Energy Modelling Platform for Europe

EMP-E 2021: Re-Energising Sustainable Transitions in Europe

Energy System Modelling, Methods & Results to support the European Green Deal

26th to 28th October · online

Energy System Models: Basic Principles and Concepts

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October 26 – Track 1: Intro to ESMs

hosted in cooperation with the European Commission

House Rules

Stay muted

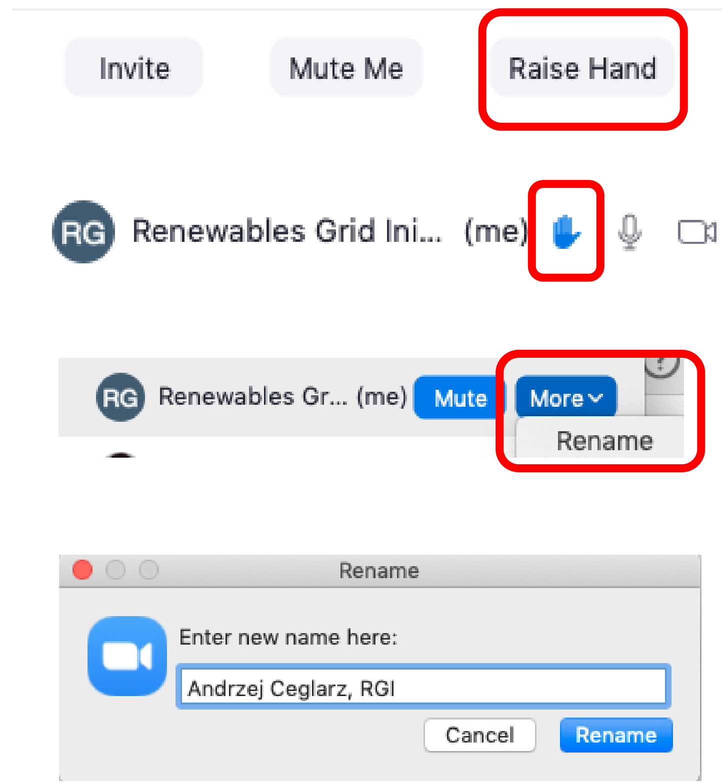
Turn your camera on (if possible)

Raise your hand in case of questions

Full name + institution

Use the chat function to ask questions/comment

Use reaction, if you like



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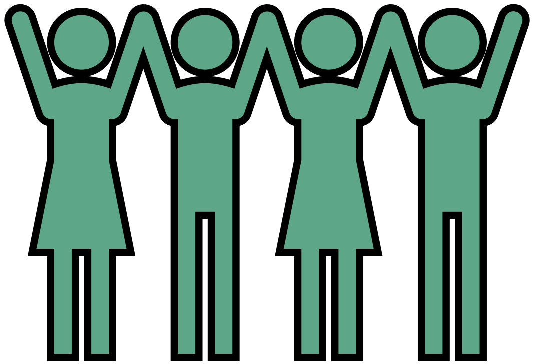
Who’s in the room?

- Zoom poll will automatically pop up on your computer screen
- The poll will remain for 25 seconds, then the results will be posted
- If you choose “other,” feel free to share in the chat!



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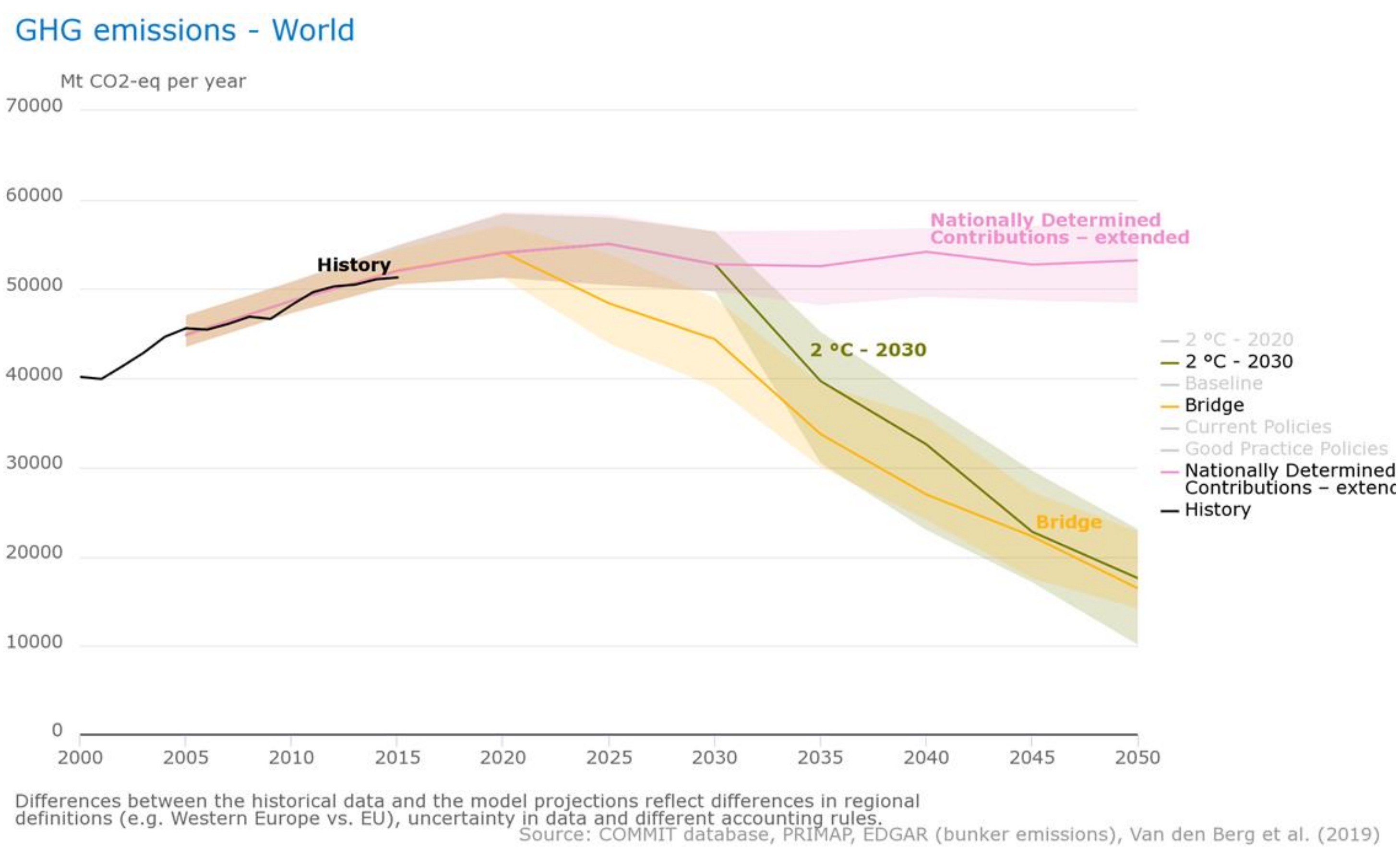
Objectives: Understand the fundamentals and basic principles of ESMs

How ESMs can inform the climate debate and IPCC assessments?



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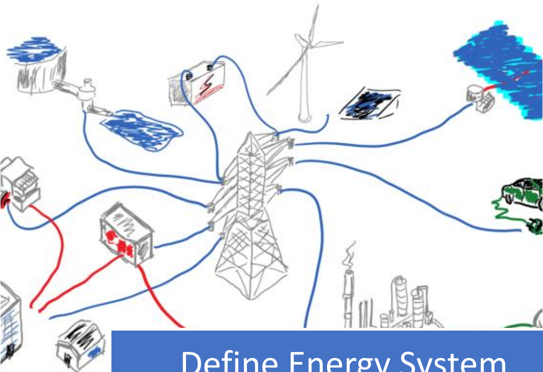
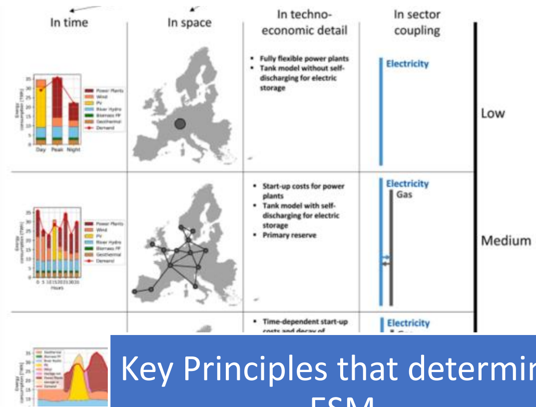
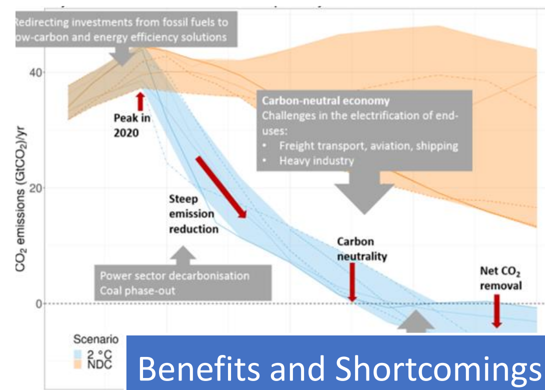
Objectives and Milestones (1st session)



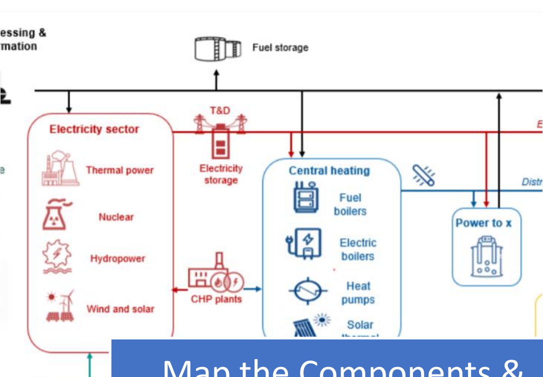
Define Energy System Modelling (ESMs)



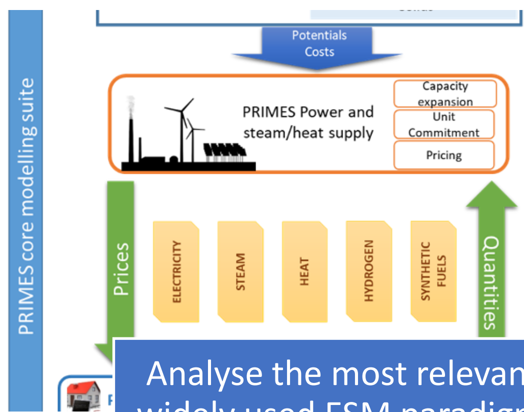
Key Principles that determine ESM



Benefits and Shortcomings of ESMs



Map the Components & Technology of a simple ESM



Analyse the most relevant, widely used ESM paradigms

COFFEE BREAK – 10 minutes

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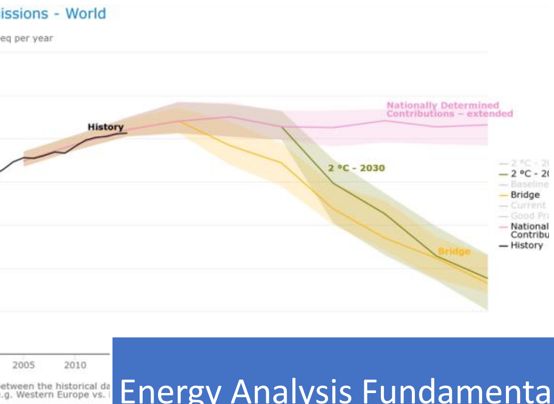
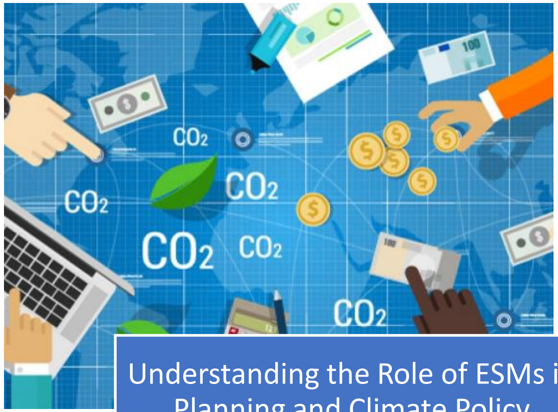
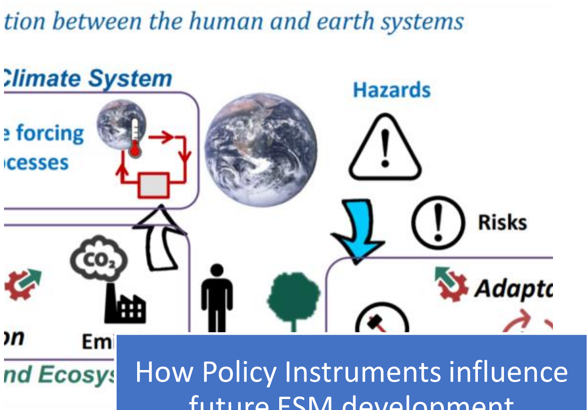
Objectives and Milestones (2nd session)



Energy Analysis Fundamentals



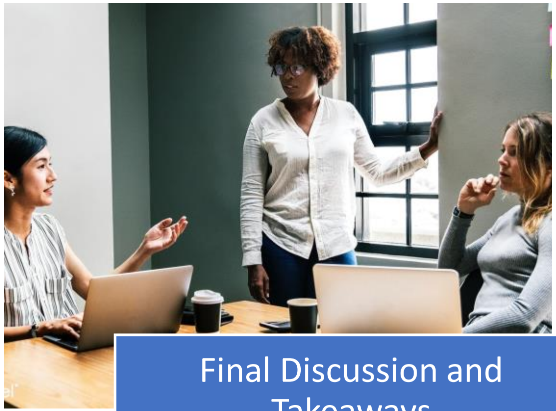
Understanding the Role of ESMs in Planning and Climate Policy



How Policy Instruments influence future ESM development

Small Group Work – Modelling challenges of net-zero energy systems

Stakeholders, Modifications and Result interpretation



Final Discussion and Takeaways

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What to expect?

