncertainties

- ❑ probabilistic
- ❑ possibilistic
- ❑ interval programming
- ❑ robust optimisation

Improving Transparency & Reproducibility



Source (figure):
Kriechbaum, L., Scheiber, G. & Kienberger, T. Grid-based multi-energy systems—modelling, assessment, open source modelling frameworks and challenges. *Energy, Sustainability and Society* **8**, 35–35 (2018).

This paper provides an overview of the current research and challenges of modelling the energy system for power sector deep decarbonization. Key modelling aspects and challenges that need careful attention in model development of modelling grid-based energy carrier systems have been discussed.

Aspects

- Robust and efficient analysis of the power system in the context of deep decarbonisation.
- Incorporate the complex interaction between various energy carriers, processes, and networks. Focusing on electricity generation, storage, distribution systems and power flows.
- Long-term capacity planning model should account for securing supply system in the short run by incorporating operation and reliability constraints in finer level of detail and spatiotemporal resolutions.
- Model formulation and data need to be adjusted to best substantiate the problem in question.

Challenges

- Coupling of short-term operation model with long-term capacity planning model increases model complexity.
- Accounting for externalities will hamper model tractability.
- Soft-link bottom-up with top-down energy economics models can provide a more tractable integrated energy system model in assessing multi-dimension feasibility.
- Open data, open source, open access supports transparency, mass collaboration, and ultimately increase modelling impacts

Annex

Electrification options and challenges

Grid extension

Interconnected grid network with long range large transmission capacities.

1. Providing access to far-reaching RES (distant from demand centers).
2. Enabling the condition for large-scale power plants.
3. Expansion challenges

Mini-grid network

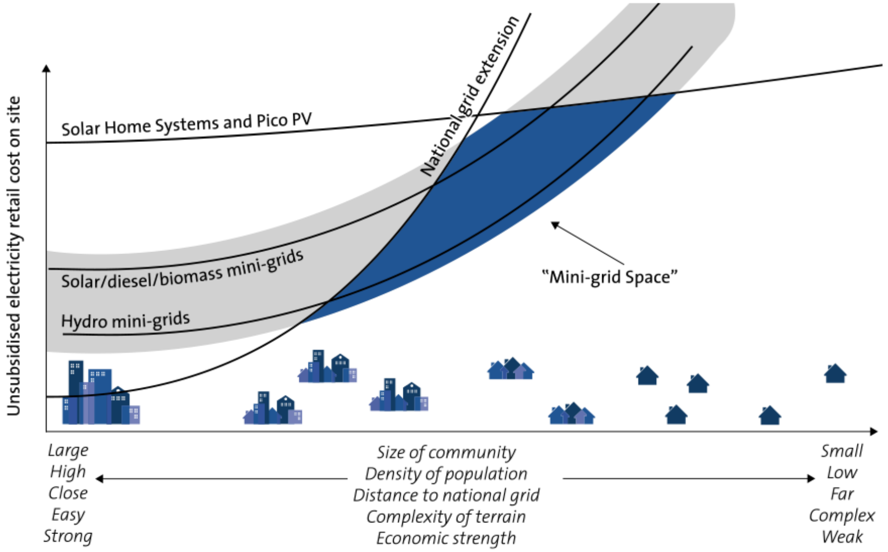
Distributed, isolated grid network of (mini) generation, storage, distribution systems.

1. Access to local RES
2. Community-sized generation (wind, PV, mini-hydro, biomass, biogas, diesel)
3. Feasibility compared to grid extension

Stand-alone system

Own generation and storage and not transmitted elsewhere.

"Last resort" due to no other access to cost-effective options for supplying electricity to the location.



