IFE

Guest Lecture
Master course

27.10.2023
10:00 -12:00

NMBU

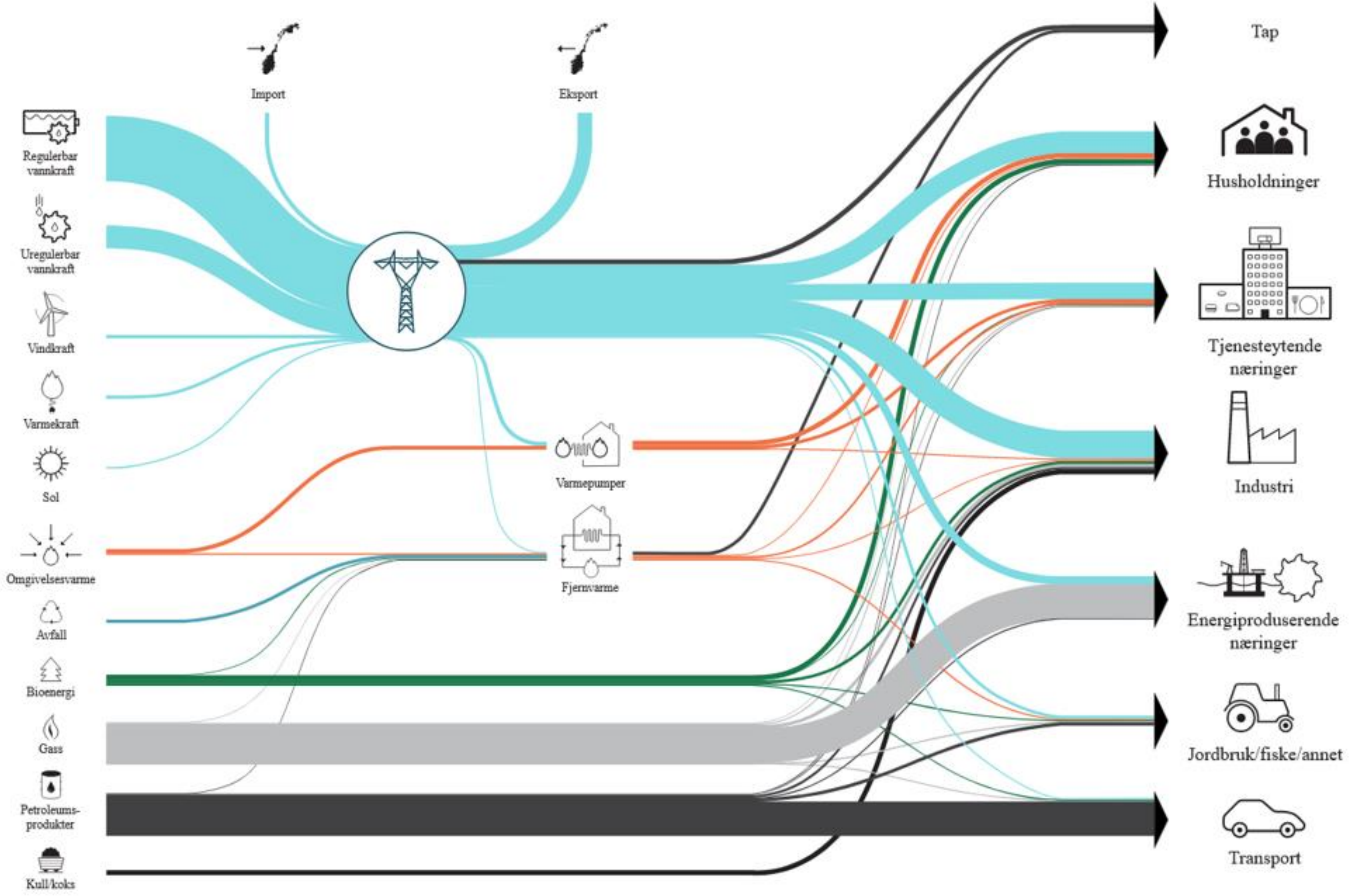
Energy system modelling: The TIMES modelling framework

Dr Pernille Seljom

Senior research scientist, Renewable Energy Systems
Institute for Energy Technology (IFE)

Associate Professor, Institute for Technology systems (ITS)
University of Oslo (UiO)

Motivation for energy system analysis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Eksport
Regulerbar vannkraft
Uregulerbar vannkraft
Vindkraft
Varmekraft
Sol
Omgivelsesvarme
Avfall
Bioenergi
Gass
Petroleums-produkter
Kull/koks
Varmepumper
Fjernvarme
Tap
Husholdninger
Tjenesteytende næringer
Industri
Energiproduserende næringer
Jordbruk/fiske/annet
Transport

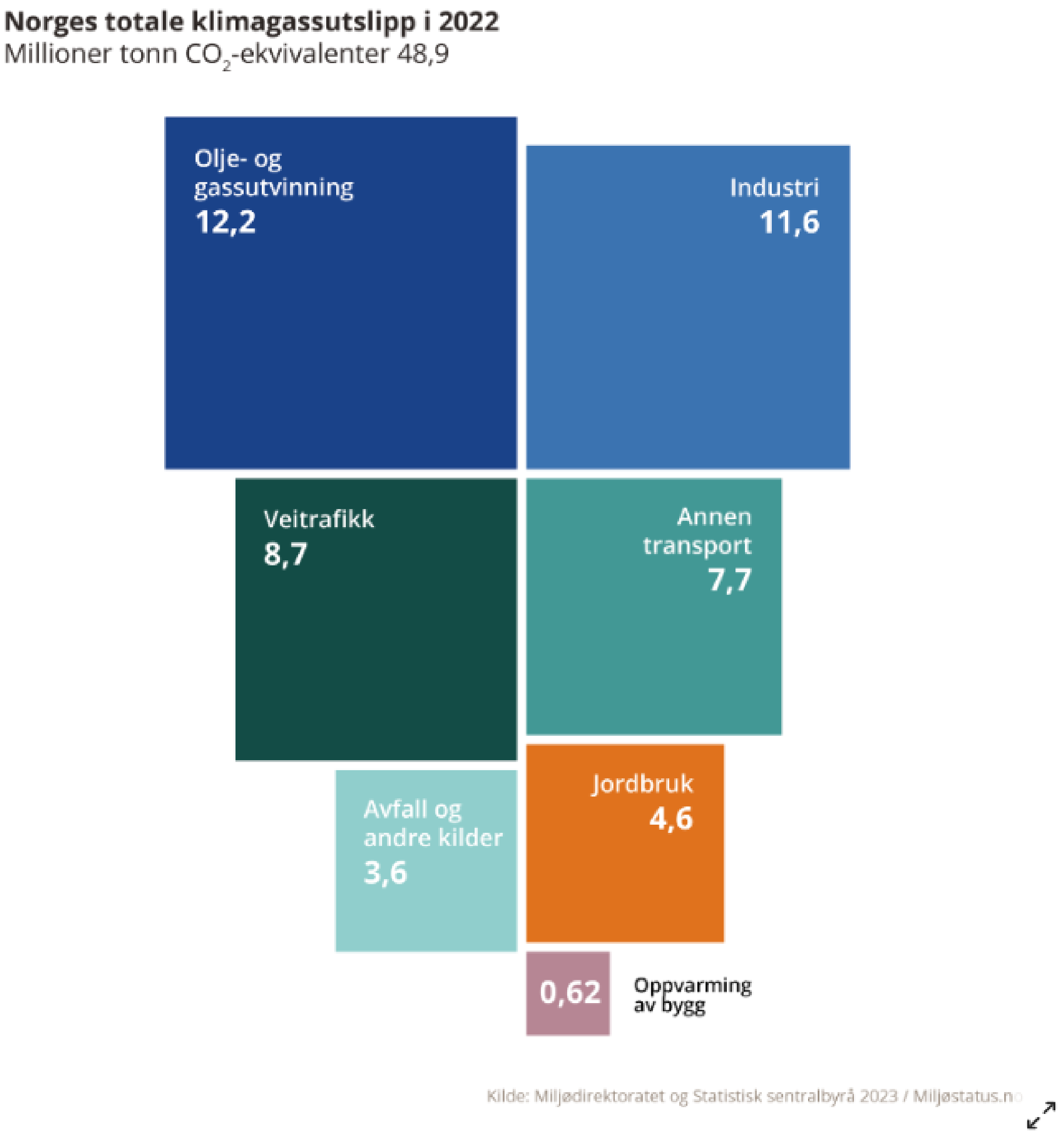
Norwegian emissions in 2022

In CO_2 equivalents:

- Oil and gas: 12.2 Mt
- Industry: 11.6 Mt
- Road transport: 8.7 Mt
- Other transport: 7.7 Mt
- Agriculture: 4.6 Mt
- Waste: 3.6 Mt
- Buildings: 0.2 Mt

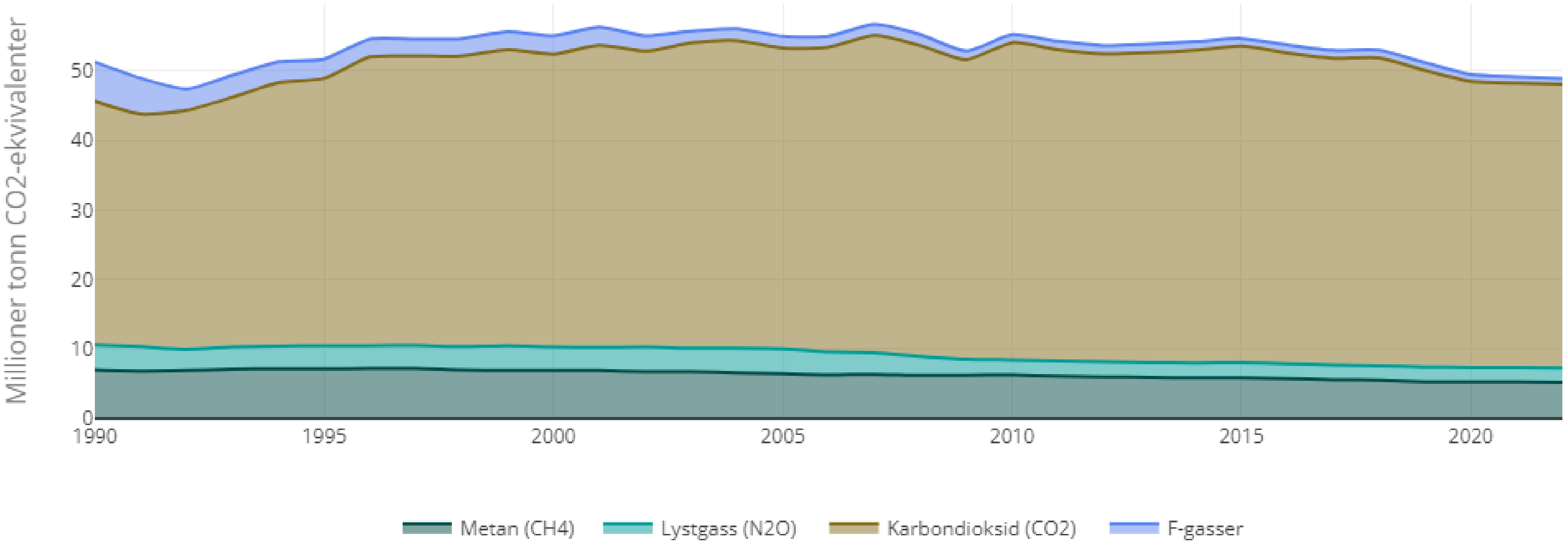
CO_2 equivalents:

- 1 x CO_2
- 25 x CH_4
- 298 x N_2O



Totale utslipp av klimagasser i Norge i 2022, fordelt på ulike sektorer. Tallene kommer fra det norske klimagassregnskapet. | | *Kilde: Miljødirektoratet og Statistisk sentralbyrå (SSB) 2022 / Miljøstatus.*

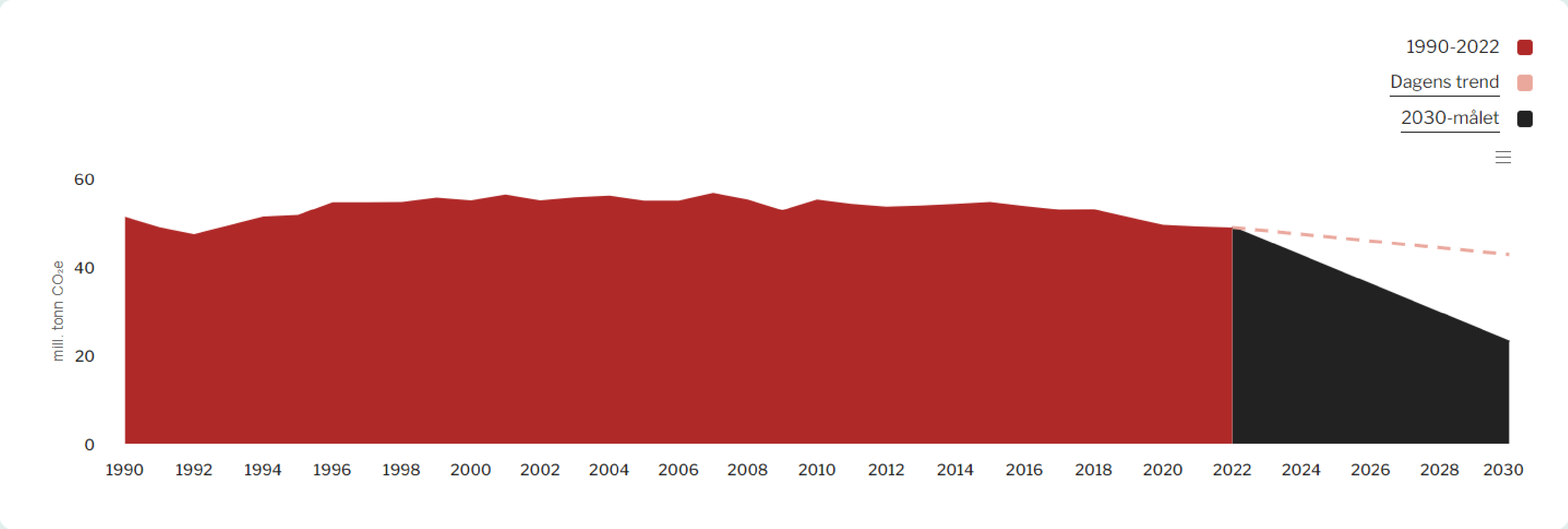
Historical climate gas emissions



Kilde : Statistisk sentralbyrå (SSB) og Miljødirektoratet

Motivation

Hvor er vi i 2030 om dagens utslippstrend fortsetter?



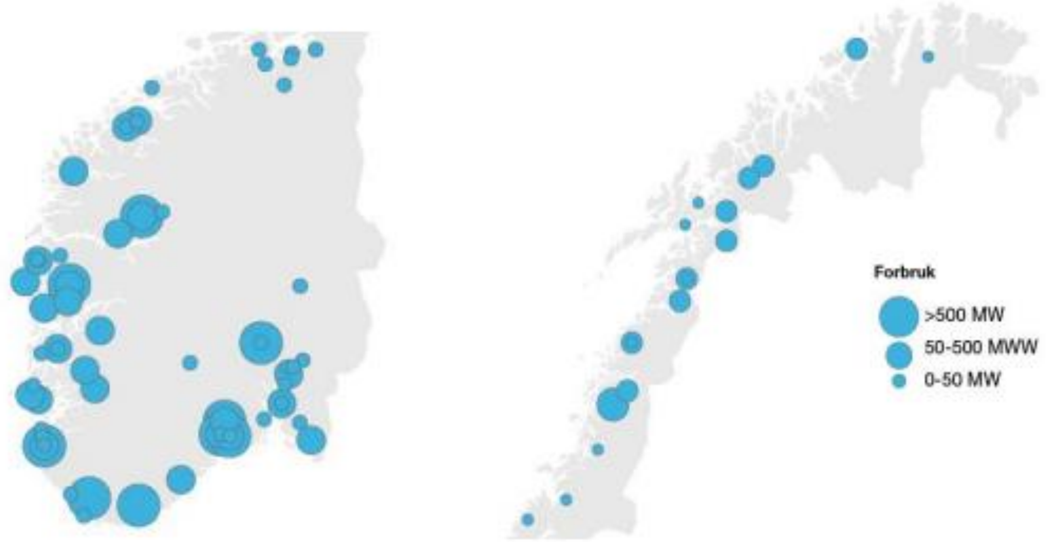
Kilde: SSB

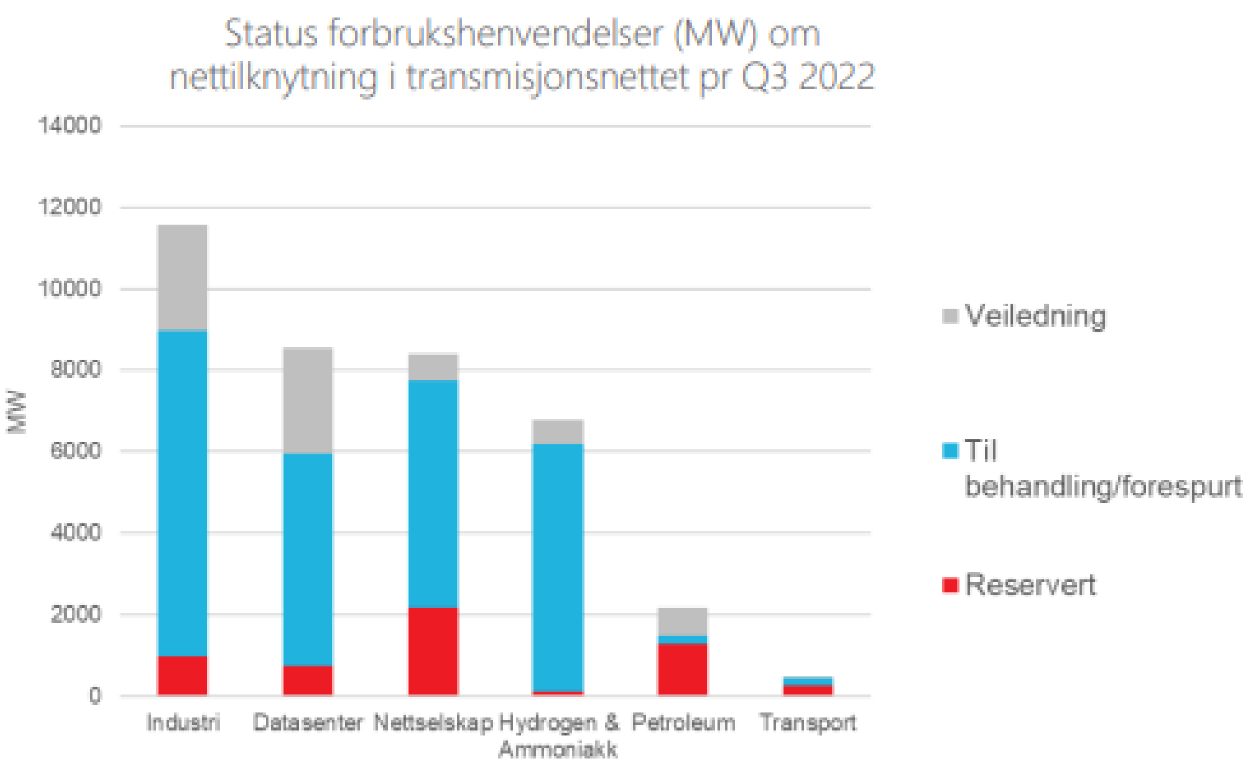
[Klimagassutslipp | tilnull.no]


NEI TIL VINDKRAFT I TYSVÆR
NEI TIL
DRAPSMASKINER
JA, TIL FOLKET
NEI TIL STØY FRA
VINDTURBINER
STOPP
TYSVÆR
VINDKRAFTVERK
Nei
til vindkraft
NEI TIL
ØDELEGGELSE
AV
LIVSKVALITET