At the end of this workshop, you will gain these key takeaways:

- Understand the key principles and features of energy systems modelling
- Map the components and technologies in ESMs
- Explore the interplay between ESMs, policy instruments and stakeholders
- Gain an overview on the role of ESMs scenario analysis in real-world policy making
- Discuss possible challenges towards modelling net-zero emission targets

Energy Systems Analysis & Modelling

- ESM is a multi-disciplinary applied scientific field based on: economics, operations research and engineering
- It considers the energy sector as a whole – as a system, as opposed to sub-sector approaches, like power economics
- The goal is to aid decision making: energy policy analysis, impact assessments, pricing and investment planning
- Often the analysis considers the interactions with other systems, especially the economy and the environment
- Usually it provides quantitative results
- It often uses <u>mathematical models</u> as a way of approaching complex problems

Fundamentals of Modelling

Models are simplified, stylized representations of reality
We use models to represent and investigate a phenomenon in real world or hypothetically.
Models are based on:

- Clear definition of the system boundaries
- Include a mathematical description
- Parametrized and solved numerically

Examples: climate models, energy system models

Elements of modelling work

- Structural relations (equations to link model input with output)
- Large data requirements
- Represent states of the system (scenarios and simulations)

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Definition of Energy System Models (ESMs)

ESMs are the mathematical models that are developed to represent as reliably as possible various energy-related problems.

They represent the energy system (or its sub-systems) at different temporal, sectoral and spatial granularity

Energy modeling has increased in importance due to climate change concerns, as energy use accounts for 75% of global GHGs

Most ESMs identify the most cost-effective way to deliver energy to final consumers

They are used for energy planning and policy impact assessment

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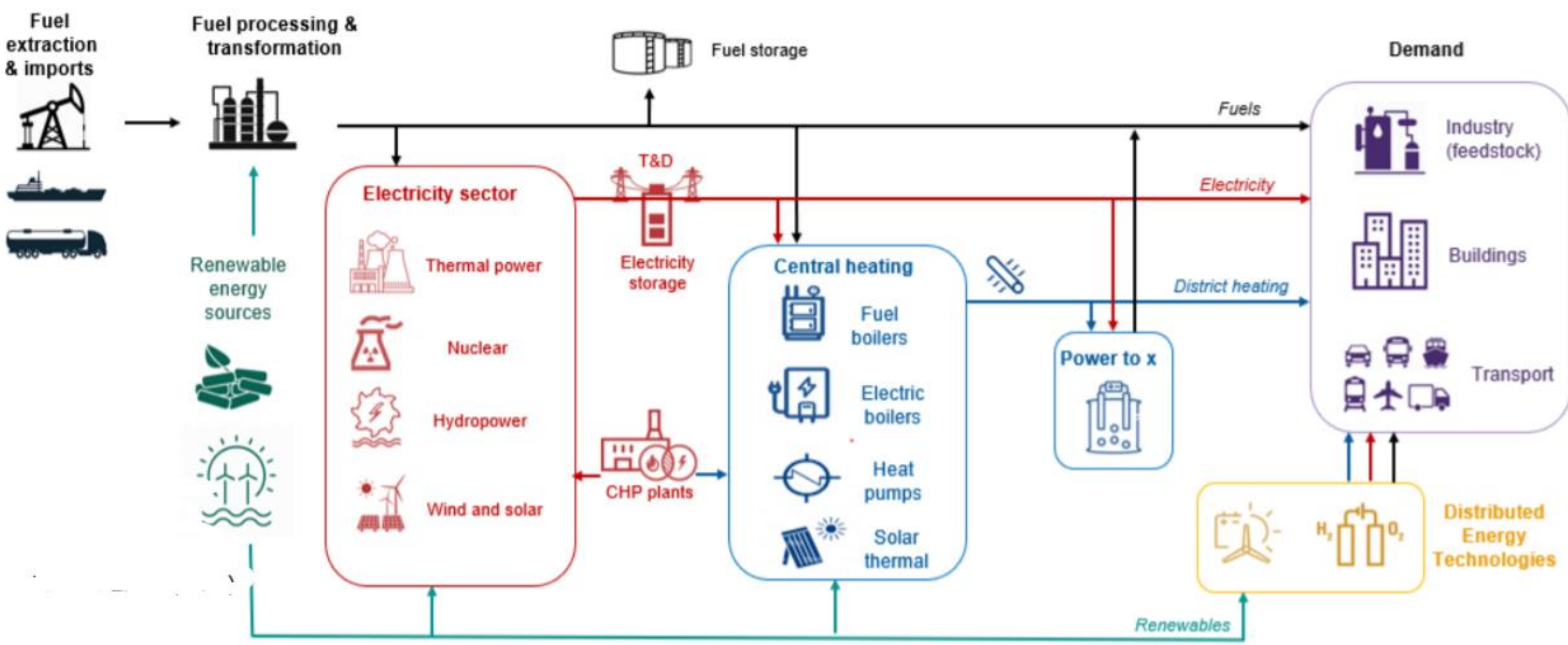
ESMs represent the links between energy resources, conversion/processing, T&D grids, technologies, and end-use services



Typical Energy System Model

Why use ESMs?

- Investment decisions cannot be tested in real world, as they involve large capital requirements
- Energy systems can be simplified and represented in organized <u>model structures</u> involving input/data, equations & output
- ESMs aim to represent components and processes of energy systems through <u>mathematical equations</u>
- We need quantified models of complex systems that can help decision makers in numerous ways
  - Enable analysts to compare different systems configurations without the costs of building them
  - Facilitate the design of energy systems and account for local/national resources, demand, policies and other constraints

What ESMs can and cannot do

- ESMs ensure the minimization of energy-related costs/consumer expenditure to meet energy demand/activity
- They can help mitigate the uncertainty in energy-related investment decisions and policy actions
- Often employ <u>scenario analysis</u> to investigate the impacts of different technology, socio-economic or policy assumptions at play
- ESMs can provide useful insights for policy design but cannot predict the future with certainty
- They commonly focus on medium and long-term and do not provide short-term forecasts

Brief History of ESMs

- **Reference Energy System**: Brookhaven National Laboratory's linear programing model
- MIT Energy Laboratory **1st Energy-Economy Model**
- **EU Joule program '80s**: First models EFOM (linear programming), MEDEE (energy demand model), HERMES (macroeconomic model)
- **OECD and IAEA '80s**: MARKAL later TIMES (linear programming), MAED (energy demand model) and WASP (power sector)
- **EU research '90s**: 1st market-oriented models, PRIMES & GEM-E3
- **1st Generalized equilibrium energy models**: NEMS '90s at USA/DOE/EIA
- **Also in the '90s**: 1st reduced-form energy models: IEA/WEO and EU's POLES and PROMETHEUS models (global energy system simulation)
- **Large expansion of ESMs in the '00s** due to rising concerns about energy security, energy prices, climate change and increasing energy demand
- **Modern ESMs**: try to integrate other aspects, move towards open source, ESMs prioritise their developments to be fit-for-purpose

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ESM Features

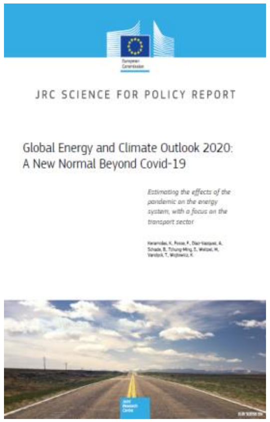
- Understanding inter-fuel substitution in various sectors
- Closed-loop energy demand and supply through market competition
- Trade-offs between demand and supply-side energy investment
- Understanding behaviour of agents and the influence of energy and climate policy instruments
- Energy system chains (e.g. H2 vs electricity economy)
- Close the loop between energy and economy

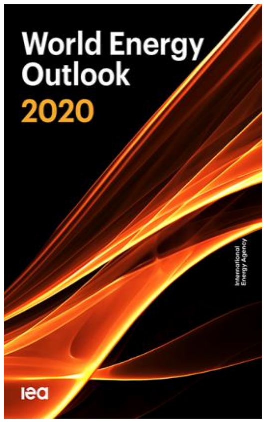
Problem Solving Methods

- **Systems Simulation**: understanding, training
- **Normative analysis, optimization**: policy analysis and investment recommendation
- **Forecasting – projections** of demand, prices, technology penetration
- **Scenario construction and comparison**: exploration of uncertain futures (by varying input parameters) and policy analysis

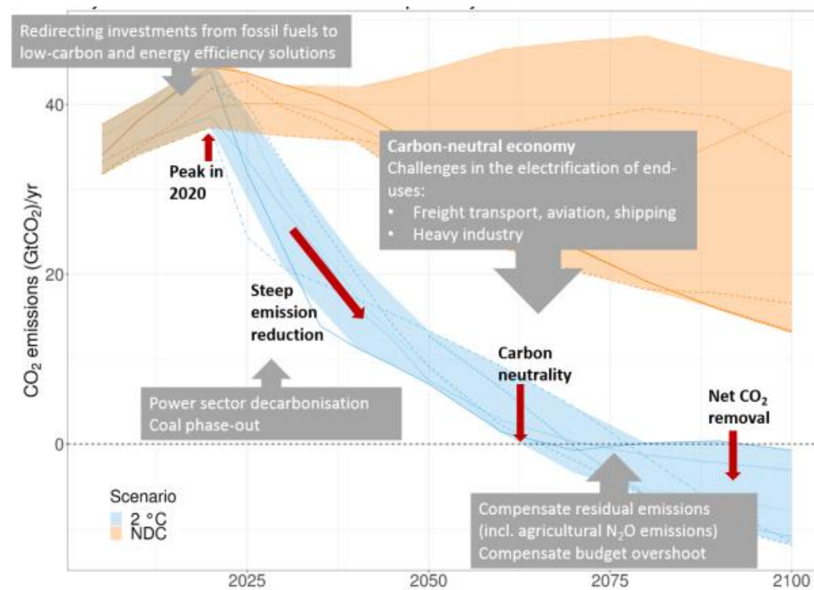
Uses of Energy System Models

Energy Outlooks (IEA, EIA, EC, JRC)

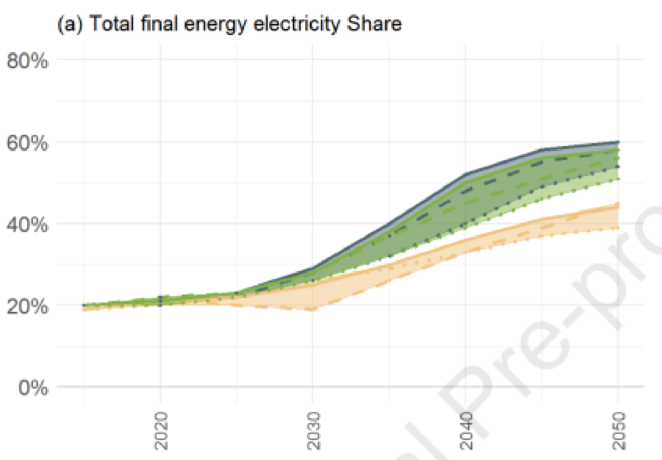




IPCC and climate change negotiations

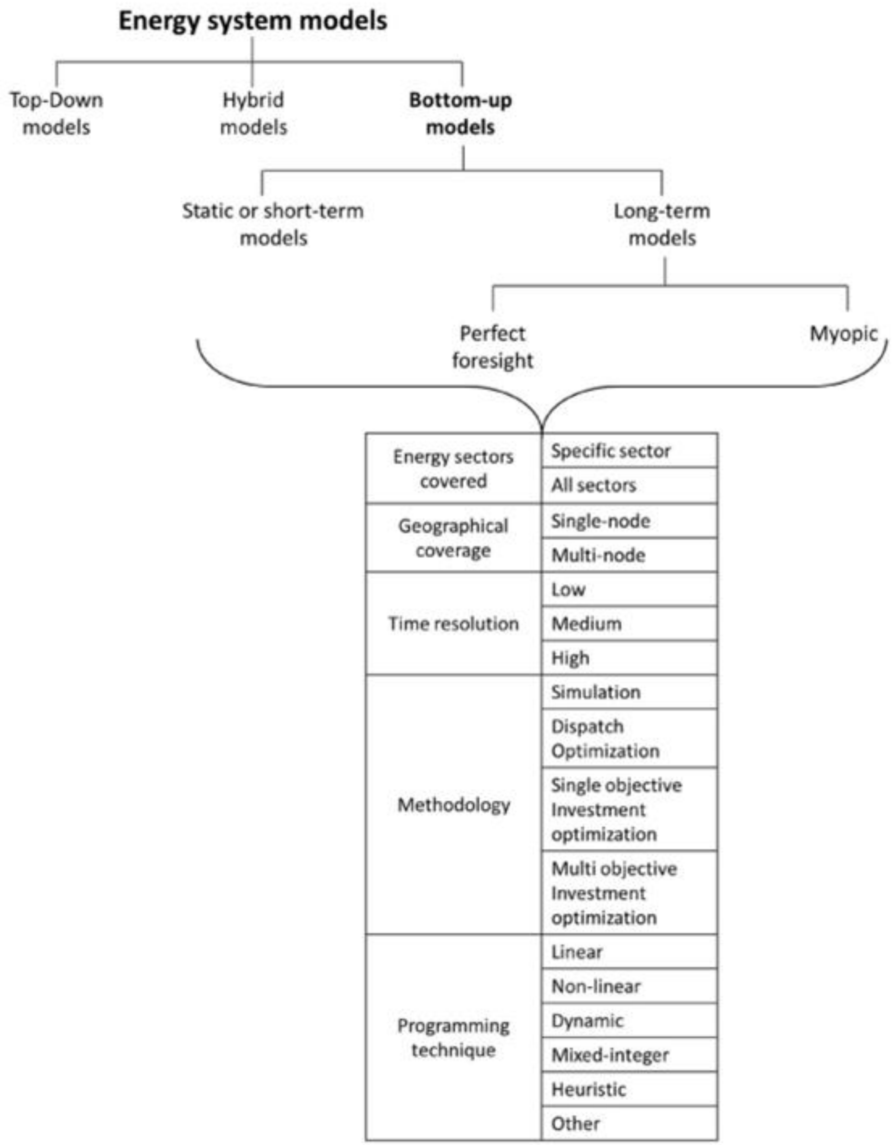


Energy Strategy for individual countries (e.g. informing NDCs or NECPs)



Inform businesses on their long-term planning and investment

Major Model categorisations



Adapted from Prina et al 2020, Classification and challenges of bottom-up energy system models - A review