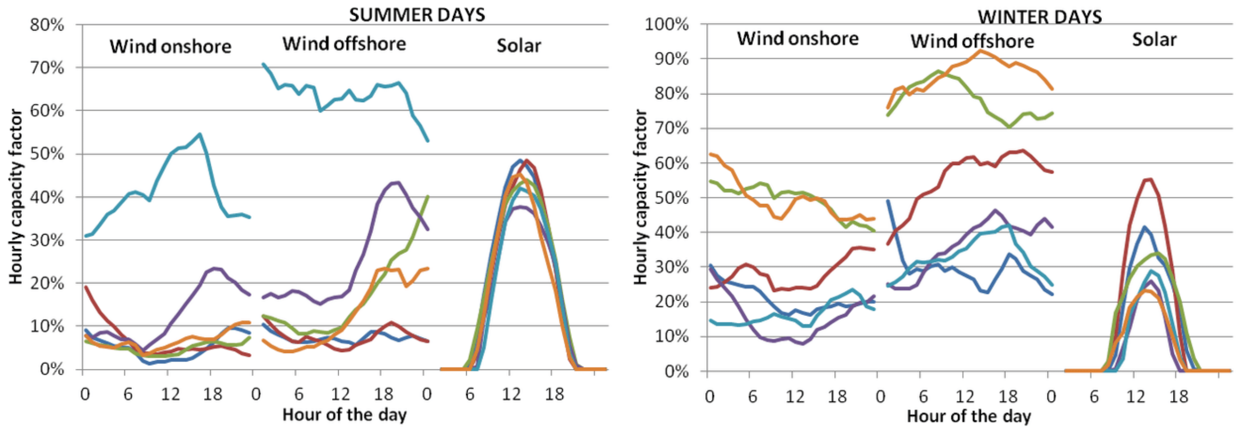
Source (figure):
EU Energy Initiative Partnership Dialogue Facility (2014).

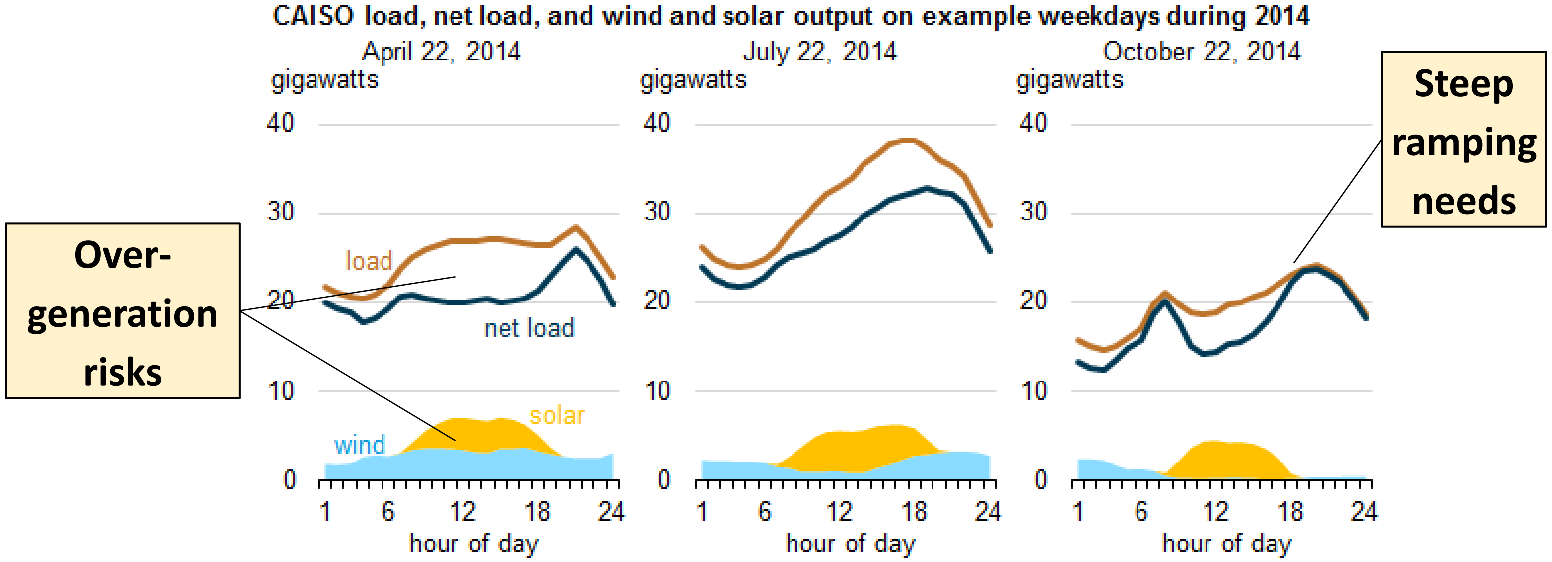
RES characteristics and integration challenges

Variability
(Profile Costs)

Intermittent RES and risks of inappropriate load-matching.