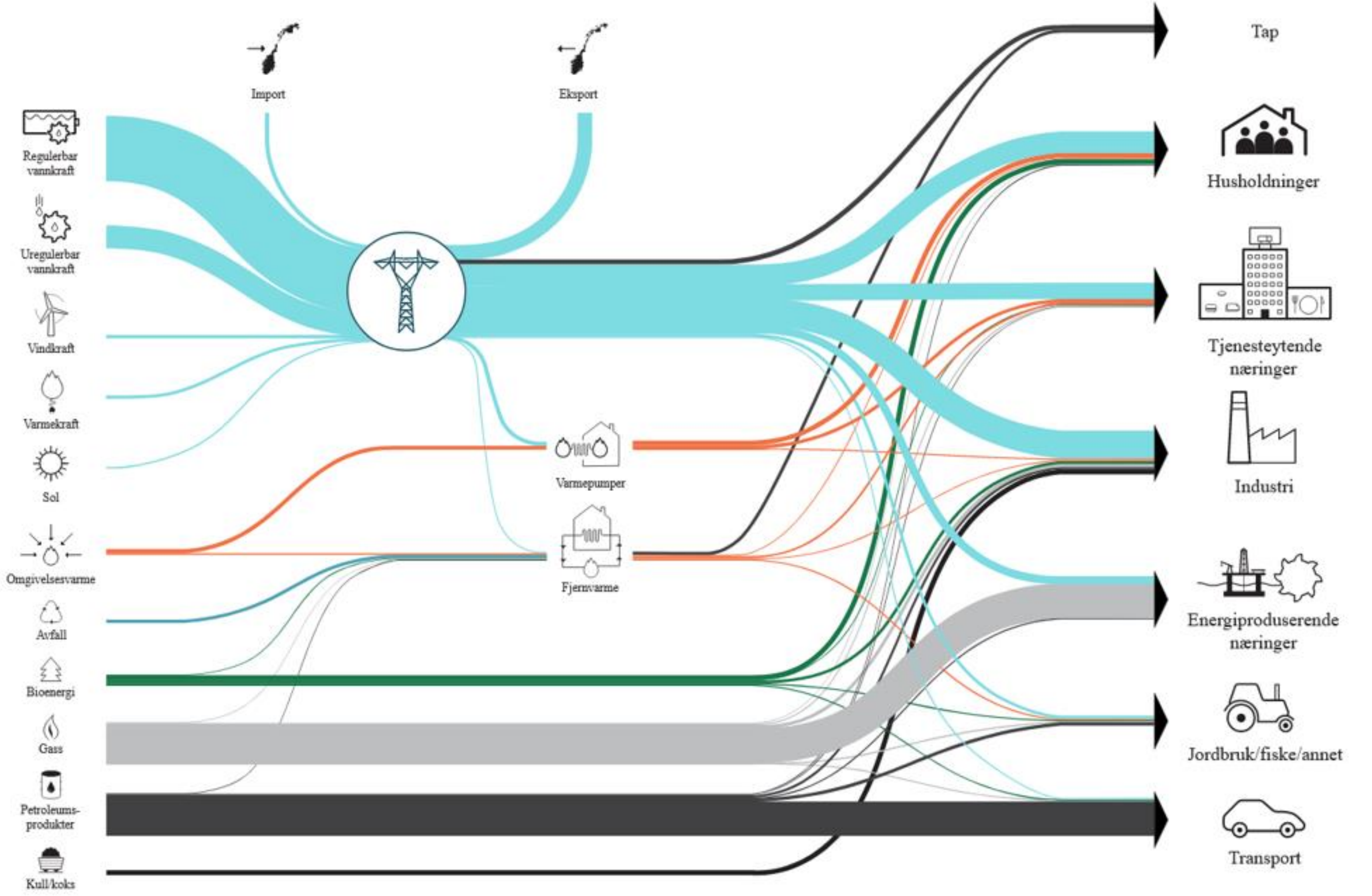
Store volumer planlagt forbruksvekst i industri og næring

Oversikt over lokalisering og volum på tilknytningssaker






Elektrifisering av Melkøya
KLIMASVINDEL OG TØV!
NEI
MOTVIND
NORGE
www.motvind.org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Industri
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Jordbruk/fiske/annet
Transport

Energy system analysis – definitions and vocabulary

Energy system

- «An energy system covers the relationship between energy carriers, energy generation technologies, energy storage, energy infrastructure and end-use sectors»

- Understanding energy system dynamics is necessary to design a future energy system
  - at an affordable cost
  - with a low carbon footprint
  - ensuring energy security

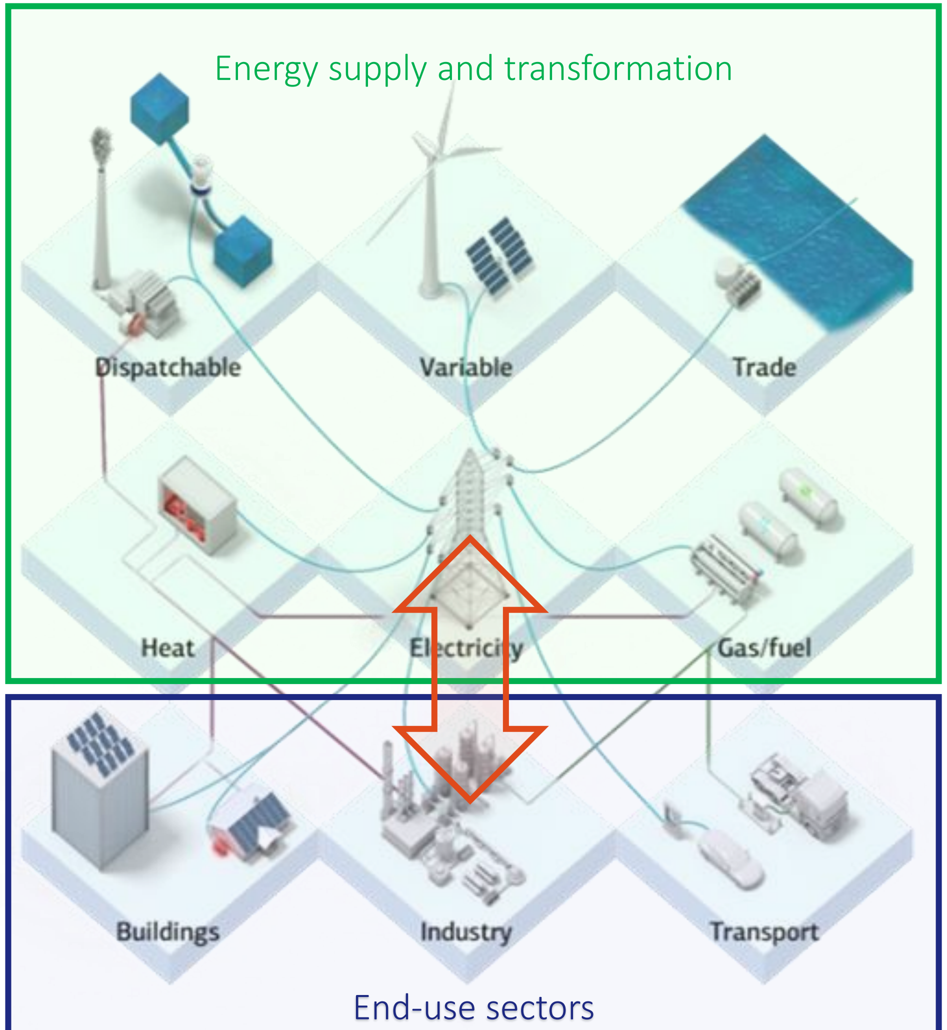


Figure: IEA, NETP 2016

Cambridge dictionary definition energy system

Meaning of ***energy system*** *in English*

energy system

noun [C]

UK US

NATURAL RESOURCES, ENVIRONMENT

a group of things that are used together to produce energy:

- This definition does not capture the linkage with end-use sectors
- Suggested rephrase: “a group of things that are used together to meet energy service demand”.