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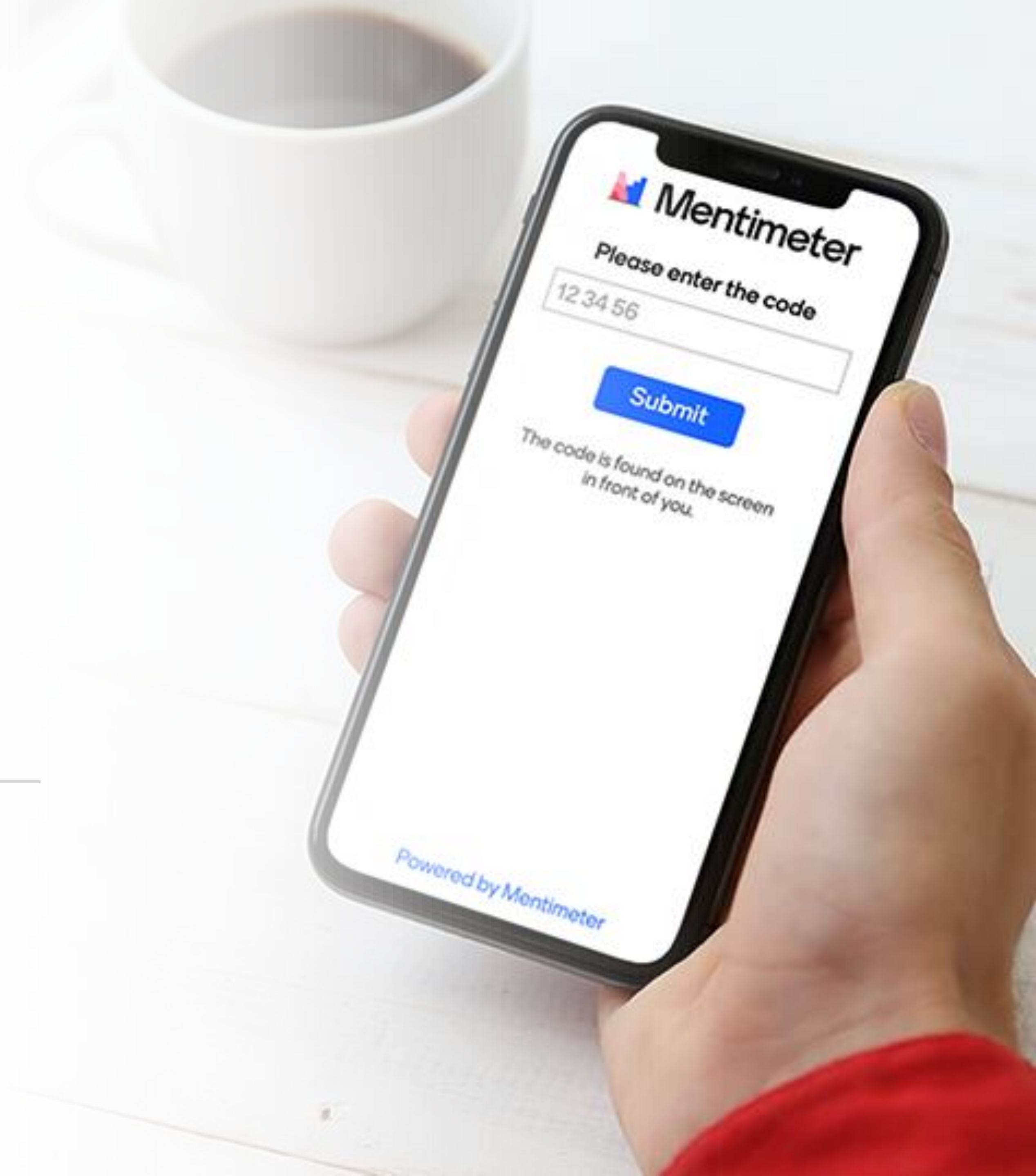
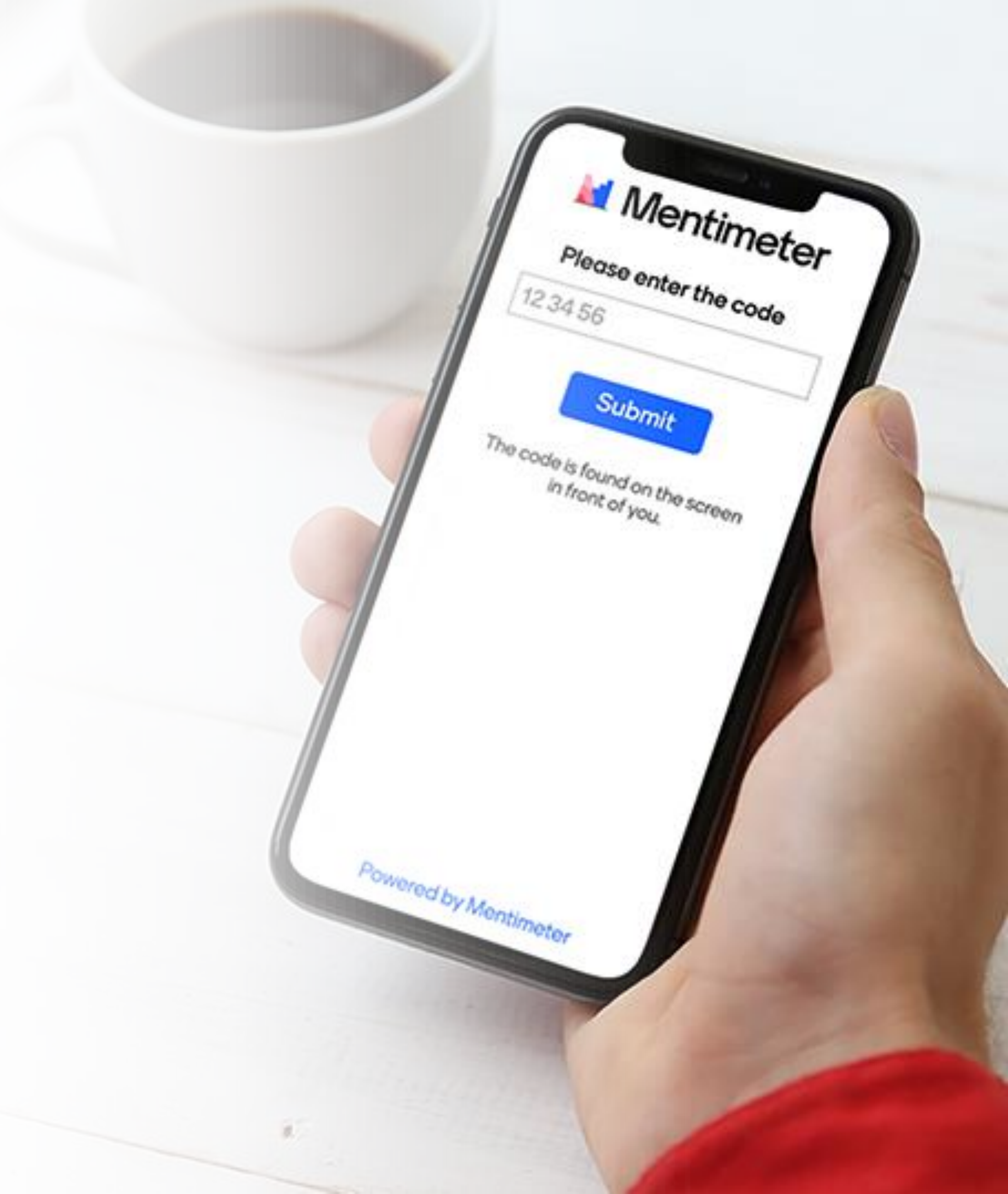
Benefits of existing ESMs

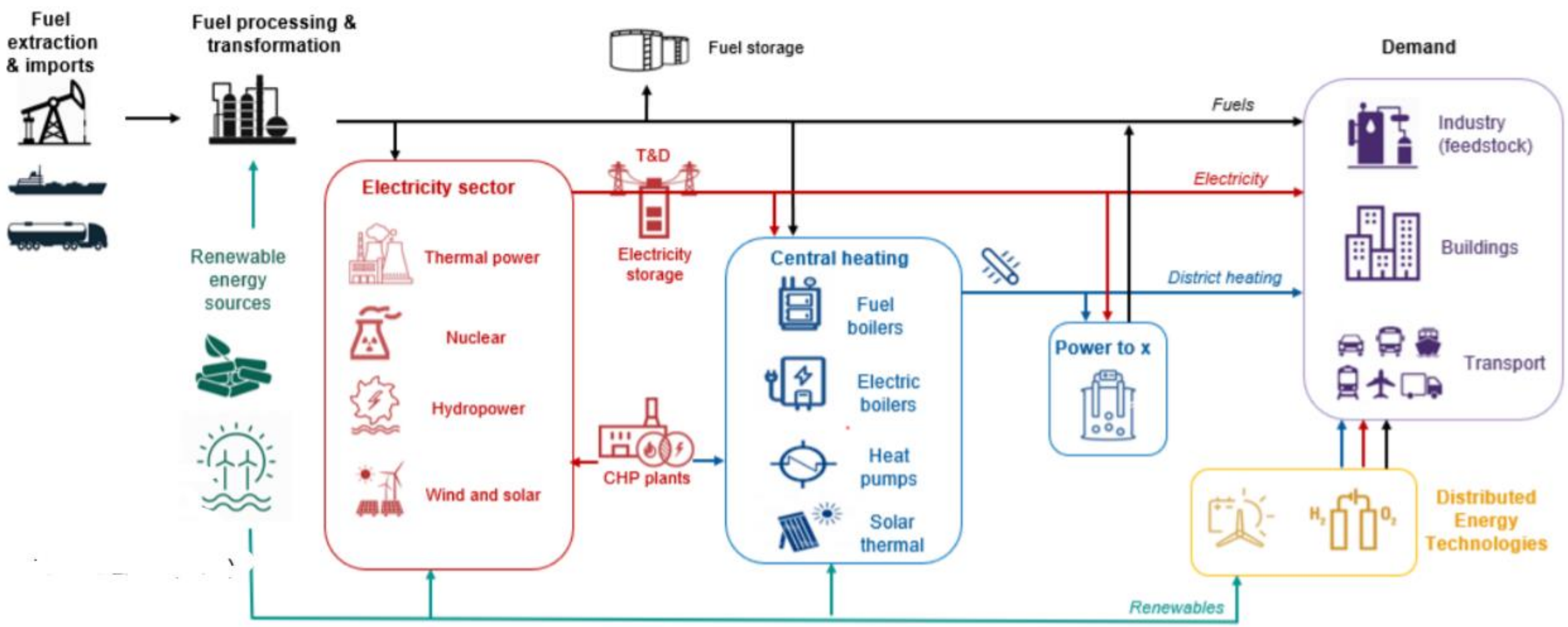


Shortcomings of existing ESMs



Mapping ESM components

A system of energy resources, conversion/processing, transmission and distribution technologies, and services



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Simplified Reference Energy System

Primary

- Oil
- Gas
- Coal
- Water
- Wind
- Solar

Secondary

- Diesel
- Kerosene
- Gas
- Electricity
- Coal

Final

- Diesel
- Kerosene
- Gas
- Electricity
- Coal

Useful

- Heat
- Lighting
- Mechanical energy

Energy Balances

Information and data structured to describe the links in energy system

Typically used in ESMs – to calibrate to historic data

EU-28, 2014 (ktoe)	Total (all products)	Solid fossil fuels	Crude oil & petroleum products	Gas	Nuclear heat	Renewable energies	Non-renewable wastes	Electricity	Derived heat
+ Primary production	770 722	149 335	70 030	117 019	226 132	195 814	12 392		
+ Primary production receipt	9 370		9 370						
+ Other sources (recovered products)	4 909	685	3 968	256					
+ Recycled products	1 125		1 125						
+ Imports	1 411 681	159 831	882 362	320 253		15 704	255	33 270	5
+ Stock changes	- 9 349	- 4 041	358	- 5 451		- 220	6		
- Exports	530 788	37 293	362 306	89 161		10 057	29	31 937	5
- Bunkers	41 622		41 622						
- Direct use	10 116		10 116						
Gross inland consumption	1 605 931	268 517	553 168	342 917	226 132	201 241	12 624	1 332	0
Transformation input	1 277 176	253 214	627 959	102 222	226 132	57 134	9 297	192	1 026
+ Conventional thermal power stations	357 010	190 639	12 879	92 227		51 703	8 536		1 026
+ Nuclear power stations	226 132				226 132				
+ District heating plants	19 484	3 816	1 048	8 521		5 146	761	192	
+ Coke ovens	39 002	38 367	624	11					
+ Blast furnaces	13 421	13 421							
+ Gas works	736	710	1	25					
+ Refineries	613 159		613 159						
+ Patent fuel plants	245	171	74						
+ BKB/PB plants	4 958	4 958							
+ Charcoal production plants	227					227			
+ Coal liquefaction plants	839	839							
+ For blended natural gas	231		175			56			
+ Gas-To-Liquids (GTL) plants									
+ Non-specified Transformation Input	1 734	293		1 439		2			
Transformation output	932 177	33 008	612 716	21 162		69		209 643	55 579
+ Conventional thermal power stations	173 718							134 296	39 422
+ Nuclear power stations	75 437							75 348	89
+ District heating plants	16 068								16 068
+ Coke ovens	35 927	28 712		7 214					
+ Blast furnaces	13 421			13 421					
+ Gas works	526			526					
+ Refineries	612 716		612 716						
+ Patent fuel plants	207	207							
+ BKB/PB plants	4 089	4 089							
+ Charcoal production plants	69					69			
Exchanges, transfers and returns	2 428		2 428			- 61 990		61 990	
Consumption of the energy branch	77 518	669	31 050	18 131		912	62	22 536	4 159
Distribution losses	24 960	48	47	2 810		25	0	17 505	4 525
Available for final consumption	1 160 881	47 595	509 255	240 915		81 249	3 264	232 733	45 870
Statistical difference	- 191	- 499	2 277	- 2 198		- 129	- 0	32	326
Final non-energy consumption	99 387	1 518	84 020	13 849					
Final energy consumption	1 061 684	46 576	422 957	229 264		81 378	3 264	232 701	45 544
+ Industry	274 769	35 281	27 671	87 233		20 523	3 033	85 764	15 263

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..Or in Sankey diagrams showing energy flows