1. Under-generation risks: **Planning capacity reserves** are needed due to a low-capacity credit of RES.
2. Overgeneration risks: RES supply might exceed demand and is thus **overproduced.**
3. Curtailment risks: The full-load hours of capital-intensive dispatchable power plants decrease due to **ramp-up and -down** more often.





Reference:
Ueckerdt, F., Hirth, L., Luderer, G. & Edenhofer, O. System LCOE: What are the costs of variable renewables? 33.
CAISO. (2014). http://www.caiso.com/market/Pages/ReportsBulletins/RenewablesReporting.aspx

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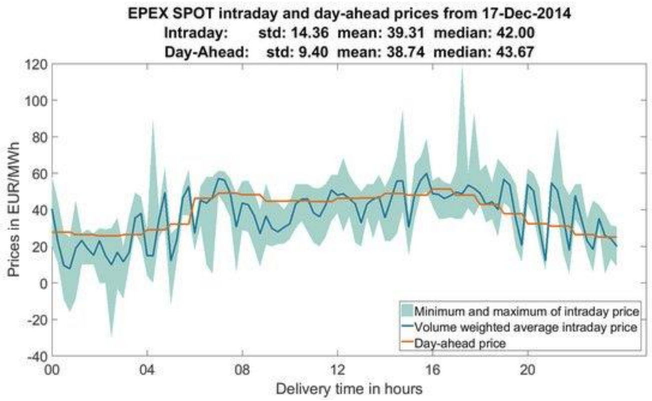
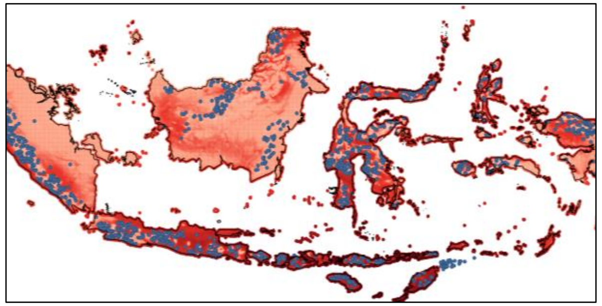
Uncertainty
(Balancing Costs)

Day-ahead forecast errors of renewable generation cause unplanned intra-day adjustments of dispatchable power plants and require **operating capacity reserves** that respond within minutes to seconds.



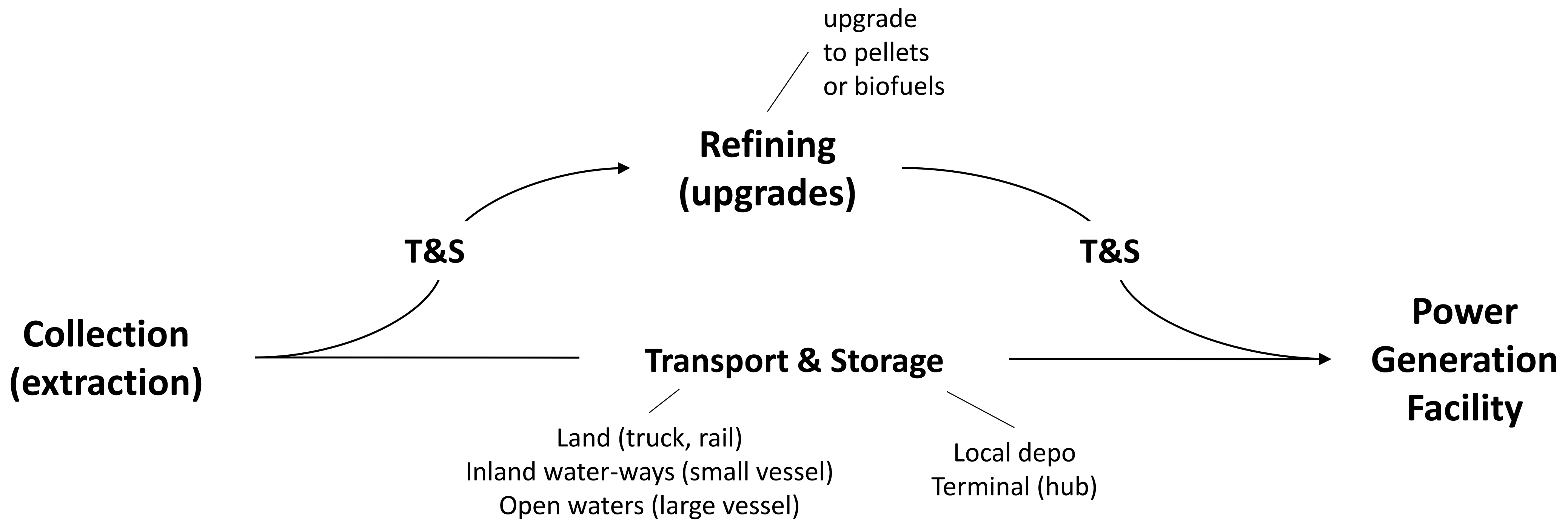
Location-specific
(Transmission Costs)