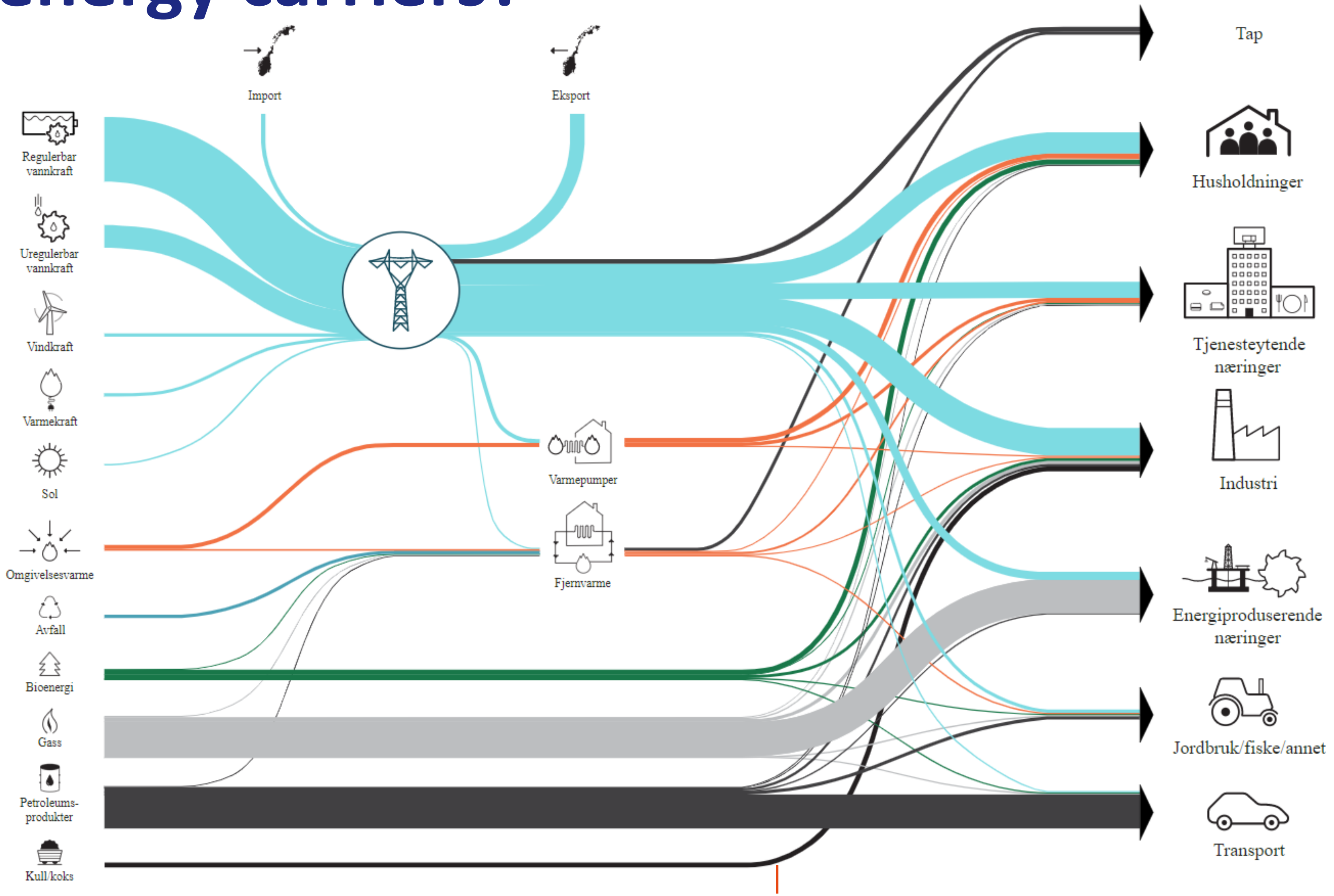
Energy service demand

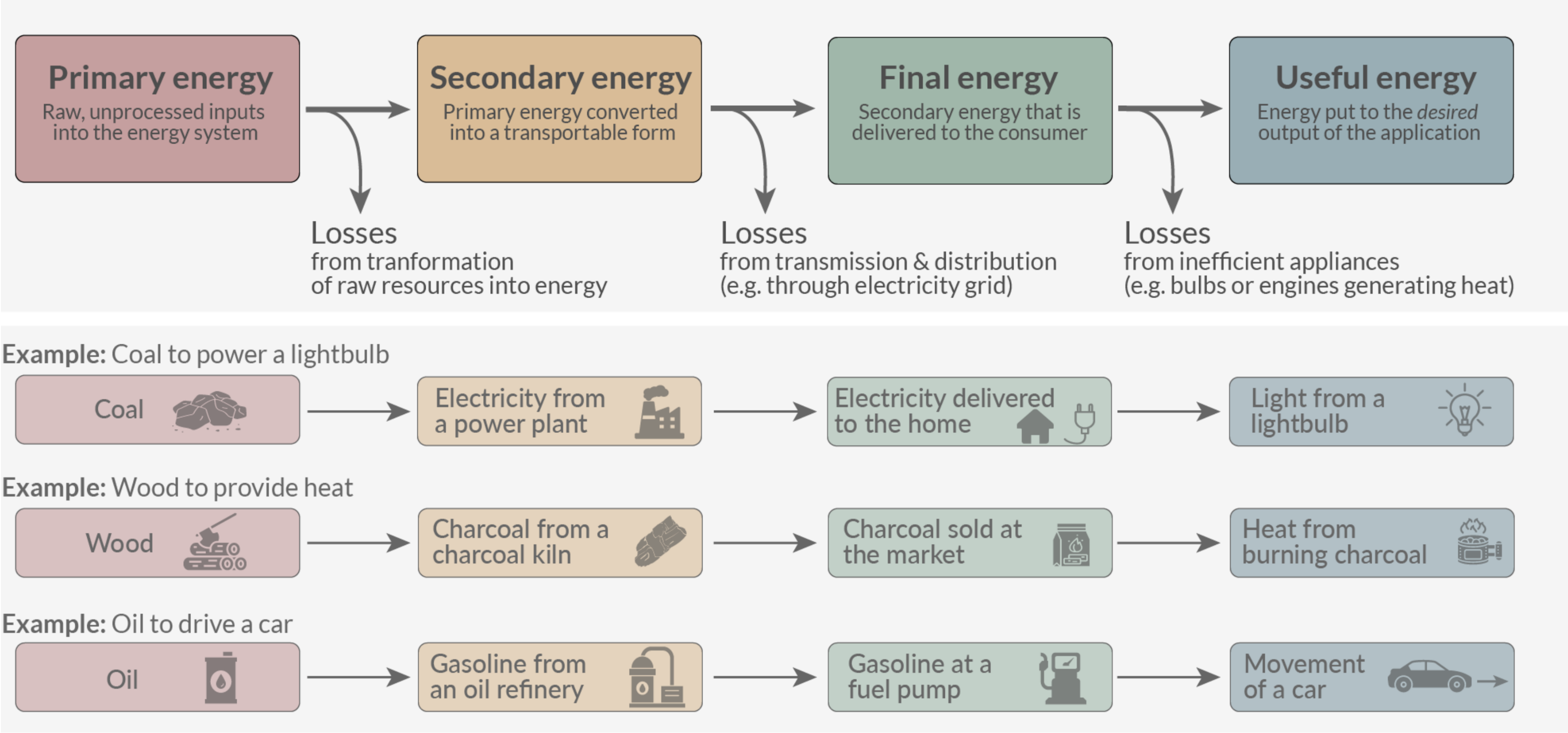
- "energy services refer to the services provided by consuming a fuel and not the fuel consumption itself. For example, the heating demand in buildings is an energy service while the fuel used to heat the building is not."

- The energy service demand influences the demand for final energy

- Examples of service demands:
  - Space heating
  - Cooking
  - Lighting
  - Personal vehicle kilometers
  - Cooling
  - Rail

Why differ between energy service demand and energy carriers?





Icon source: Noun Project.

Electrification of the energy system

- A future energy system consumes more electricity than today

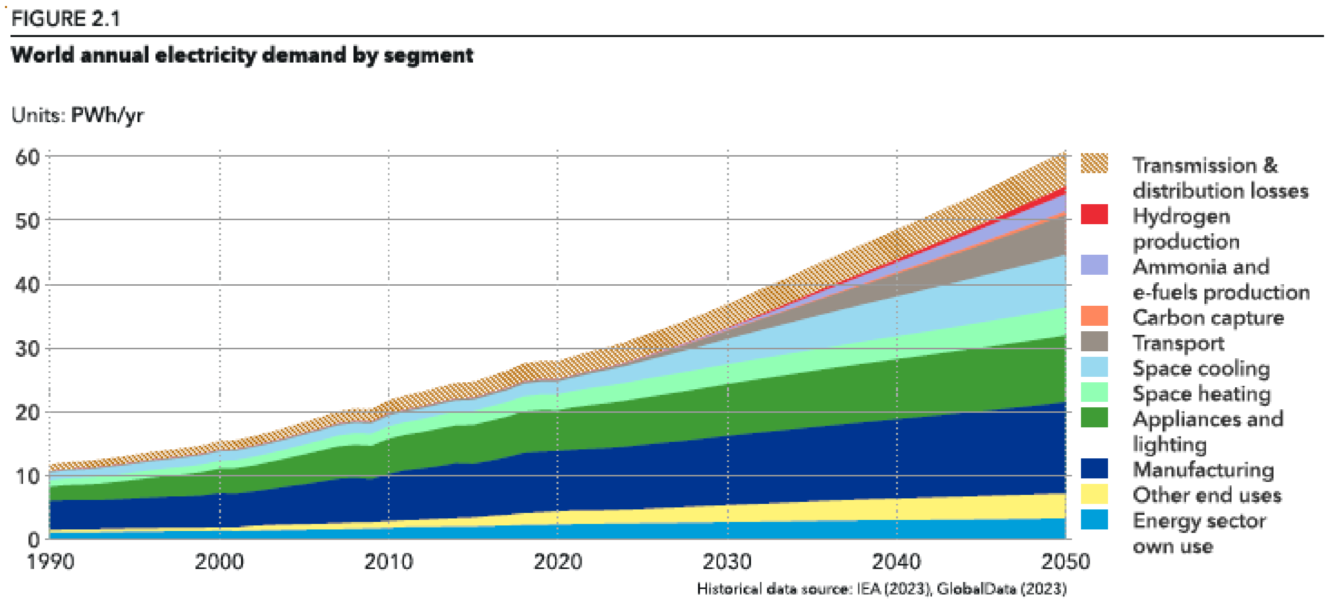


Fig. Energy Transition Outlook 2023, DNV-GL

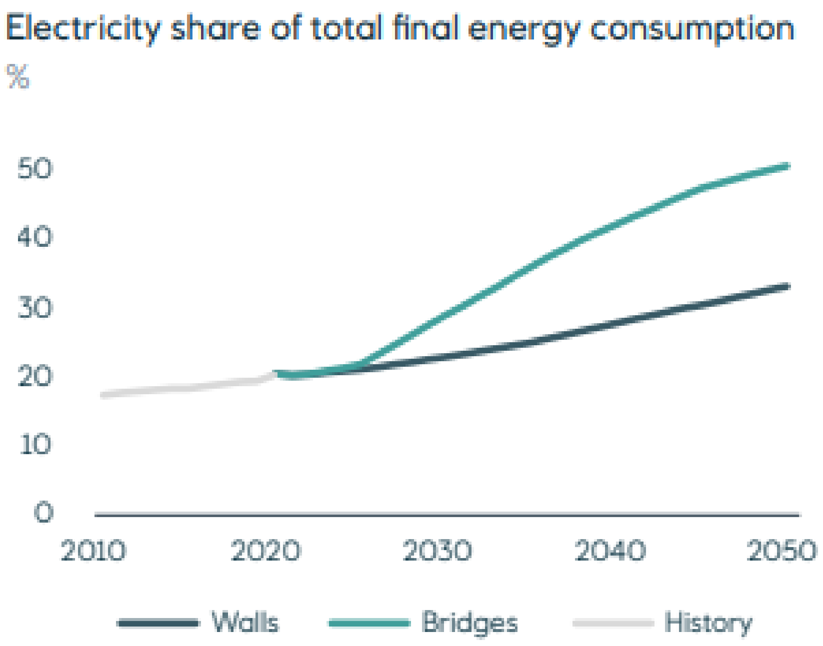


Fig. Equinor Energy Perspectives

Electrification of the energy system

“Electrification refers to the process of replacing technologies that use fossil fuels (coal, oil, and natural gas) with technologies that use electricity as a source of energy. Depending on the resources used to generate electricity, electrification can potentially reduce carbon dioxide emissions.”

- Use of green hydrogen is sometimes defined as electrification when replacing fossil fuels.

Sector coupling

“Sector coupling involves the increased integration of energy end-use and supply sectors with one another. This can improve the efficiency and flexibility of the energy system as well as its reliability and adequacy. Additionally, sector coupling can reduce the costs of decarbonization”.

Sector coupling

There is no universally agreed definition of sector coupling. From IRENA's perspective, it can be defined as the process of interconnecting the power sector with the broader energy sector (e.g. heat, gas, mobility).

1.3 Sector coupling provides the enhanced flexibility that energy systems need

What is sector coupling?

While the term "sector coupling" is relatively new, the concept has been explored for decades.[2] It was first applied in Germany to underline the importance of electrifying energy end uses other than those of the power sector, such as in the transport, industry, buildings and heating sectors. Initially, the concept centred on making good use of excess electricity generated from VRE sources, particularly solar PV and wind power, which otherwise may be curtailed and wasted (Van Nuffel, 2018). Sector coupling can also provide clear benefits for a more efficient, electrified and renewable-based electricity system by enabling ancillary services in the organised wholesale electricity markets, if demand response can be enabled to participate in these markets through better design.

Over time, the scope of sector coupling has been expanded to cover the enhanced system flexibility that an energy system would require to address the emerging challenges of grid stability posed by integrating high shares of VRE. With the support of digitalised and smart systems, sector coupling technologies – such as electric vehicles (EVs) with smart charging, electric boilers and heat pumps, and electrolysers for hydrogen production – enable the demand to be more responsive to electricity prices or other signals in a physically interconnected network.