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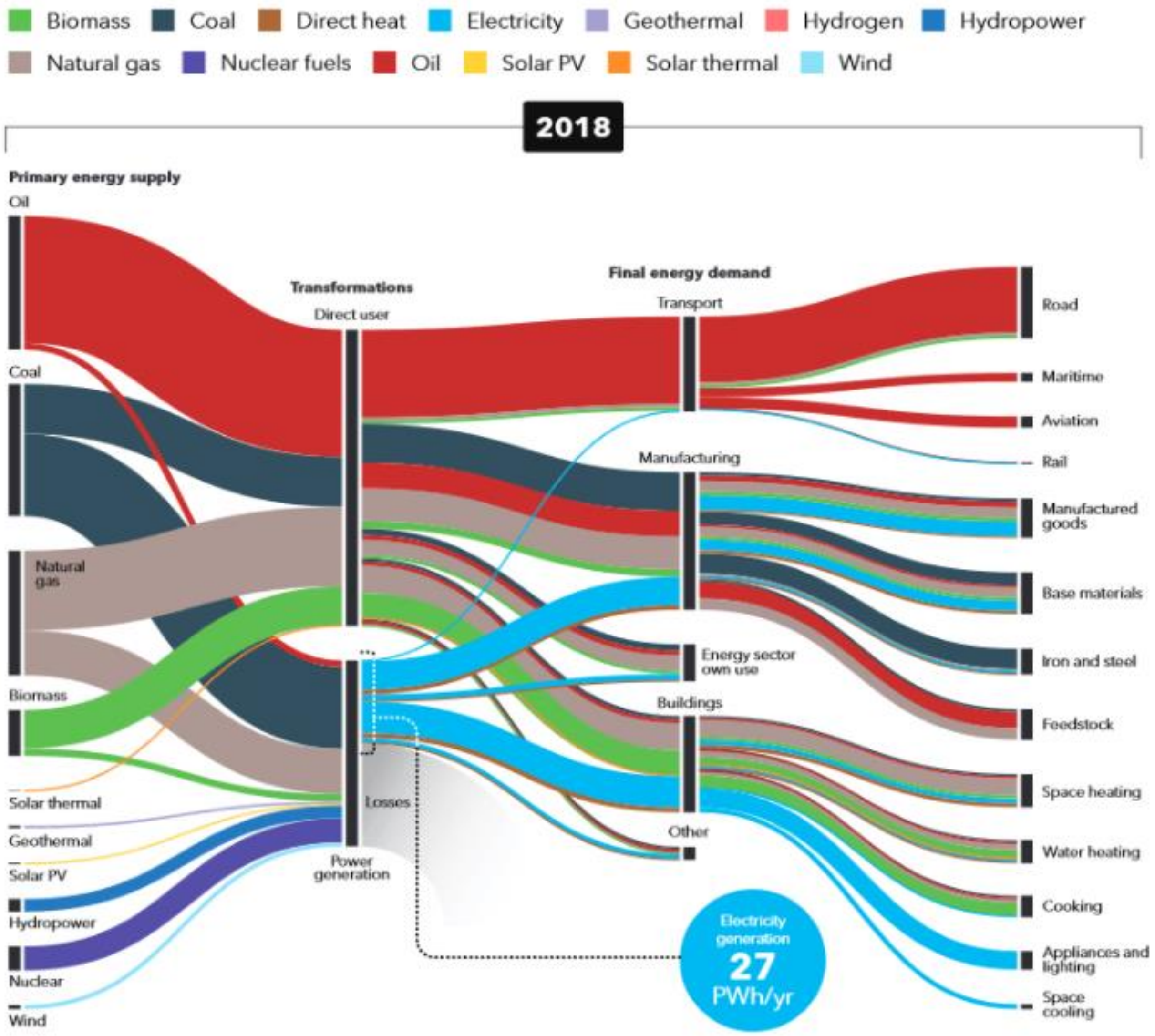
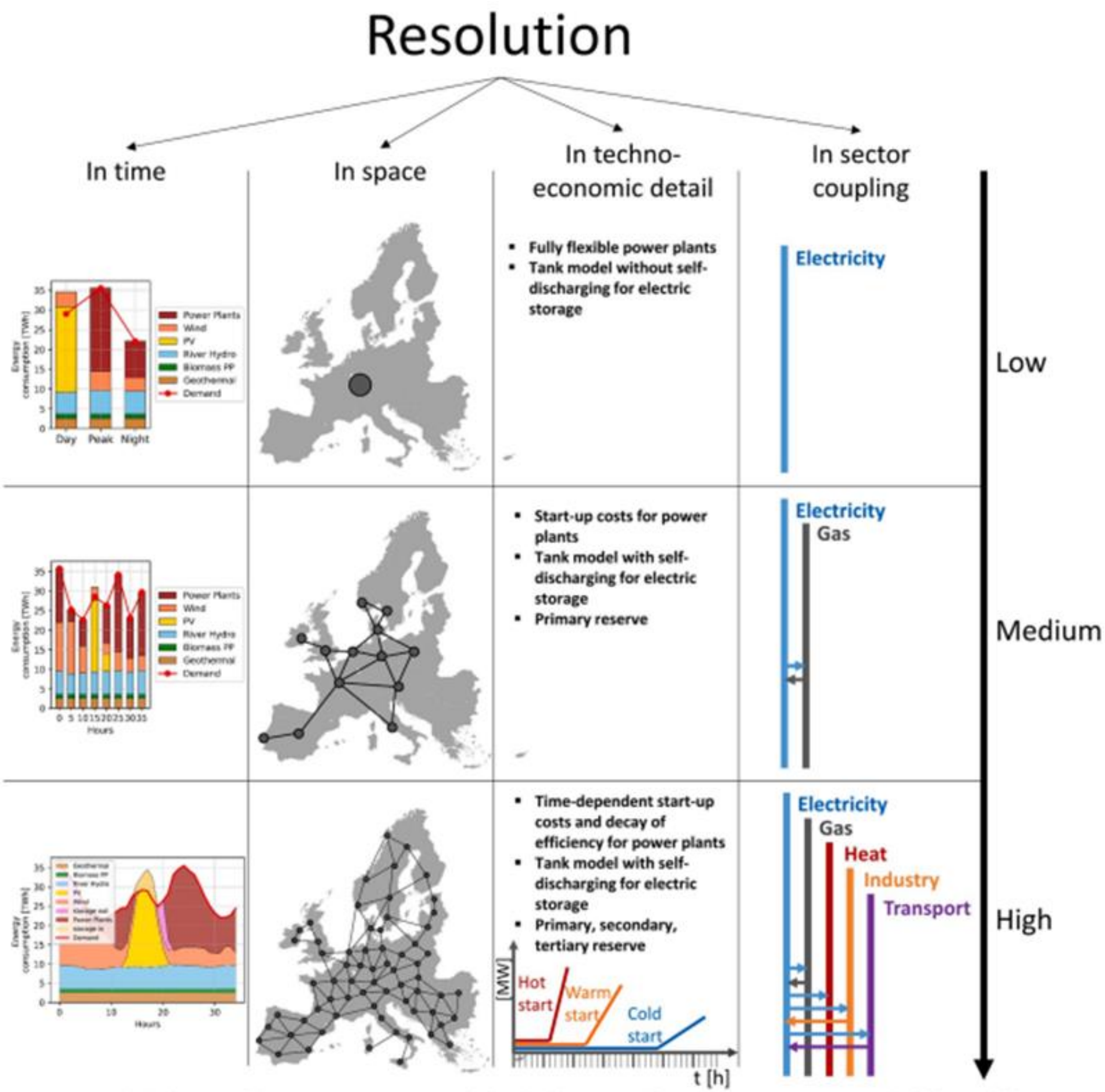


ESMs work at vastly different scales and granularity



Adapted from Prina et al 2020

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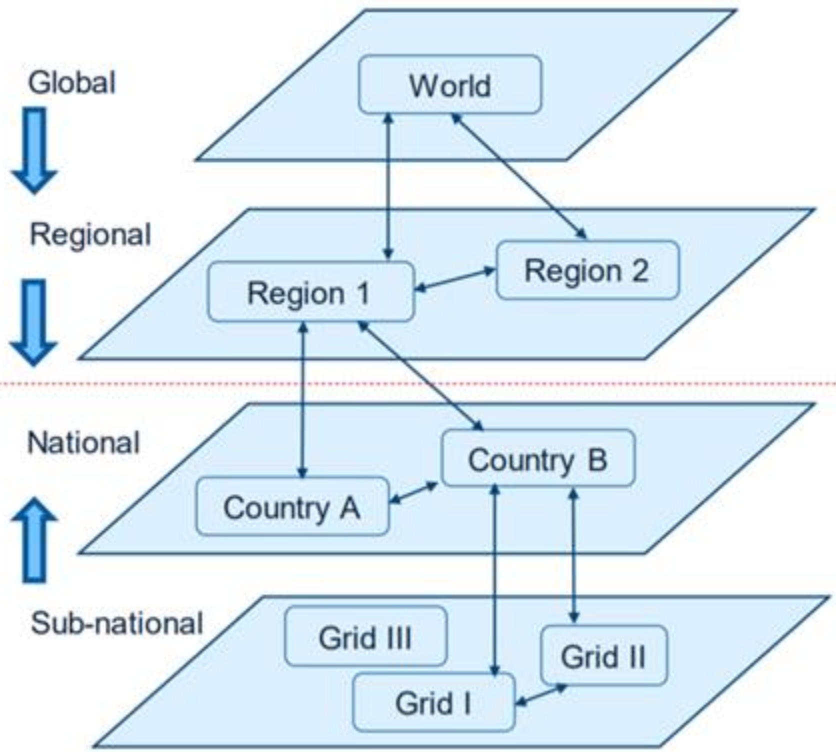
Geographic scope of ESMs

Regional Coverage



Analysis to perform

Global emission pathways
Global energy demand
Global energy trade

Regional energy and emission markets
Regional energy transitions
Energy trade

National energy and environmental policies
Energy security
Energy prices
Implications of international agreements

Electricity transmission planning
Renewable potentials and integration
Energy demand

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Most widely used ESM paradigms

Bottom-up optimisation: MARKAL, TIMES, Calliope, DNE21+
Bottom-up accounting: LEAP, Green-X
Top-down Simulation-based: DTI energy model
Hybrid models: POLES, IEA-WEM, PROMETHEUS
Partial equilibrium: GCAM, TIAM-ECN, AIM-Enduse
Hybrid-market equilibrium: PRIMES, NEMS
Electricity models: OSEMOSYS, WASP

Optimal growth IAMs: MESSAGE, IMAGE, REMIND, WITCH
General Equilibrium: IMACLIM, GEM-E3, GEMINI, GTAP, ICES

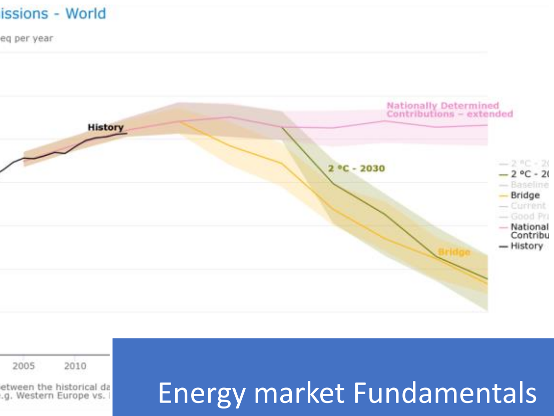
This classification changes as models develop further to examine new policy questions (e.g. link with CGEs) or change their features to improve their properties (e.g. adding behavioral equations in BU models)

Coffee Break

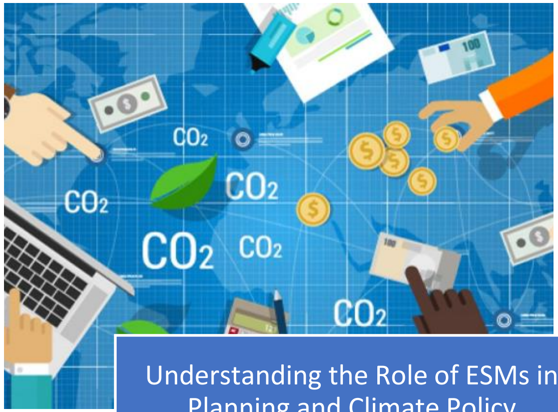
End of first half

See you in 10 minutes

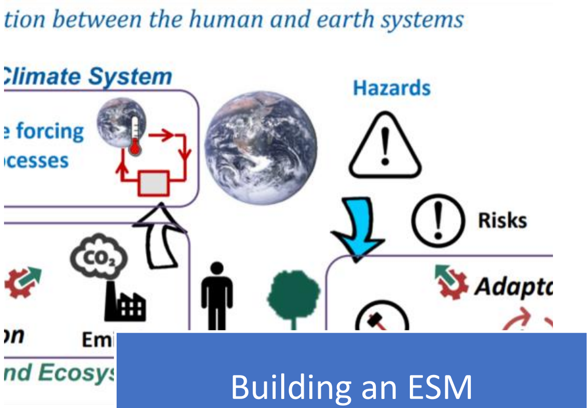
Objectives and Milestones



Energy market Fundamentals



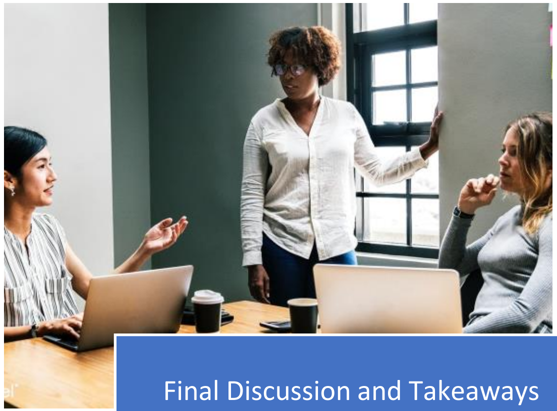
Understanding the Role of ESMs in Planning and Climate Policy



Building an ESM

Small Group Work – Modelling challenges of net-zero energy systems

Stakeholders, Modifications and Result interpretation



Final Discussion and Takeaways

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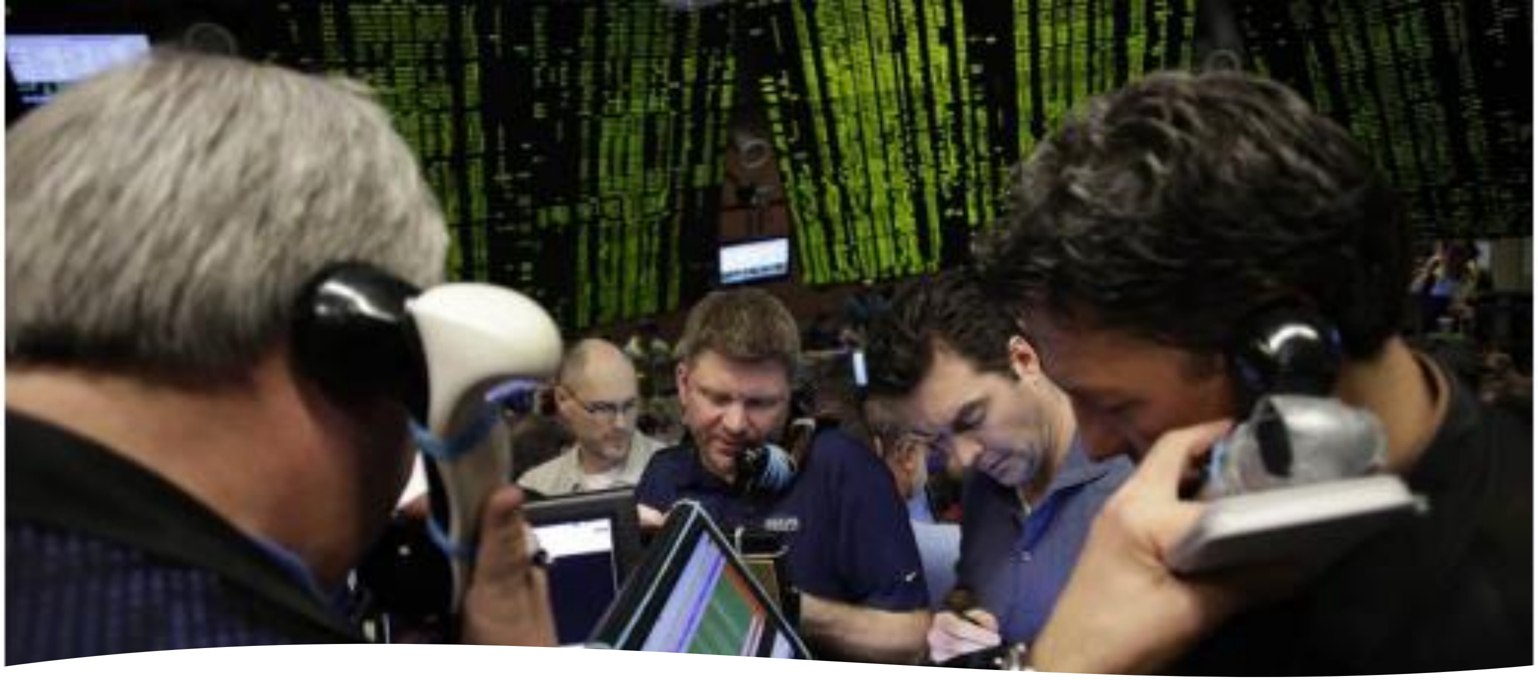