1. When RES is located far from load centers investments in **transmission-distribution expansion** are necessary.
2. If grid constraints are pushed-to-limit by RES, the costs for **congestion management** like re-dispatch of power plants increase.



Reference:
Ueckerdt, F., Hirth, L., Luderer, G. & Edenhofer, O. System LCOE: What are the costs of variable renewables? 33.
Martin, H. & Otterson, S. *German Intraday Electricity Market Analysis and Modeling Based on the Limit Order Book*. (2018). doi:10.1109/EEM.2018.8469829.

Costs of biomass and fossil-fuels feedstock for electricity generation are largely influenced by how resources are procured, treated, and transported.



Adapted from:
Nunes, L. J. R., Causer, T. P. & Ciolkosz, D. Biomass for energy: A review on supply chain management models. Renewable and Sustainable Energy Reviews 120, 109658 (2020).

CCUS technologies and challenges

CO2 capture
Post-combustion

Oxy-fuel

- **Large-scale coal-fired power plants "low-hanging fruit"**
- **Biomass and coal co-firing option for BECCS**

Direct-air carbon capture and storage (DACCS)

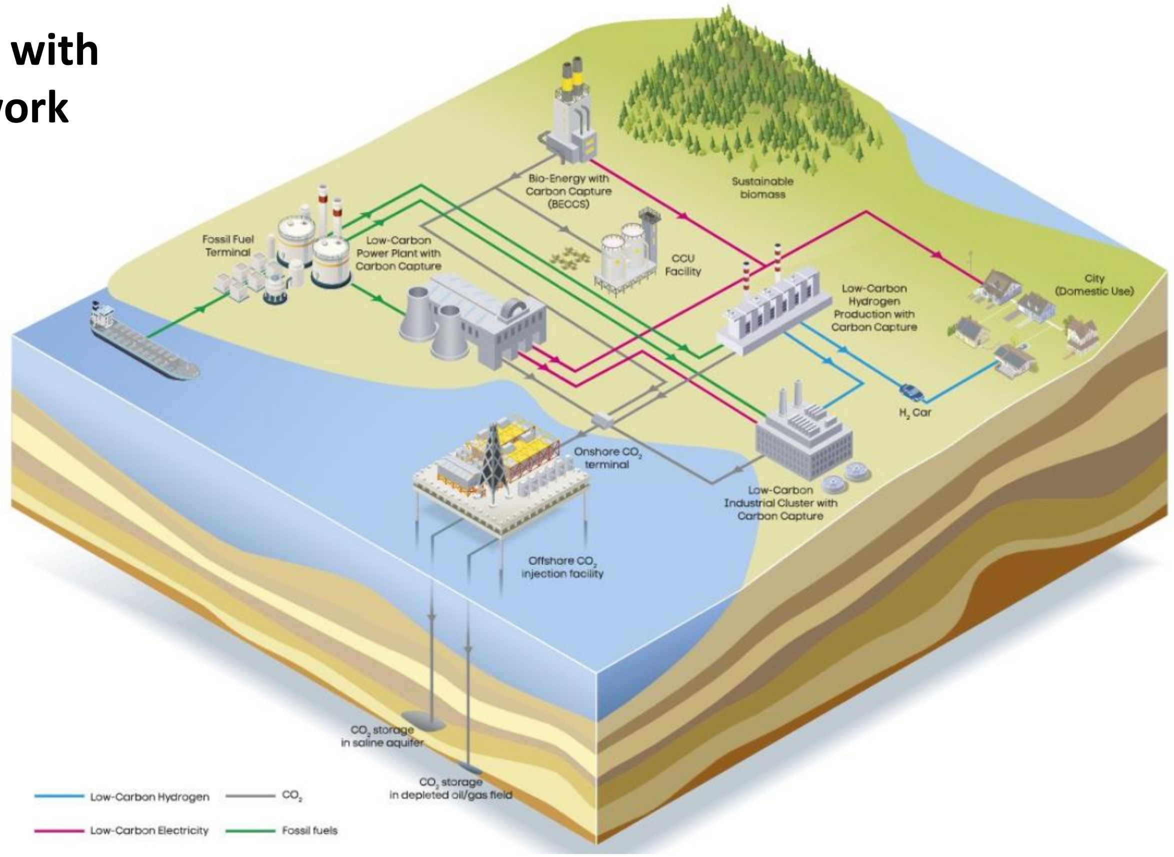
CO2 network
Piping

Vessel

Trucking/rail