IRENA
International Renewable Energy Agency

SECTOR COUPLING
IN FACILITATING INTEGRATION
OF VARIABLE RENEWABLE
ENERGY IN CITIES

Questions for reflections

- What is energy service demand of this building?

Building mass upgrade

- What are consequences for the building owner?
- What are consequences for the energy system?
- How will it influence cost of distribution grid tariff?

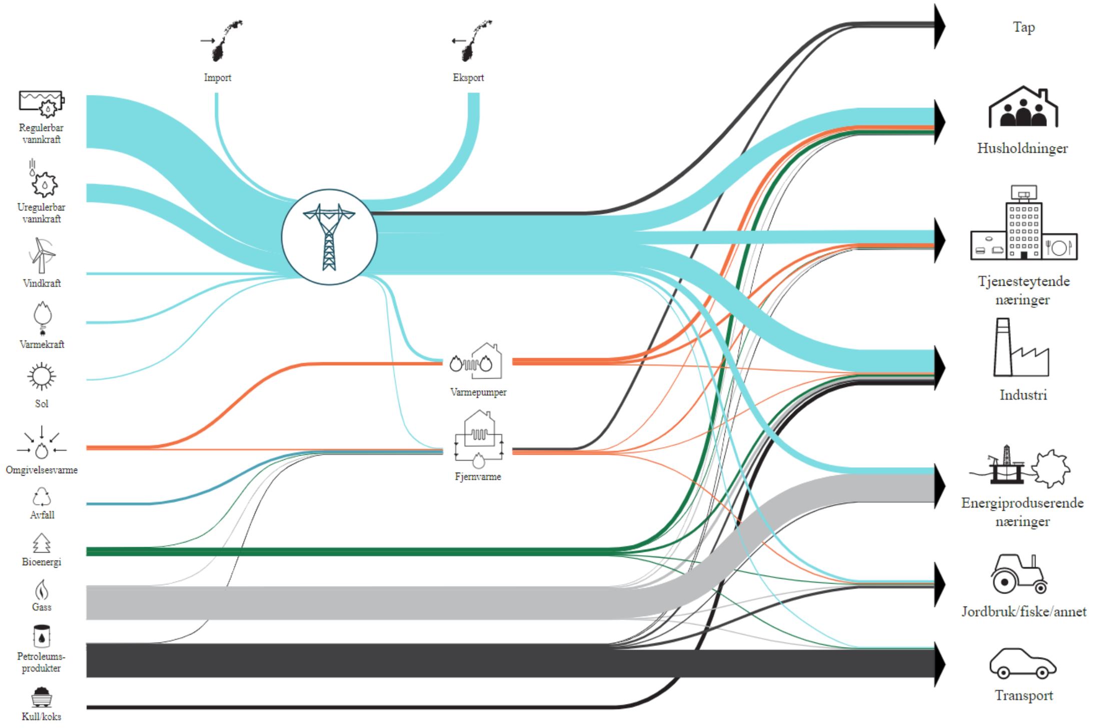
Questions for reflections

- What are main energy carriers in the Norwegian energy system?

- What is energy service demand ? And how does it relate to final energy use?

- What is the benefit of modelling the demand for energy service rather than the demand for energy carriers in an energy system model?

- What is the consequences and value of sector coupling in the energy transition?



Energy system models

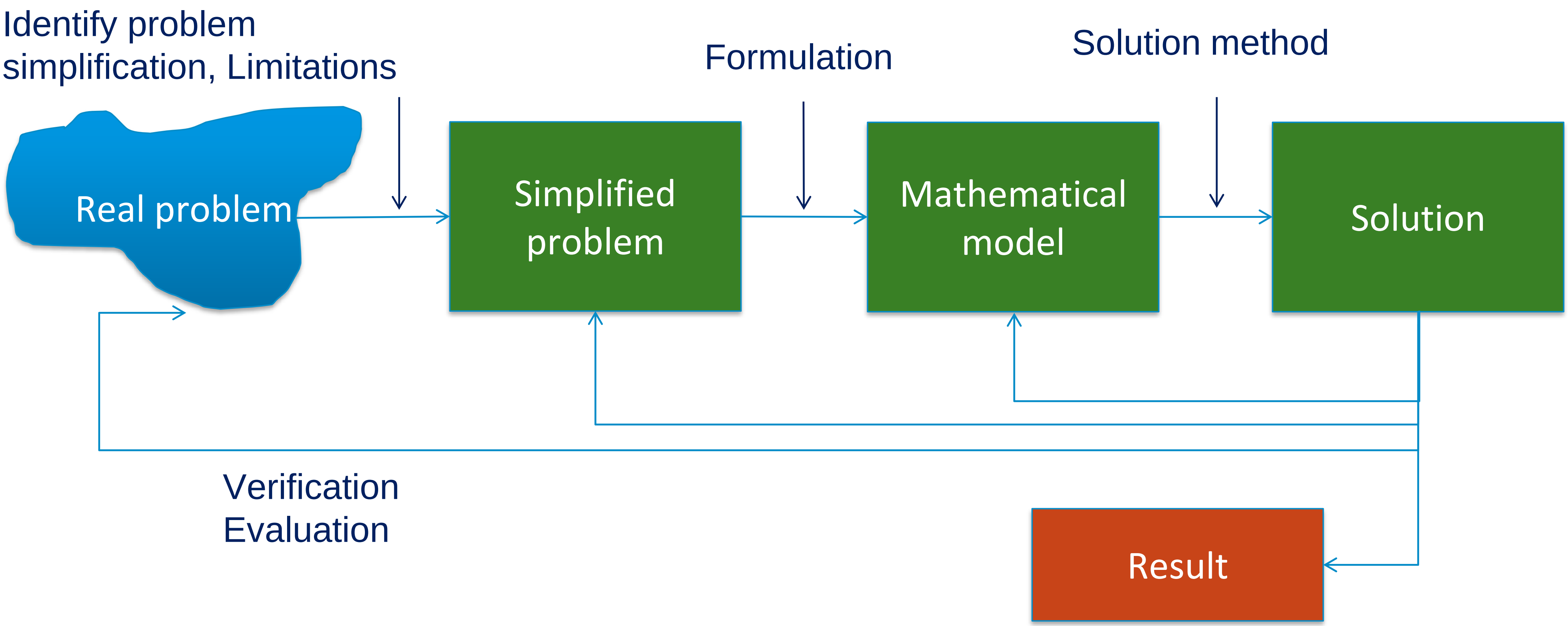
Mathematical modeling

«Mathematical modeling is the art of translating problems from an application area into tractable mathematical formulations whose theoretical and numerical analysis provides insight, answers, and guidance useful for the originating application"

From: https://www.mat.univie.ac.at/~neum/model.html

Energy system model: A tractable mathematical formulation of an energy system that provides insights, decision support for energy system design

A mathematical model is a simplification of reality



- How do we best proceed from a real problem to a stylized simplified set of mathematical equations?

Energy system model

- Tool to systemize complex energy systems
  - Interaction between sectors, energy carriers and technologies
  - Infrastructure and investment requirements
  - Requirements to meet policy goals, e.g. CO_2 emission target
  - Efficient energy resource utilisation
  - Impact of various energy prices, technical learning curves, energy service demand & political decisions

Figure: Adobe Stock

Energy systems models

- Energy system - energy supply, distribution & consumption
- Energy system model: A mathematical formulation that provides insights and decision support for energy system design
  - at an affordable cost
  - with a low carbon footprint
  - ensuring energy security
- A tool to systemize complex energy systems for knowledge-based decision support