Energy Market Fundamentals

- Energy market: “An actual or nominal place where buyers and sellers interact to trade energy commodities”
- Energy markets, such as oil, gas, and coal markets
  - ➢ Buyers (they demand that commodity)
  - ➢ Suppliers (they supply that resource)
- Market price (such as oil or electricity price) is defined by the market equilibrium between demand and supply

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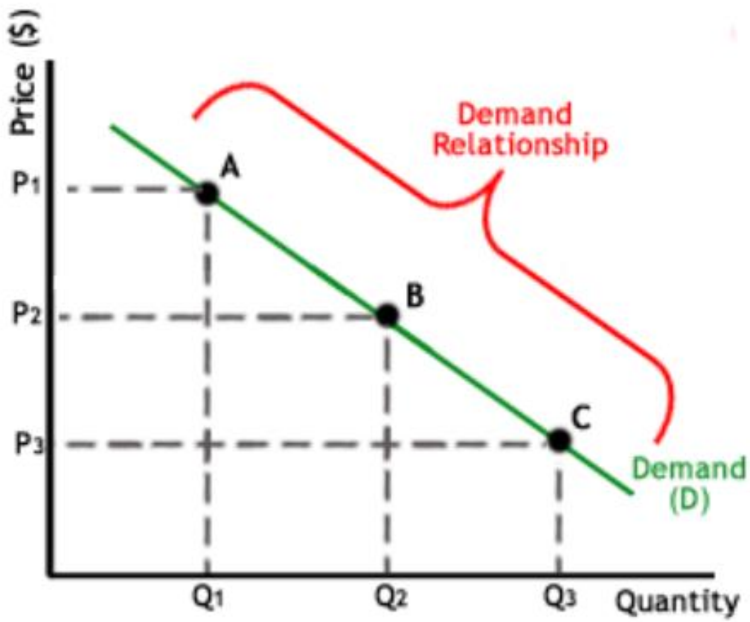
ESM Fundamentals: Energy Supply and Demand

Demand curve: relationship between demanded commodity and price

The higher the price, the less willingness to buy (inverse relationship)



Supply curve: relationship between supplied commodity and price

The higher the price, the more supply of a commodity by producers

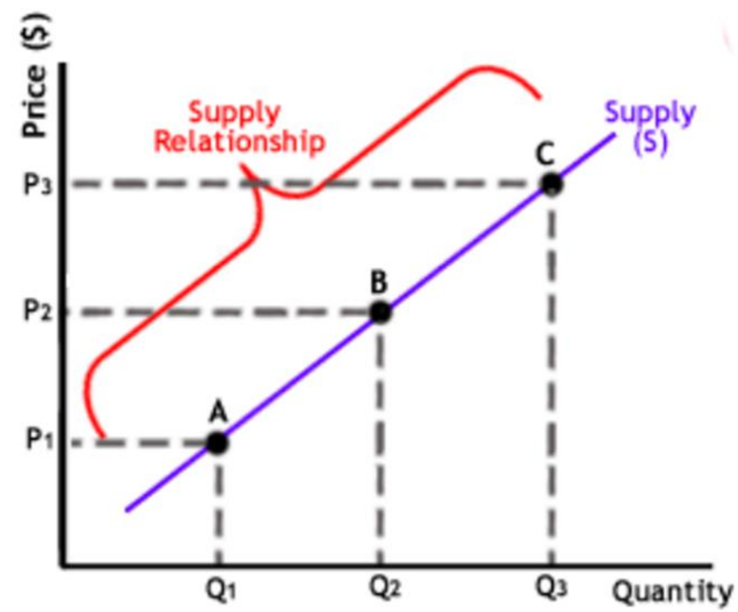


Image: https://investopedia.com

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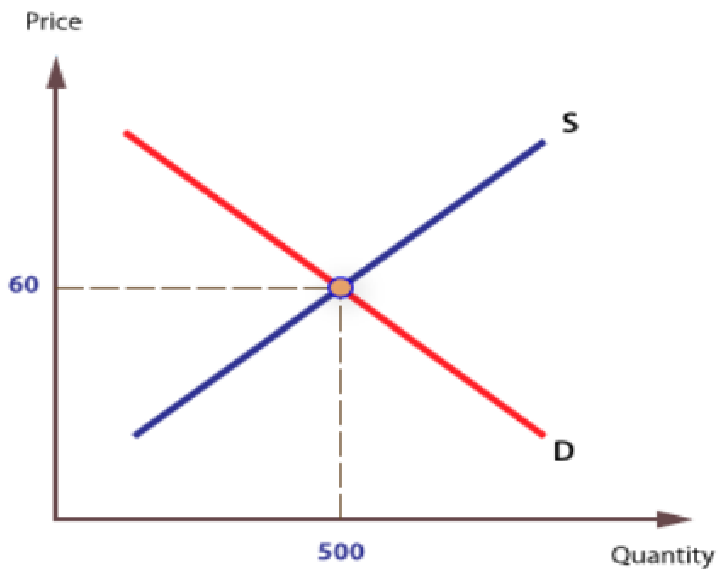
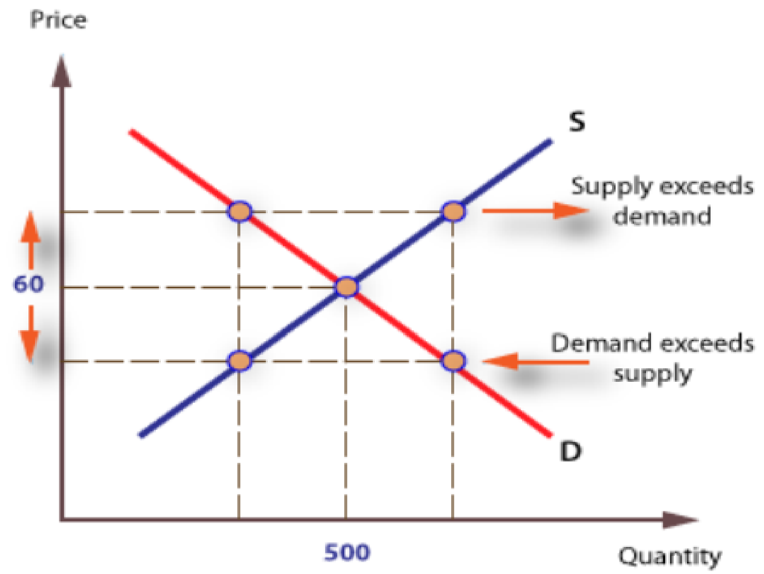
Market Equilibrium

When supply and demand curves cross each other ensuring market balance/equilibrium
Price becomes stable (market price)





Images: https://www.economicsonline.co.uk

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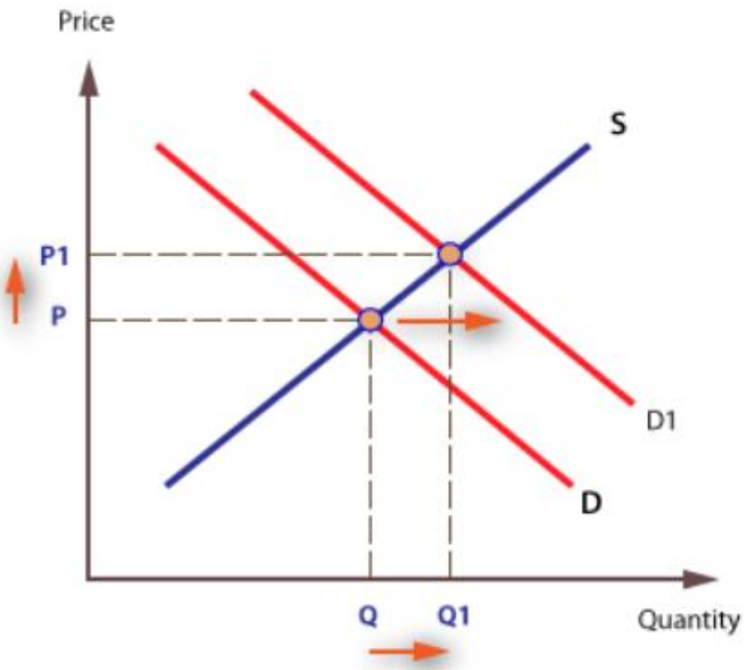
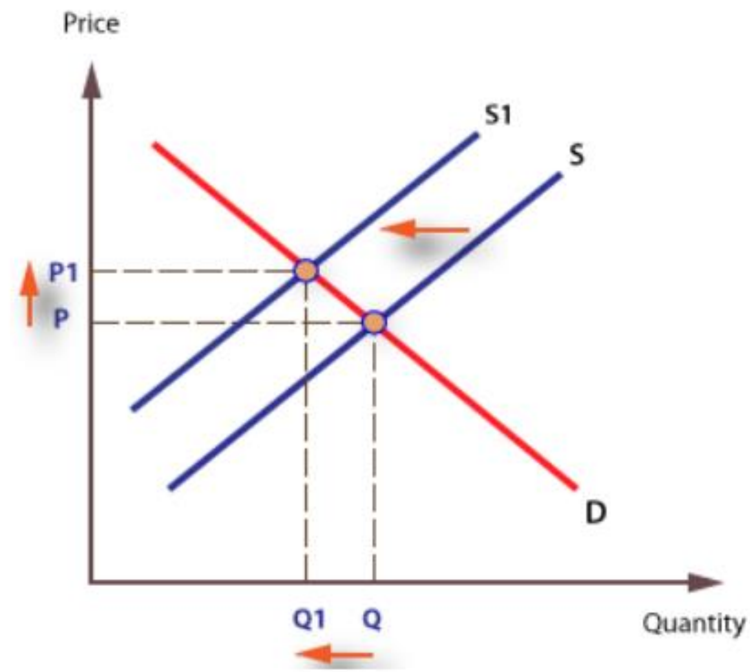
Causes of price changes

An increase in demand ➔ Price increase (as the equilibrium point moves to the up & right)

A decrease in supply ➔ Price increase



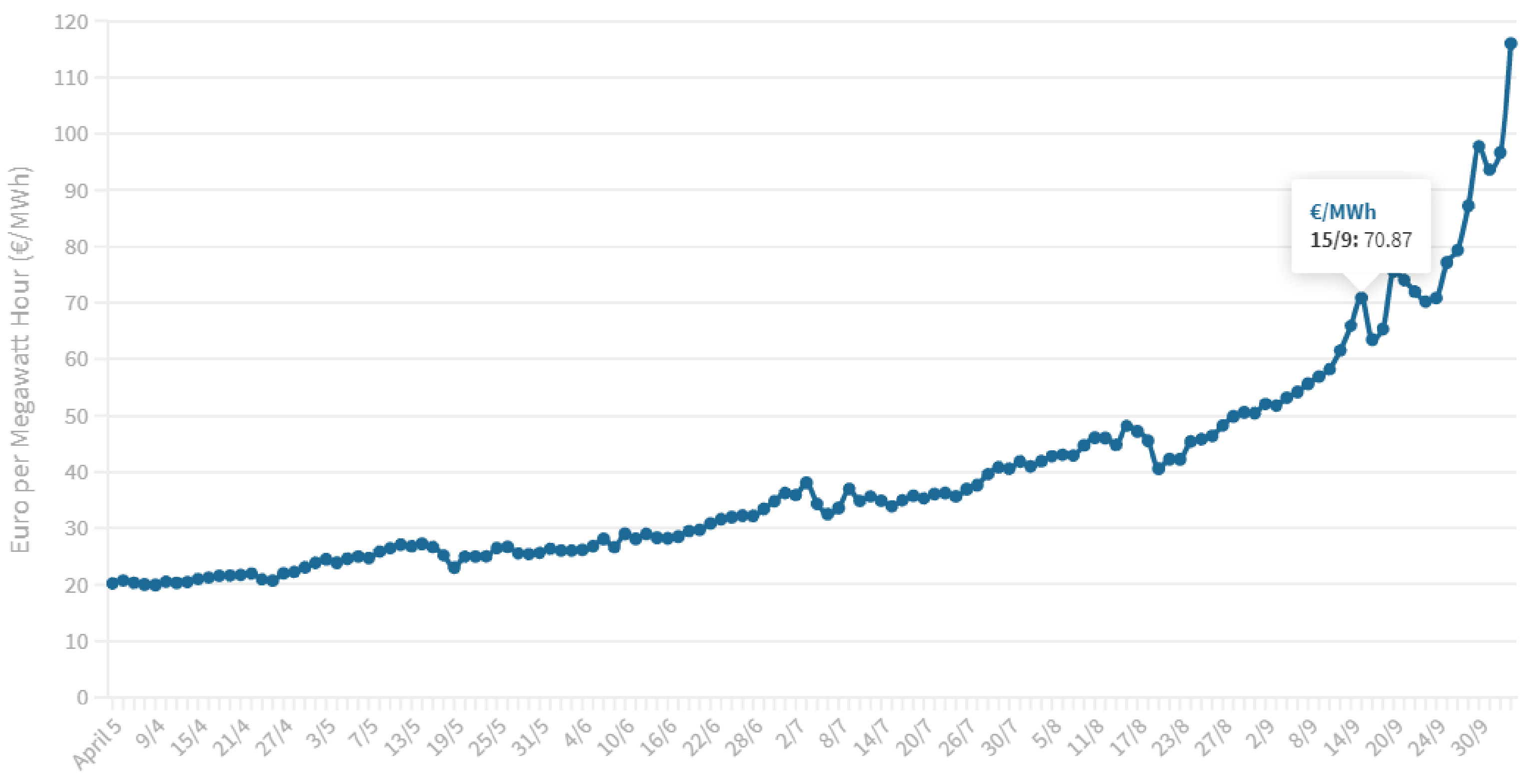


From Behnam Zakeri

An example of a market with tight supply conditions and increasing demand: EU gas prices skyrocket