- **CO_2 hub and cluster with bulk transport network**
- **Economies of scale**

CO2 utilisation & storage
Incentives for CCUS made available by the power sector

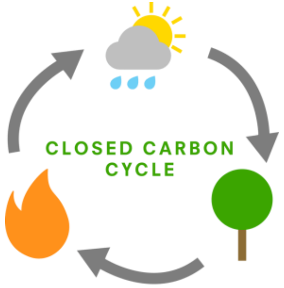


Source (figure):
https://zeroemissionsplatform.eu/event/how-european-co2-transport-and-storage-infrastructure-can-enable-an-innovative-industrial-transition/

Protection and conservation values implication to energy sector development

Resource
(usage limitations)

- Sustainable sourcing of biomass with considering protected areas limit.
- Carbon neutrality?



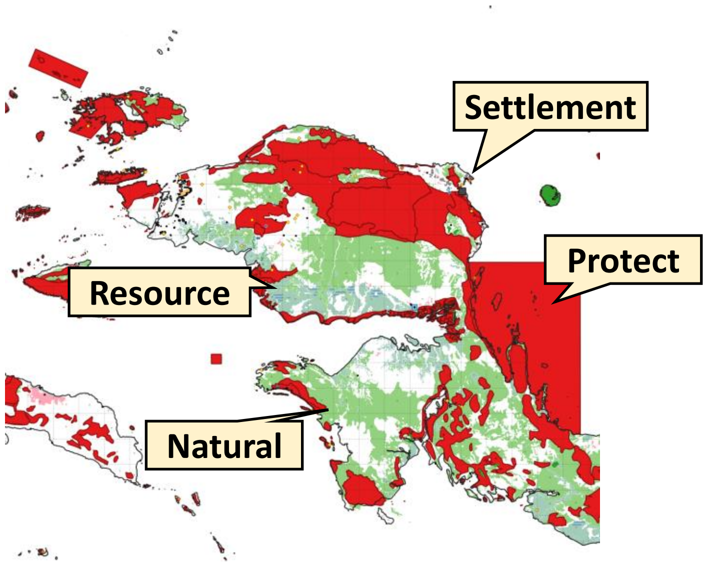
CO_2 released from biomass burning

(+) Sustainably sourced biomass and Sustainable Forest Management (SFM)

(=) Closed Carbon Cycle or Carbon neutral

Infrastructure
(sitting suitability)

- Restricted (protected) lands for development of energy infrastructures.
- Targeted investment subsidies for technologies with high-environmental benefits.



Operation
(environmental regulations)

- CO_2 pricing and quotas:
    - Emissions tax penalty
    - Removals tax credit (CCUS/BECCS/DACCS)
    - Emissions and removals targets
- Pollution control
- Renewables' feed-in-tariffs