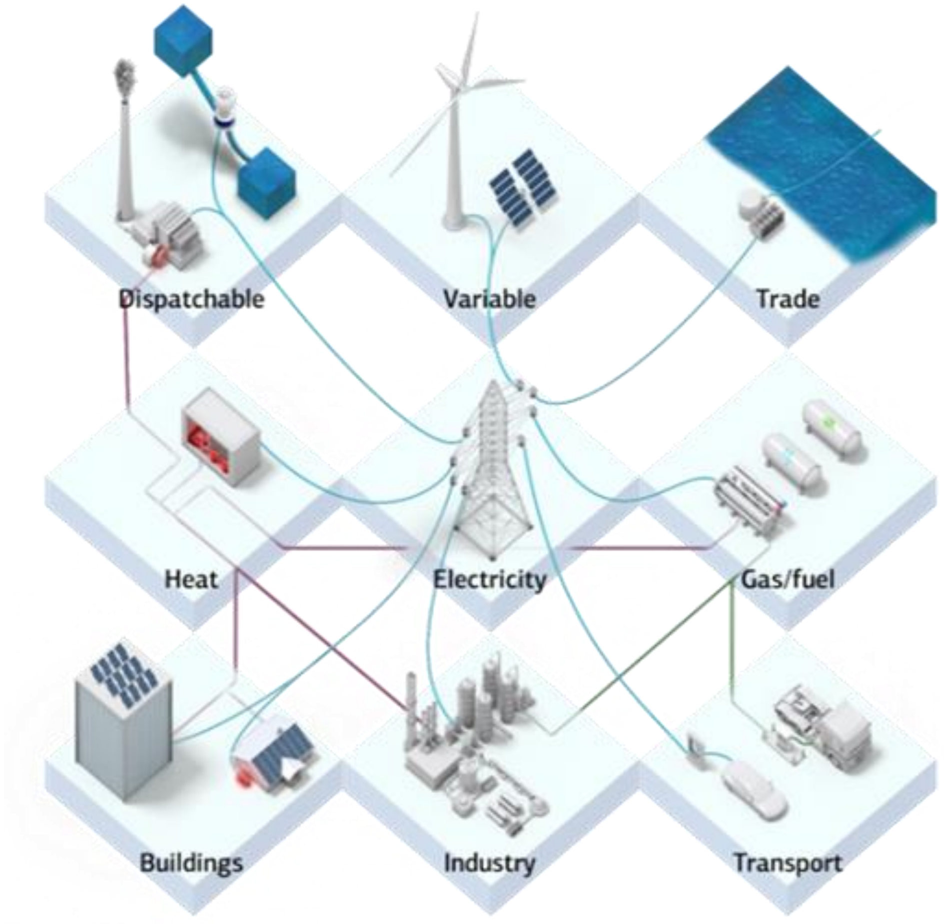


Figure: IEA, NETP 2016

Energy system model

- Tool to provide insights
- Improve knowledge base

↓

- Provide insights to decision makers

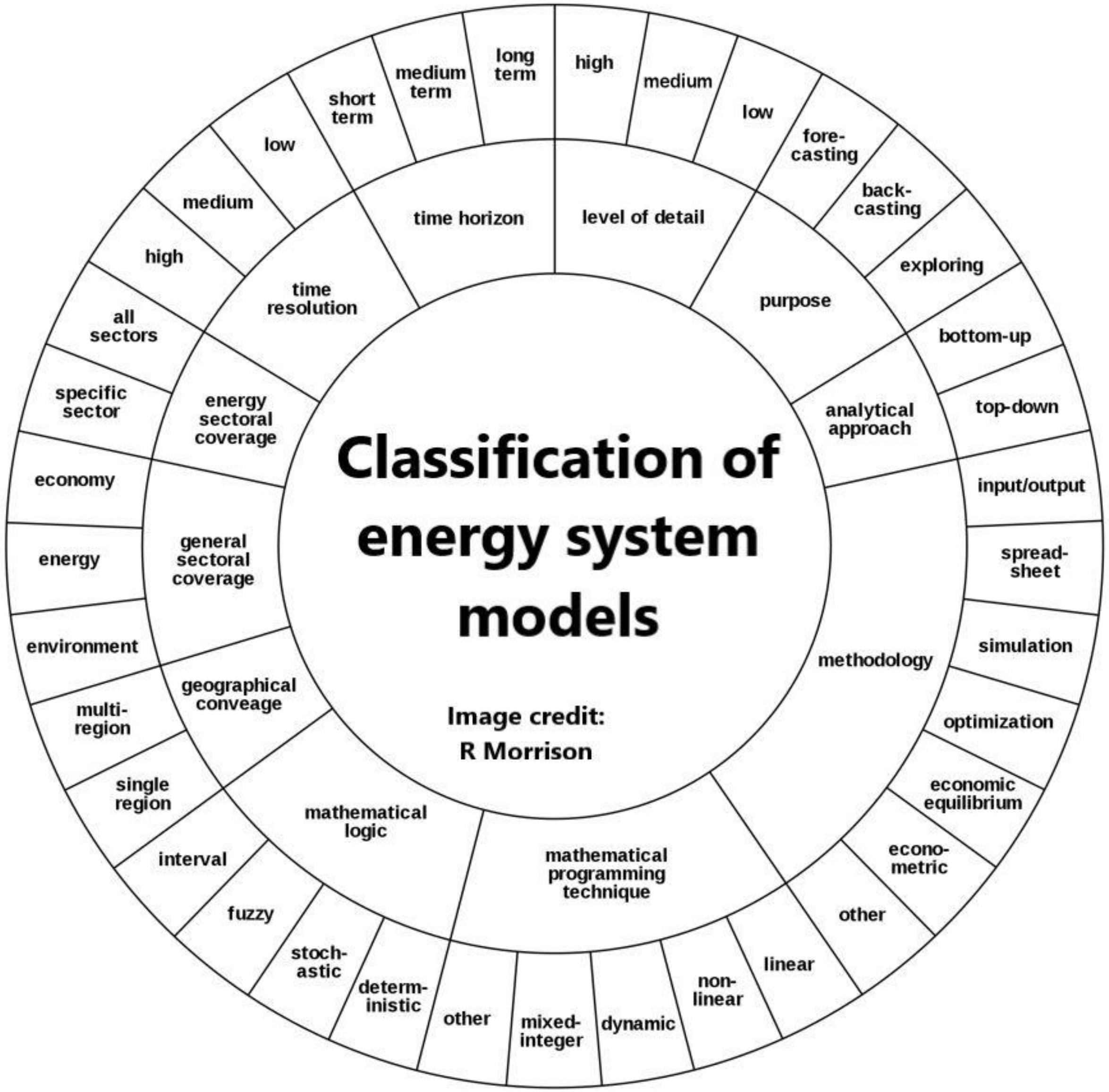
↓

- Knowledge-based
  - energy system development
  - quantification of alternative pathways and energy system effects

Figure: UnSplash

Example: Can Norway be decarbonised without further wind power expansion?

- At what cost?
- How does it influence
  - Electricity price?
  - Need for other electricity generation?
  - Final energy consumption?
  - Electricity trade


Classification of energy system models
Image credit: R Morrison
time horizon
level of detail
purpose
analytical approach
methodology
mathematical programming technique
mathematical logic
geographical conveage
general sectoral coverage
energy sectoral coverage
time resolution
long term
high
medium
low
fore-casting
back-casting
exploring
bottom-up
top-down
input/output
spread-sheet
simulation
optimization
economic equilibrium
econo-metric
other
linear
non-linear
dynamic
mixed-integer
other
determ-inistic
stoch-astic
fuzzy
interval
single region
multi-region
environment
energy
economy
specific sector
all sectors
high
medium
low
short term
medium term

Long-term energy system model

Time horizon: medium to long-term (2050)

Purpose: exploring

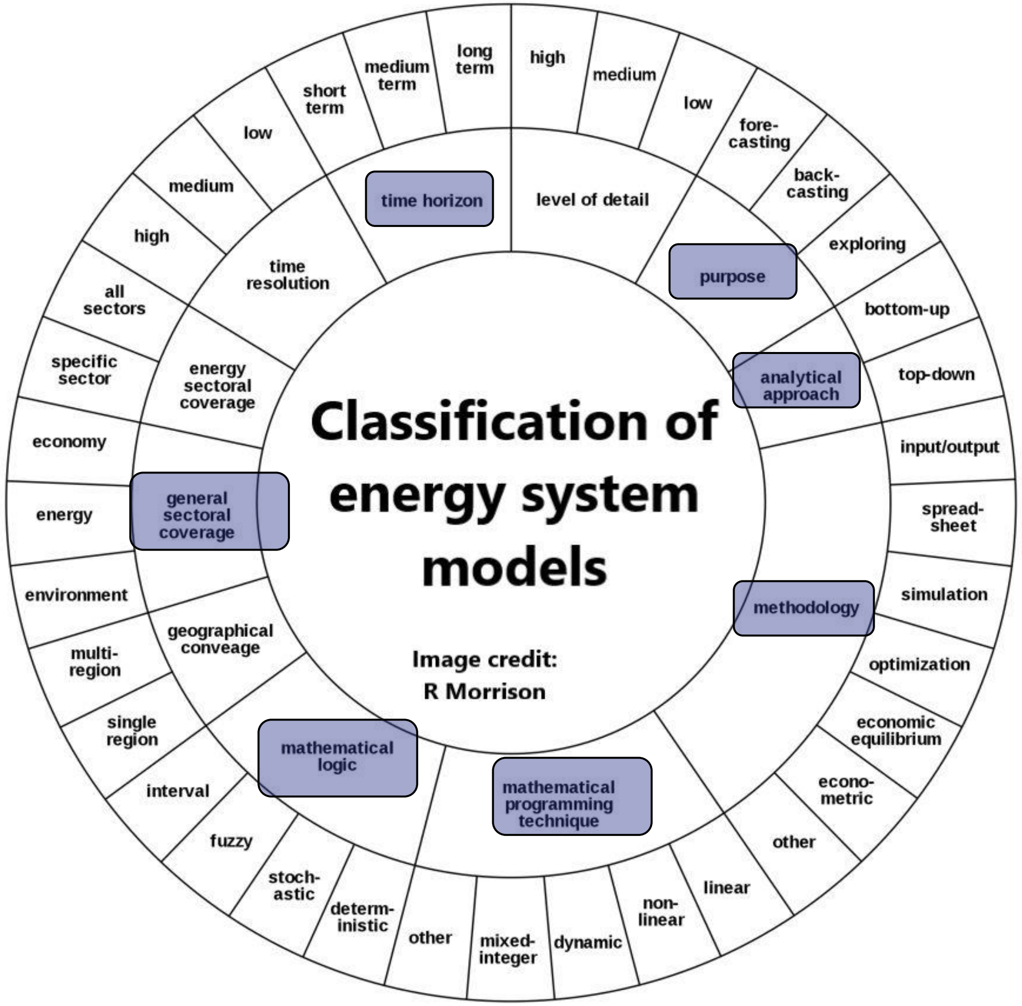
Analytical approach: bottom-up

Methodology: spread-sheet, Simulation, Optimization

Mathematical programming techniques: Linear, non-linear, mixed-integer

Mathematical logics: deterministic, stochastic

Sectoral coverage: Energy



There is no perfect model !

- No universal model or method of modelling which will answer all questions
- It is best to design models to answer specific type of research questions
- It is important to understand the strength and weaknesses of the used model
- Models are only as good as the data, assumptions and structure
- More computational power allows for more complex models

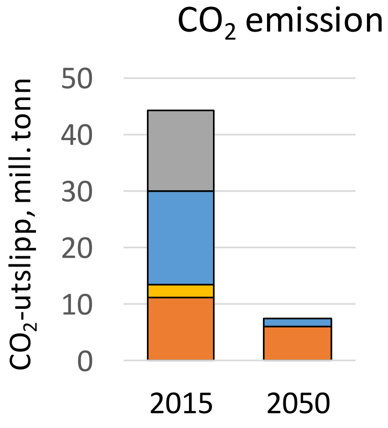
Long-term energy system models

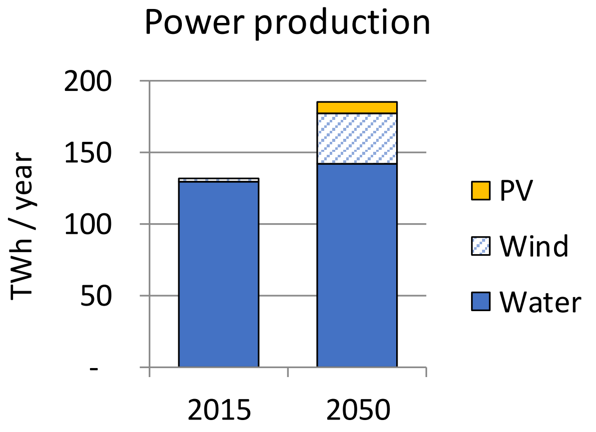
- Definition: **Endogenous** investments and operation of the energy system transition
  - Endogenous: model decision
  - Exogenous: model input
  - Models several model periods