Evolution of natural gas prices in European markets since April

Dutch TTF gas futures



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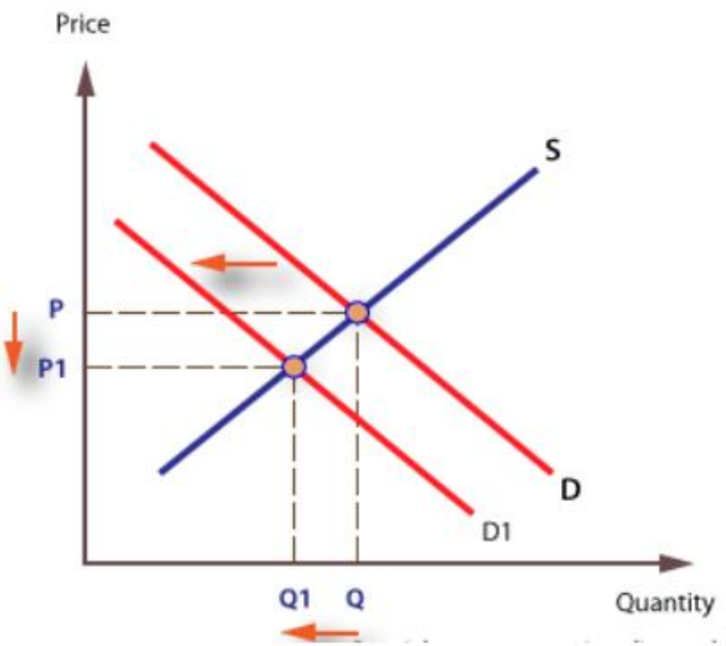
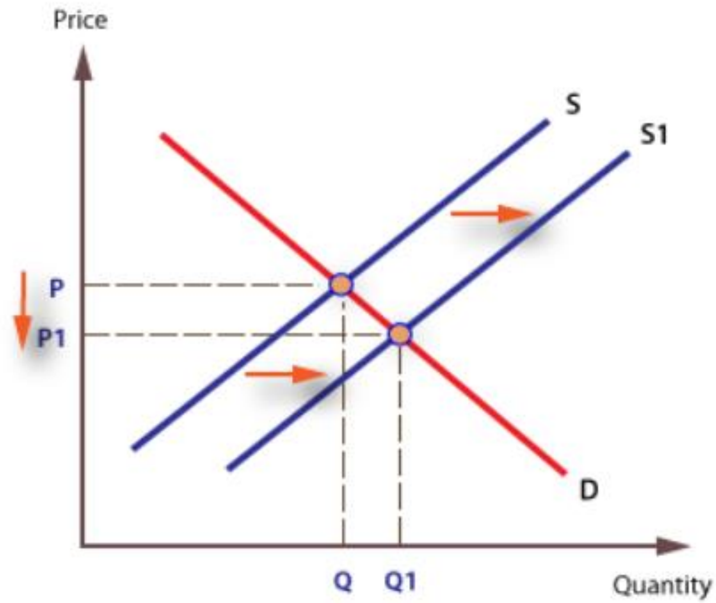
Causes of price changes (2)

A decrease in demand ➔ Price decrease
An increase in supply ➔ Price decrease





Prices are influenced by changes in energy demand & supply
Principal drivers of ESM projections

Policy drivers influence energy demand and/or supply

<u>Large focus on market-based policy instruments</u>:

- Carbon taxation by sector/ Emission Trading Schemes
- Taxes or subsidies in energy products
- Feed-in tariffs and other renewable support schemes
- Energy efficiency standards
- Subsidies for low-carbon technologies and energy efficiency
- Eco-design regulation, energy labeling
- Technology Standards/ Clean fuel support schemes
- Price caps and grid tariffs

<u>Some ESMs also include non-market policies</u>:

- Institutional mechanisms and regulations to induce lower risk perception for actors and lower interest rates
- Information campaigns to lower subjective costs

Targets, policies and scenarios in ESMs

- In ESMs the desired outcomes can be imposed as targets/ constraints in model equations or can be induced by policies
- ESMs include a rich representation of policy instruments and measures.
- Impact assessment of policies draws on comparisons of <u>scenario projections</u>, which differ regarding policy options
- A scenario is a projection into the future which includes explicit policy assumptions, often as a <u>collection of policies</u>
- <u>Targets</u> can be directly (or indirectly) included in the model at various levels, by sector, by country, and EU-wide
- The targets concern emissions, renewables, energy efficiency, security of supply, fossil fuel independence, and others.

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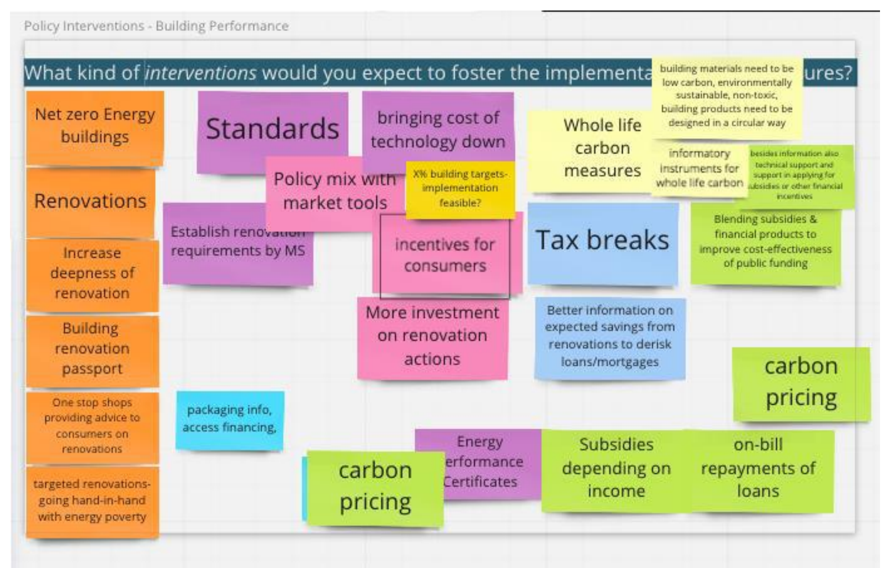
The role of stakeholders

Engaging external stakeholders in ESM development is enabled to:

- Learn about current trends and challenges from many practitioners’ perspectives
- Increase the transparency and outreach of ESM research



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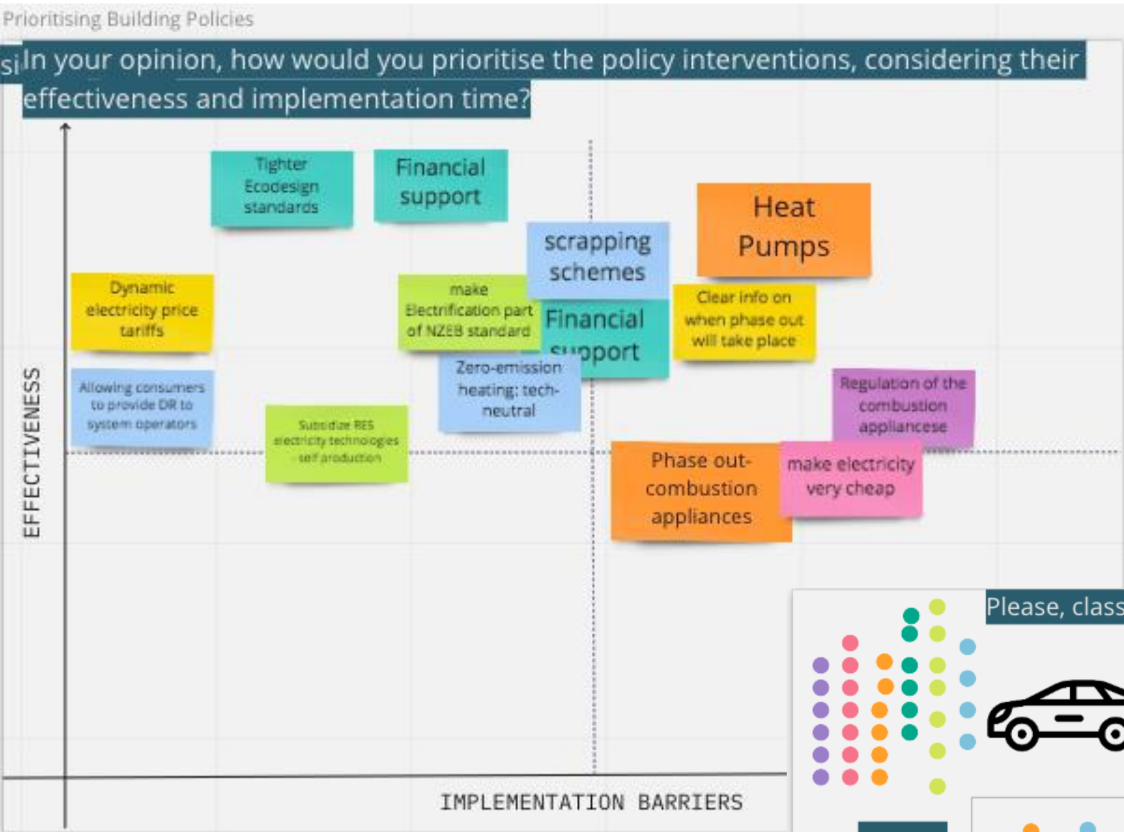
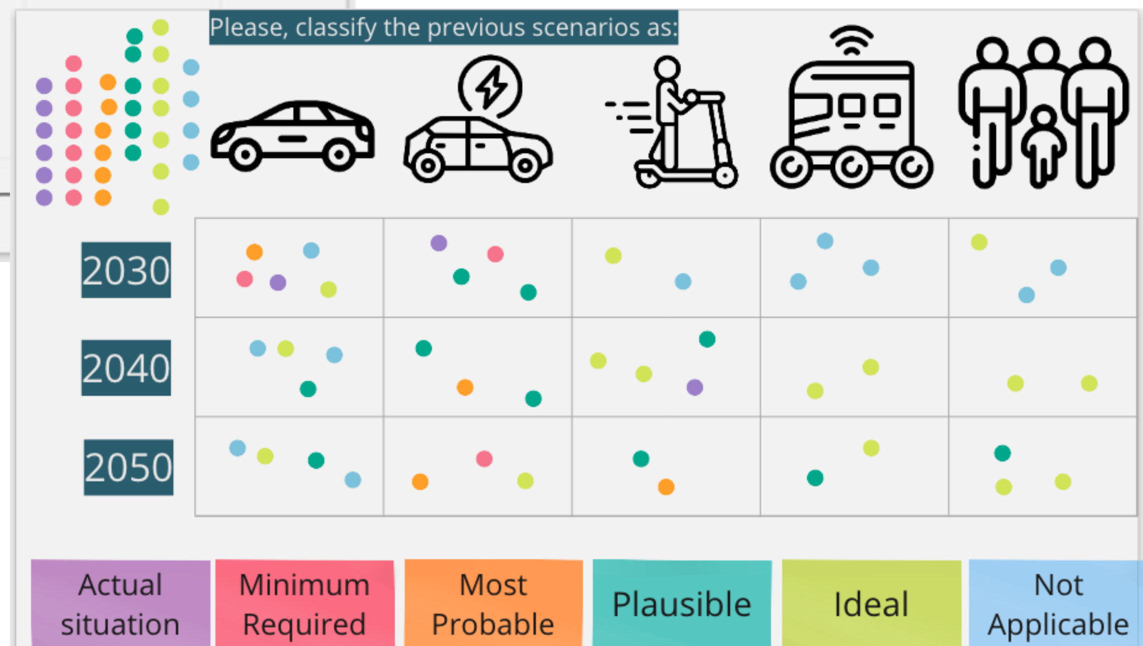
The role of stakeholders





Building an Energy System Model

Before start modelling:

1) **What is my research questions?**
   - ➢ Point of reference- focus on key requirements to answer questions
   - ➢ Distinguish “essential” features from “nice-to-have”
   - ➢ Has it been addressed already? Room for new insights?

2) **What is the hypothesis?**
   - ➢ What hypotheses should be tested?
   - ➢ What are the expected results?
   - ➢ What additional information can I provide other than the obvious?

3) **Who is my target audience?**
   - ➢ Research community, policy makers, students
   - ➢ Determines messages and level of detail/complexity to be communicated to the target audiences

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10 Steps to build an ESM

1. Decide on model objective and features
2. Gather underlying raw data
3. Process the data into usable formats
4. Import data from excel into programming software (GAMS, PY)
5. Formulate the model equations (link input with output)
6. Solve the model (for Business-As-Usual trends)
7. Generate model output- Test and validate model results
8. Create alternative “test” or “policy” scenarios
9. Post-processing & plotting of scenario results
10. Analysis of model-based results to inform research or policy

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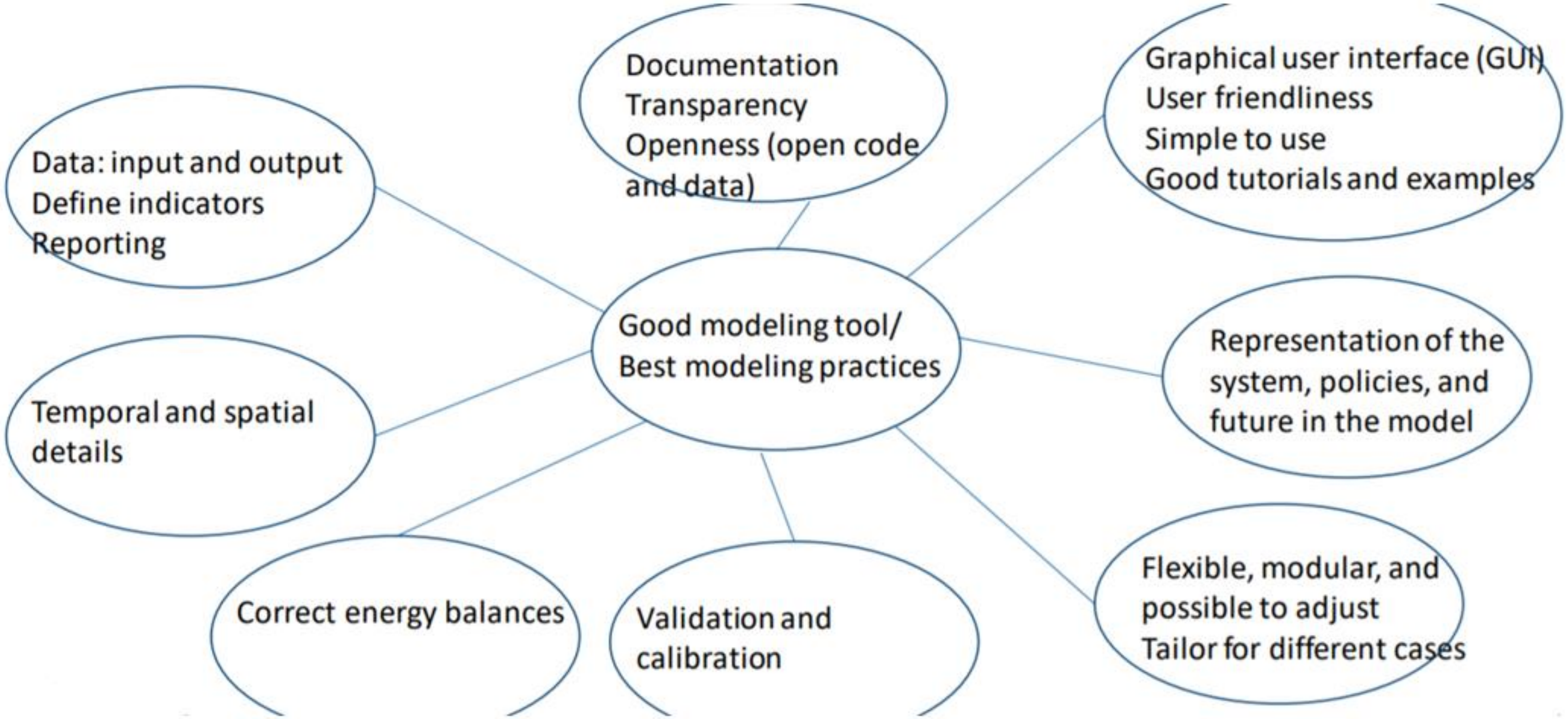
Desirable features of ESMs



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Practical considerations for building an ESM

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Choose an appropriate methodology for your research question

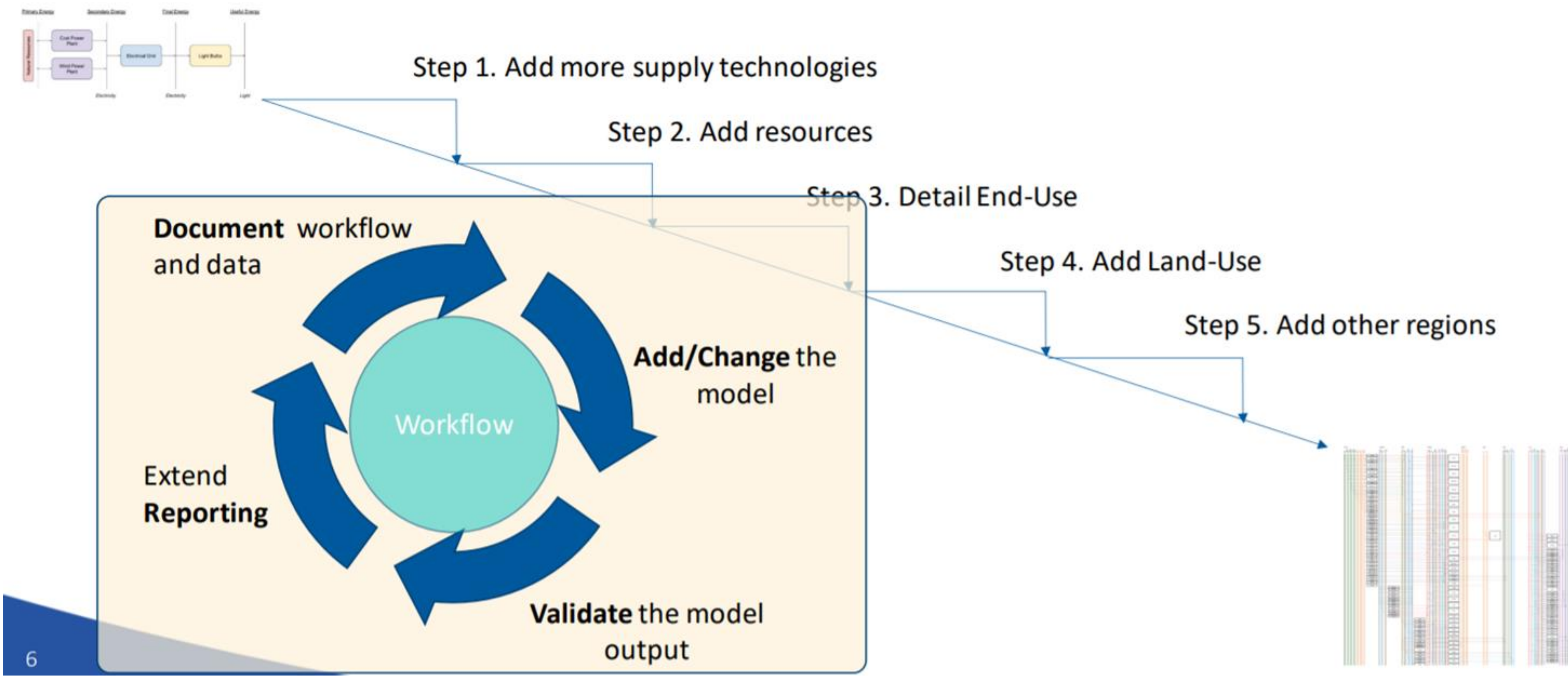
Commonly used methodologies:

- **Optimisation**: determines the optimal system according to a metric
- **Simulation**: determines the system given decision rules
- **Equilibrium**: determines system as a result of interacting agents

Dealing with uncertainty:

- **Deterministic optimisation** (perfect foresight): all future states (exogenous parameters) are known at the beginning of model horizon
- **Myopic optimisation**: decisions in period t are taken under no knowledge of future assumptions
- **Stochastic optimisation**: all future states along an “uncertainty tree” are known, including probabilities of each branch

Building an ESM: Start simple and add complexity



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Typical mathematical structure of ESMs

Minimising total discounted cost of the energy system

- Objective: least cost option to meet certain energy services
- System: a network of technologies, processes, resources and commodities (energy or non-energy products)
- Cost of system: purchasing and installing equipment/capacity, O&M of activity, taxes, emission penalties, other costs
- Constraints: meet useful energy needs, capacity factors of techs, RES intermittence, max use of technology, resource potential, growth/decline rates, reserve margin, policy constraints etc
- Technology examples: cars, power plants, buildings, ships, airplanes, industrial processes
- Commodities: oil products, natural gas, electricity, hydrogen, etc.

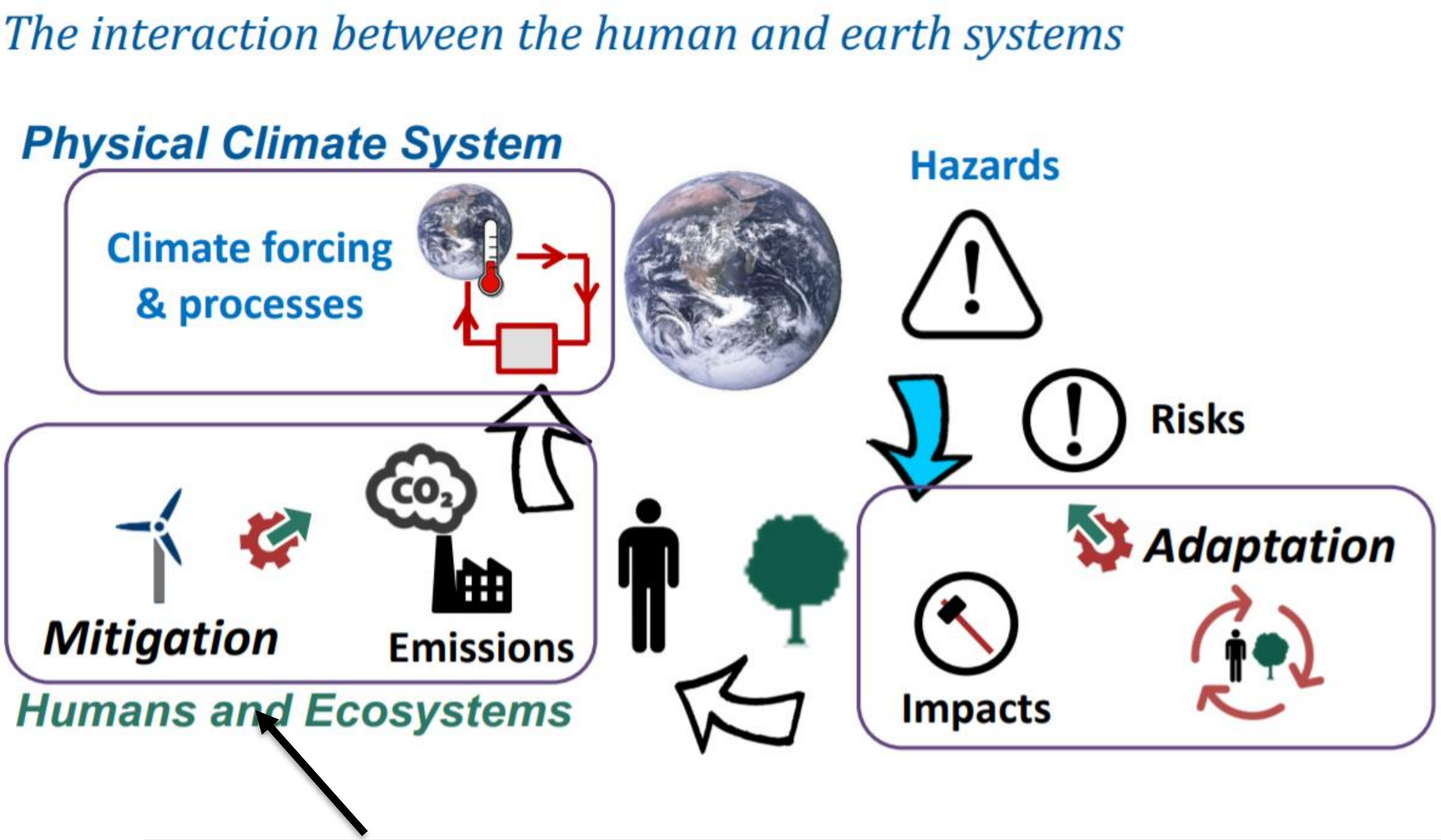
Issues to consider when you develop ESMs

- **Model Horizon**: What is the target? “end-of-horizon” effect
- **Level of temporal & spatial granularity**: What is the scope of the analysis?
- **Model Uncertainty**: is the methodology appropriate for the problem? Are the results dependent on the methodology used?
- **Parameter Selection**: Are you confident about input assumptions used?
- **Model simplifications for numerical tractability**: What are the trade-offs between high level of detail vs losing focus ? (e.g. how integrate to combine large amounts of variable RES)
- **System Boundaries**: Should be defined based on the model scope (e.g. it captures the energy system only or links with the economy?)
- **Model Closure:** Are assumptions to close the model valid? (e.g. trade)
- **Transparency**: documentation, open data/scenarios, open code?
- **Fit for Purpose**: to be used by policy makers or energy practitioners

How to test model behaviour?

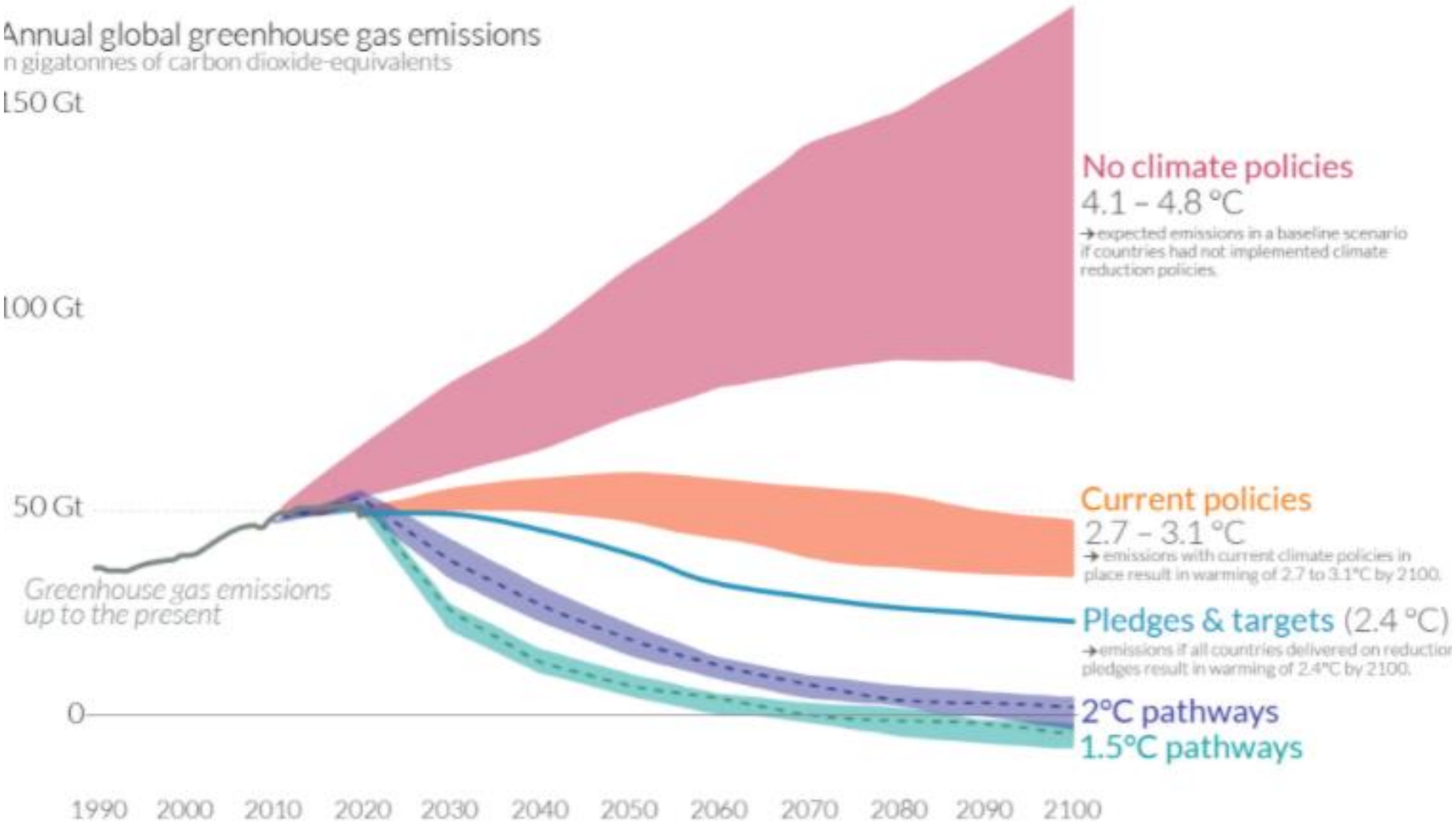
- Sensitivity analysis: Structured variation of key input parameters to understand the impact on results.
  - Relatively easy to do, but cannot be done for all model parameters
- Scenario analysis: Test the model in alternative scenario settings, exploring combinations of changes in parameters.
  - This cannot be done for all parameters and combinations
- Multi-criteria analysis: Include multiple dimensions/metrics in objective function and solve the model with different weights
  - Requires extra modelling work and is prone to modelling artefacts
- Model diagnostics (widely used in ESM and IAM communities): prescribe exogenous values for model parameters (e.g. carbon price) and evaluate the model behavior- by comparing it with other models
- Run the model in stochastic, Monte Carlo version