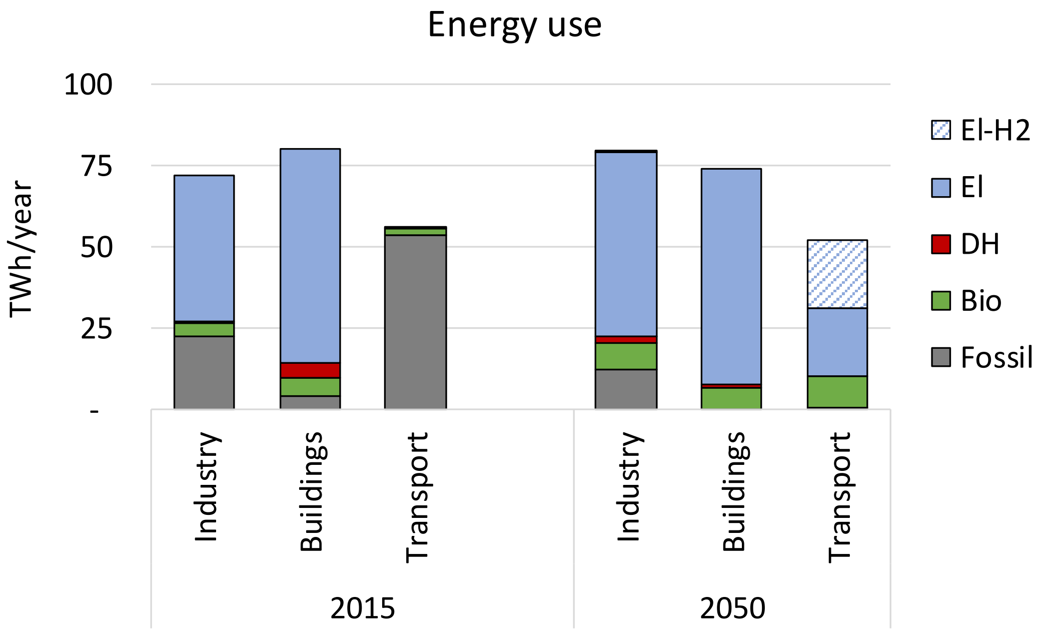
- Developments by:
  - Modelling frameworks; TIMES, OseMOSYS
  - Programming language like Python/ Pyomo, GAMS, Julia

Energy system models

- Objective: Energy system cost
- Input: CO2-price
- Results:
  - Emissions
  - Power production
  - Final energy use
  - Capacity expansion







Long-term energy system models

- **Objective function**: Energy system cost (discounted to present value) of a user defined energy system
  - User defined regions, energy system coverage (supply, transformation, end-use) and model horizon
- **Decision variables**: Investments and operation of the energy system
- **Constraints**:
  - Future energy service demand; annual and load profile
  - Resource availability and characteristics
  - Technology characteristics
  - Phasing out of existing capacity
- **Optimisation**: Minimize energy system costs

Mathematical characteristics of LP problems

- Mathematical *structure* of LP problems
- Originates from the fact that all functions describing the objective and constraints are *linear functions*
- An LP problem can be written as:

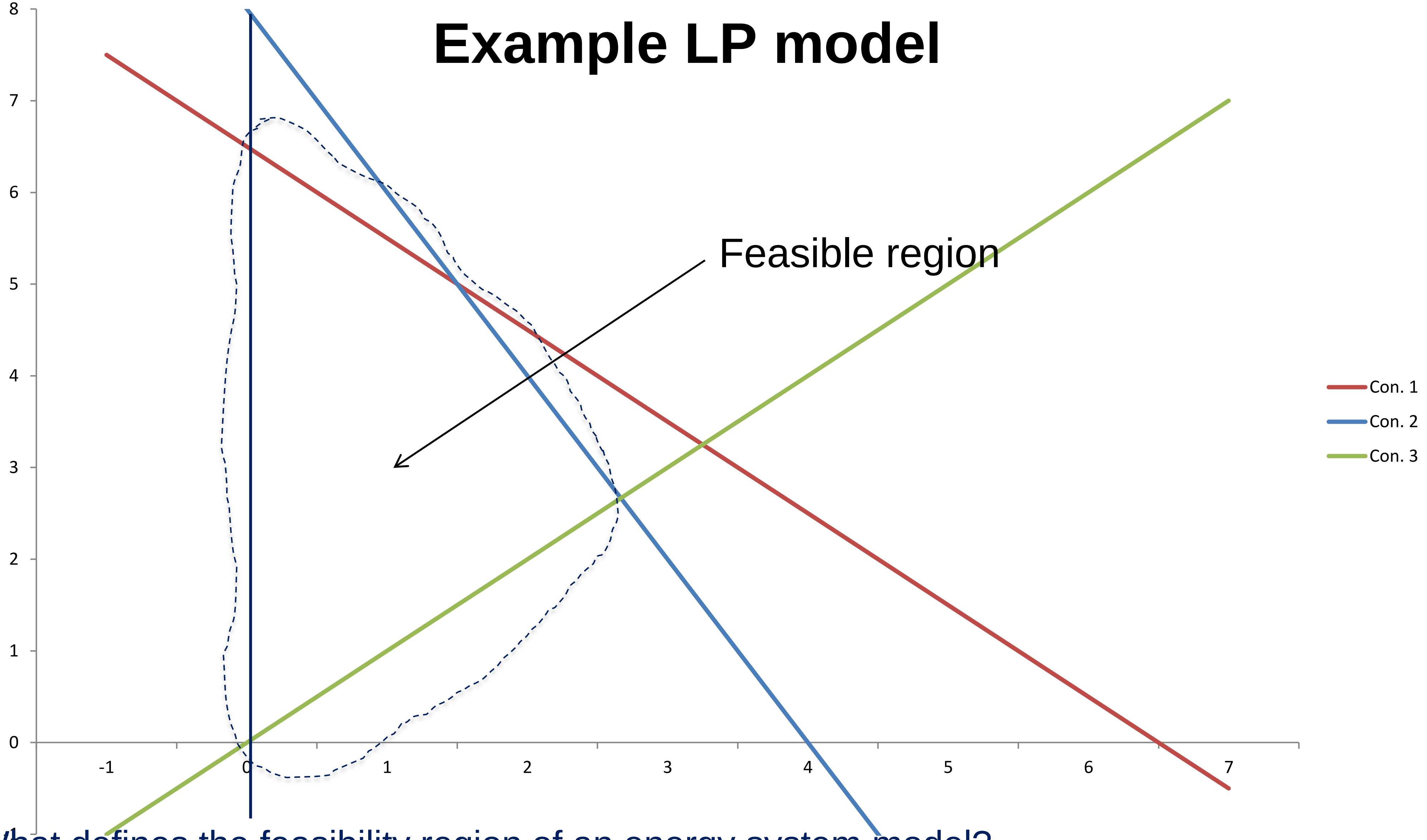
$$\min z = \sum_{j=1}^{n} c_j x_j$$

$$s.t. \sum_{j=1}^{n} a_{ij} x_j \le b_i, i = 1, \dots, m$$

$$x_j \ge 0, j = 1, \dots, n$$

Where c_j is the objective function coefficient for variable x_j
a_{ij} is the constraint coefficient for variable x_j in constraint i
b_i is the right hand side coefficient in constraint i

Example LP model



What defines the feasibility region of an energy system model?

Main equations

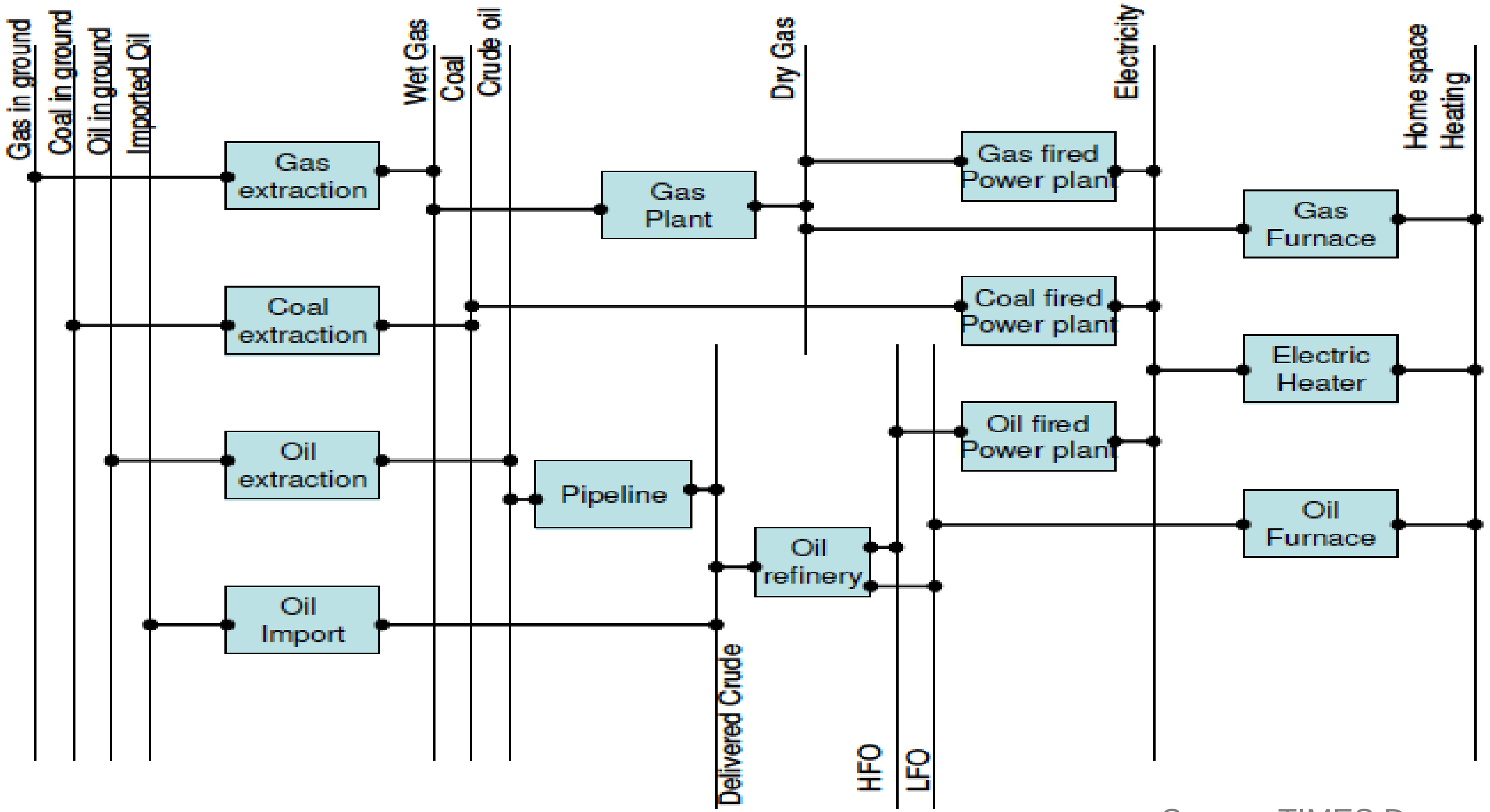
Input data
Cost data
Efficiencies
Emission factors
Demand
Load curves