The "big" picture required to inform climate policy



Energy system modelling only one part of the overall picture

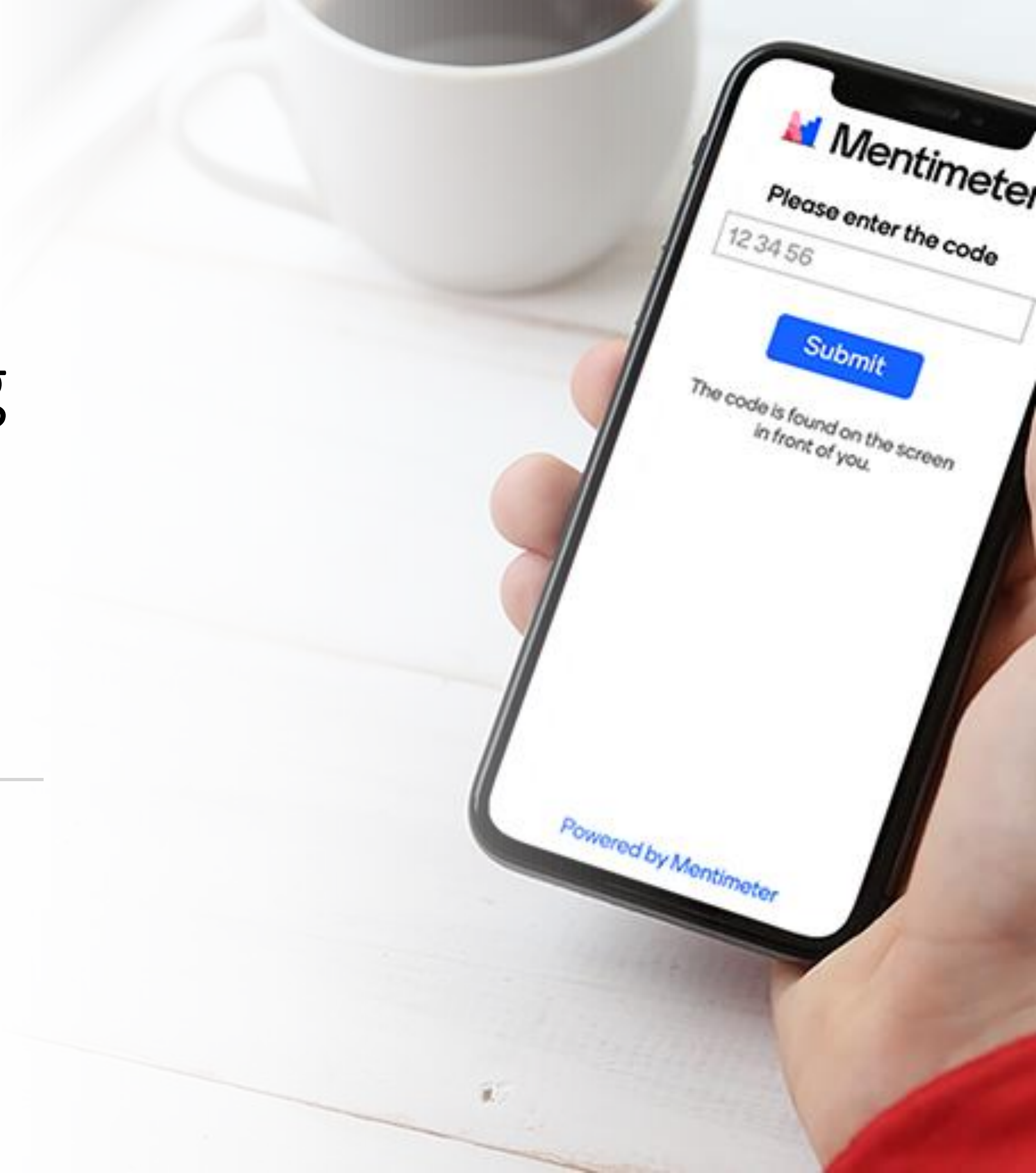
Global GHG emissions need to rapidly decline to meet Paris goals and reach net zero by or slightly after 2050



Net zero targets gain momentum with large emitters (EU, CHN, USA, Japan) announcing pledges to reach net zero by 2050 or 2060

https://ourworldindata.org/future-emissions

Challenges to modelling net zero energy systems



Significant challenges to model net zero energy systems

- Integrate novel technologies (e.g. CCU, electric trucks, electric aircrafts, e-fuels), whose uptake is very uncertain
- Integrate new disruptive options, e.g. CDR, BECCS, hydrogen, clean synthetic fuels, extreme RES etc.
- Modelling lifestyle changes in energy, transport and food systems
- Capture the interplay between decentralised RES and green H_2, optimal geolocation of electricity, hydrogen and e-fuel production plants
- Represent the uptake and competition of multiple storage options (e.g. batteries, pumping, H_2, e-gas)

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Significant challenges to model net zero energy systems

- Integrate circular economy and material flows
- Role of digitalisation, smart grids, automation, car sharing, MaaS, improved logistics
- Capture social and distributional aspects of decarbonization
- Capture links of energy transition with climate impacts (e.g. on HDDs/CDDs or the operation of power plants)

Modelling challenges in WHY project

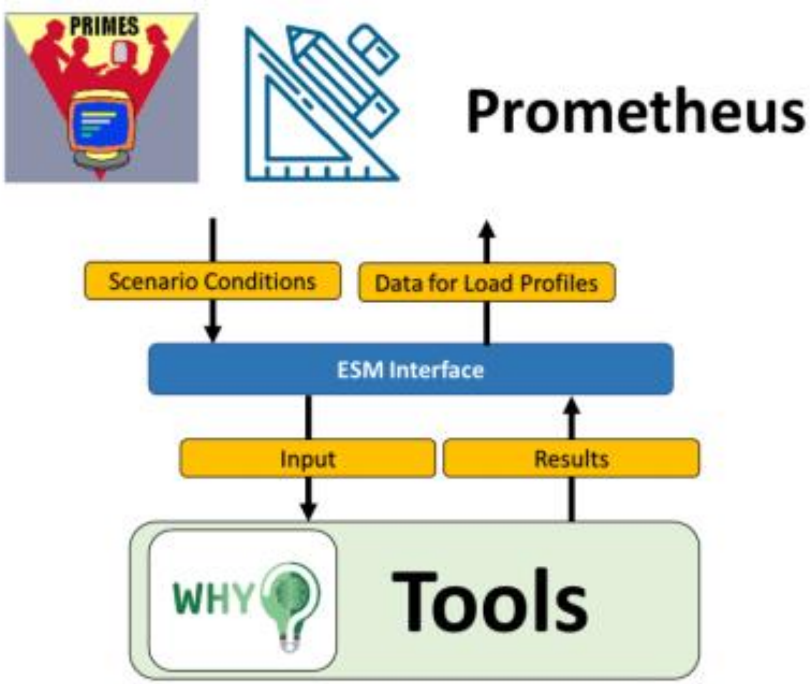
First, large-scale ESMs (PRIMES, PROMETHEUS, TIAM-ECN) will be enhanced with new mitigation options, which are required for the transition to climate neutrality by 2050:

- Represent non-market barriers and behaviors: Detailed segmentation of households and dwelling types
- Integrate new technologies and mitigation options (e.g. H2, clean fuels, prosumaging, deep renovation, demand response, deep electrification)
- Assess the synergies and trade-offs of the mitigation options, including the behavior of consumers
- Explore sector integration of buildings with other energy sectors through electrification, demand shifts, H_2 uptake, and mobility (EVs)
- Model the impacts of new policy interventions (e.g. ETS, renovation subsidies, blending mandates, measures targeting low-income classes)

Modelling challenges in WHY project (2)

Second, link large-scale ESMs with detailed modelling of energy consumers and highly disaggregated load profiles of the WHY Toolkit

- Develop interfaces between the bottom-up tools (high granularity up to household or appliance level) and large-scale ESMs
- Data exchange routines between the tools (upscale load profiles to integrate in ESMs)
- Model iteration algorithms need to be developed



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WHY project challenges: How to model COVID-19 impacts?

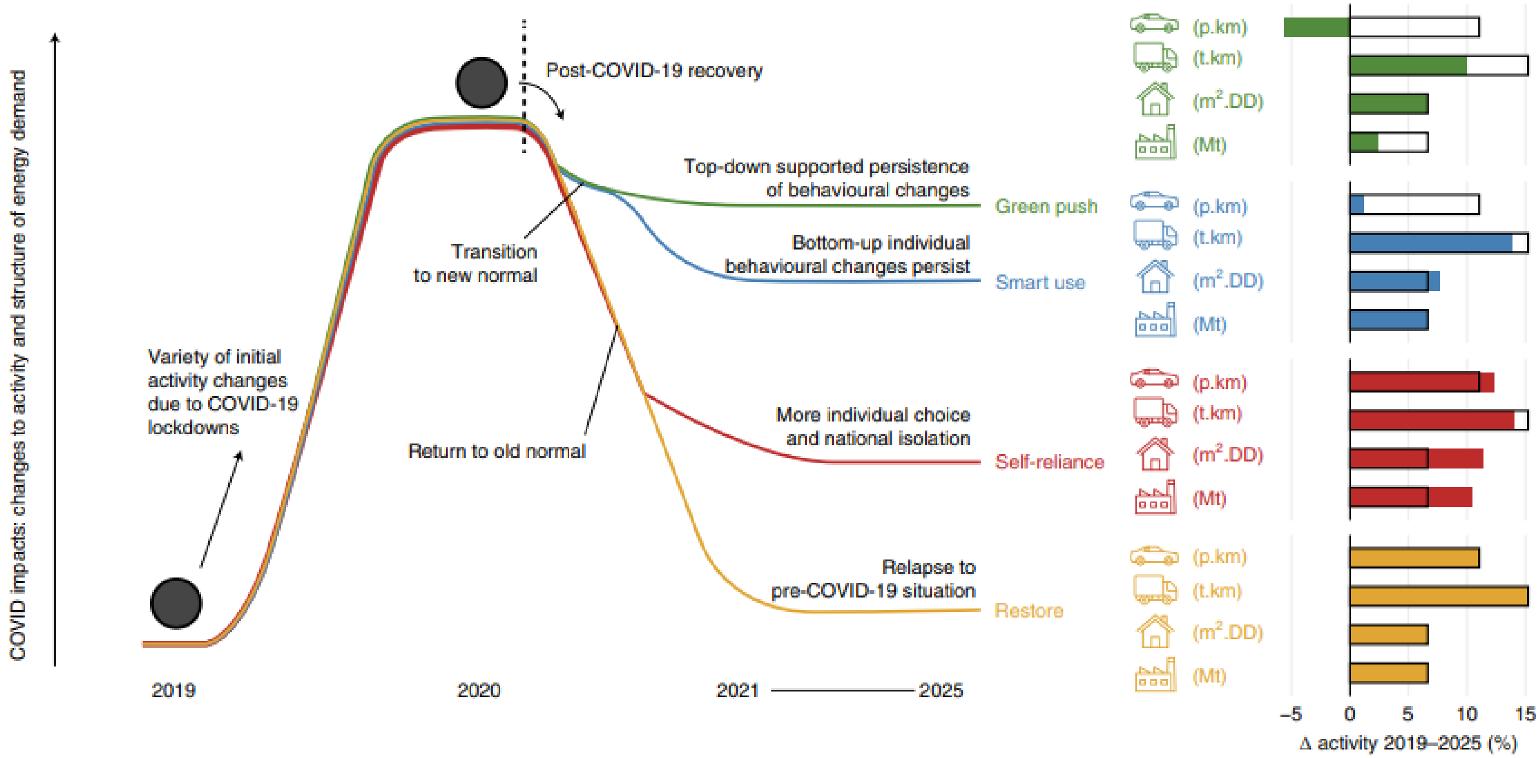

Fig. 1 | Scenario design along the axis of COVID-related impacts. Note that the *y* axis denotes disturbance compared with pre-pandemic 'normality' and not an increase in demand. Bar charts show relative changes in energy-related activity between 2019 and 2025 in passenger mobility (car icon), freight transport (truck icon), buildings (residential and non-residential; house icon) and industrial sectors (factory icon) for the four recovery pathways. The black outline boxes indicate the 2019–2025 change in the 'restore' scenario (yellow) and serve as a common reference point for the 'self-reliance', 'smart use' and 'green push' scenarios (red, blue and green, respectively). Indicators are passenger-kilometre (p.km), tonne-kilometre (t.km), metre squared-degree days (m^2.DD) and material production in million tonnes (Mt). This image has been designed using resources from Freepik.com.

Source: Kikstra et al. Climate mitigation scenarios with persistent COVID-19 - related energy demand changes, Nature Energy, 2021

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Summary

Large importance of ESMs in energy planning, investment decisions and climate policy impact assessment

However, always keep in mind that ESMs are not crystal balls and cannot predict the future with certainty, but can provide interesting insights

Several methodologies to use: Choose the one that is appropriate for the specific problem/research question

ESMs adapt to changing policy priorities (e.g. from oil planning to integration of renewable energy)

The net zero targets pose new challenges to ESMs

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EMP-E 2021: Re-Energising Sustainable Transitions in Europe

Energy System Modelling, Methods & Results to support the European Green Deal

26th to 28th October · online

Thank you for your attention
Q&A session

For questions/comments please contact:

Panagiotis Fragkos (fragkos@e3modelling.com)

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WHY

Renewables Grid Initiative

hosted in cooperation with the European Commission