Objective function
Minimizing discounted system costs
= sum of investment costs, variable costs and import/ extraction costs

Model equations
Energy and emission balances
Capacity activity constraint
Transformation relationship
Storage equations
Cumulated constraints over time
Peaking constraint
Load curve equations
Scenario specific constraints

Decision variables
Process activities
Energy & emission flows
New capacities
Fundamental prices

Reference Energy System

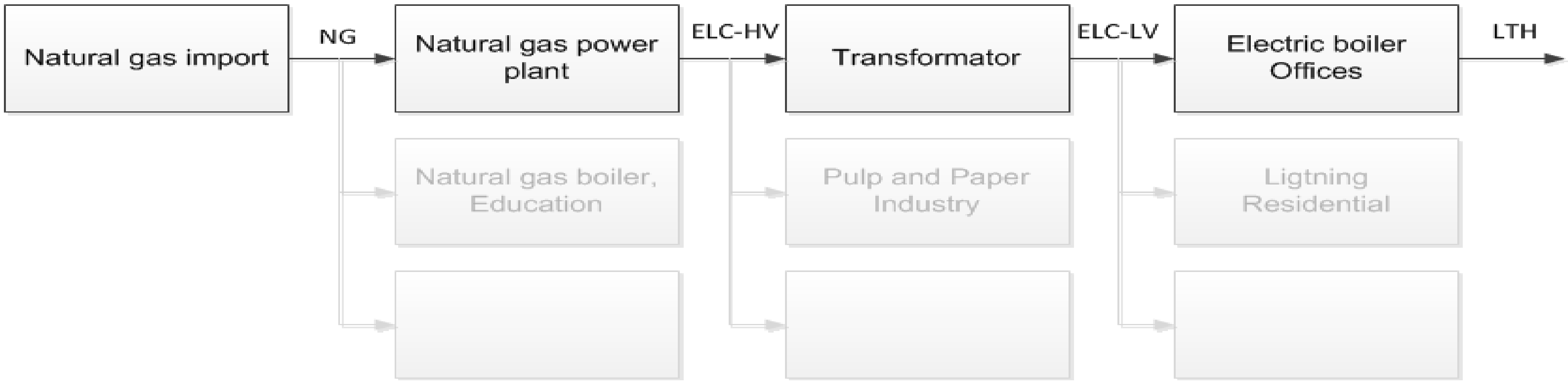


Source: TIMES Documentation part I

Reference energy system components: Energy carriers & Technologies

Horizontal linkage: Technology chains

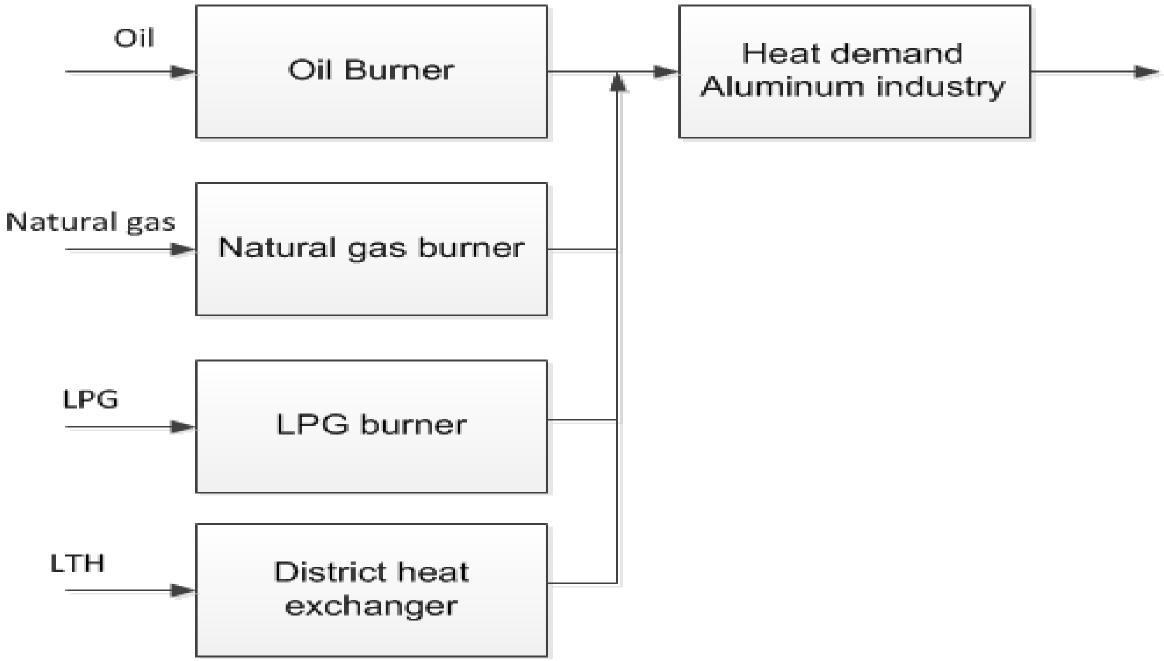
Example: Import of natural gas to heat office buildings



Vertical linkage: Competition

Example: Competition to meet the heat demand to aluminium industry between

- technologies and energy carriers
- old and new technologies



Technology choice depend on

– cost
– efficiency
– emissions
– fuel prices
– taxes and subsidies
– model constraints

Rolf Golombek, Arne Lind, Hans-Kristian Ringkjøb, Pernille Seljom
The role of transmission and energy storage in European decarbonization towards 2050
Energy (2022), Volume 239

Example of results:
- impact of technology learning

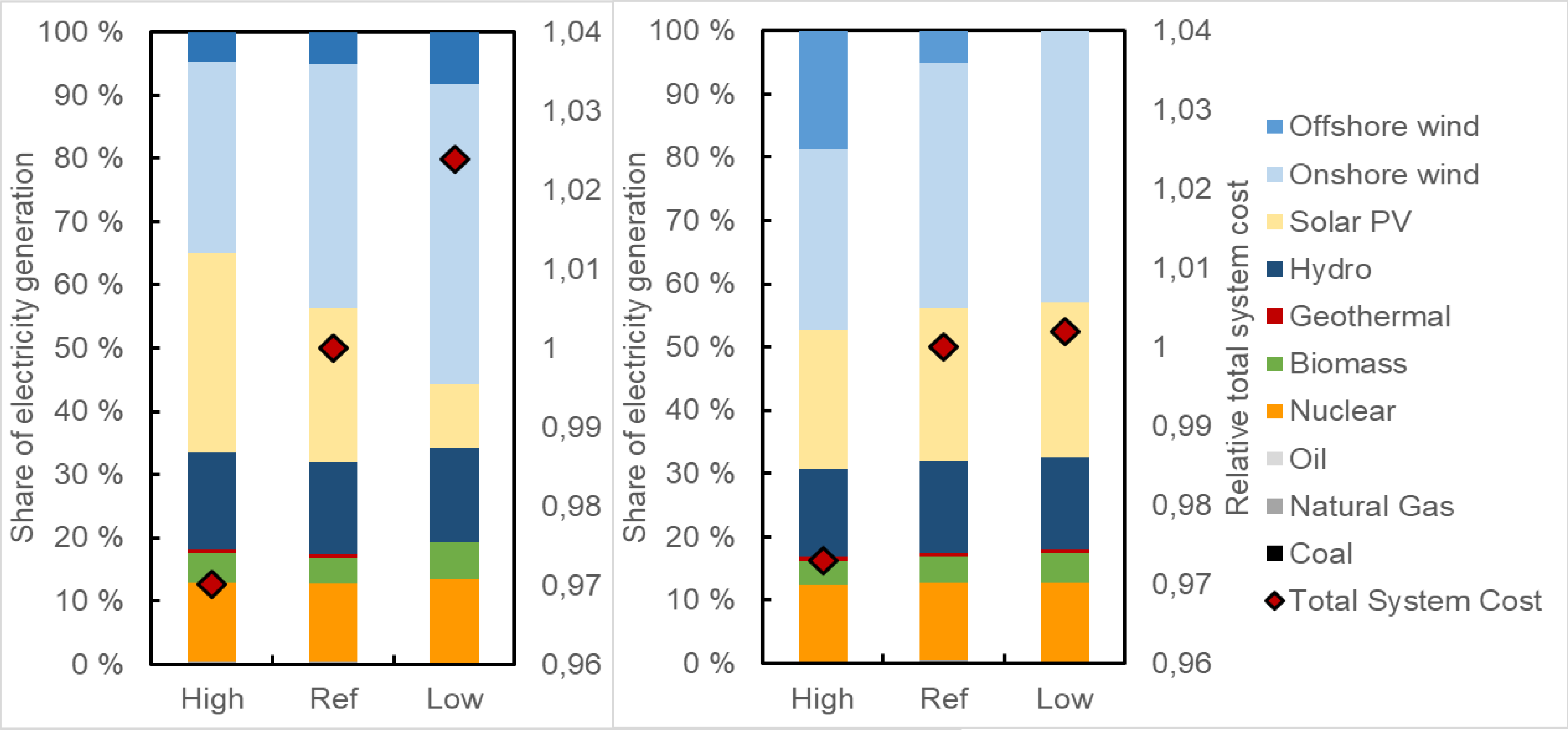


Figure 7: High and low PV technology learning (left) and high and low offshore wind technology learning (right)

Interpretation of energy system model results

- Provide decision support but cannot predict

- **Model results deviate from actual dynamics of the energy system**
  - Model assume a given future evolvement that will differ from reality
    - Energy service demand
    - Fossil fuel prices
    - Technology learning curves
  - Actors does behave according to a system optimum
  - Actors does behave according to cost-optimality

Challenges for energy system modellers

- **Major Challenge = Balance detail level with computational tractability**
  - Optimal detail level depends on data availability, type of analysis and computation power
  - Unnecessary complex model is not desirable
- **Exampled of user-defined assumptions**
  - Temporal resolution
  - Regional coverage
  - Sectoral coverage
  - Technology detail
  - Representation og uncertainty

Uncertainty in long-term energy system models

- Weather dependent production & demand
- Technology development
- Future demand
  - Consumer behaviour
  - GDP and population
  - New industry
- Energy prices and markets
- Policy and regulations
- Climate change
- Energy behaviour

Long-term uncertainty - Scenario planning

- Scenarios are description of plausible futures that identify uncertainty that can have a great impact on decisions
- An internally consistent view of what the future might turn out to be (Michael Porter 1985).
- Drawbacks
  - Complexity
  - Uncertainty in conclusions
  - Time consuming

Kodak moment

/ˈkəʊdak ˈməʊm(ə)nt/

noun

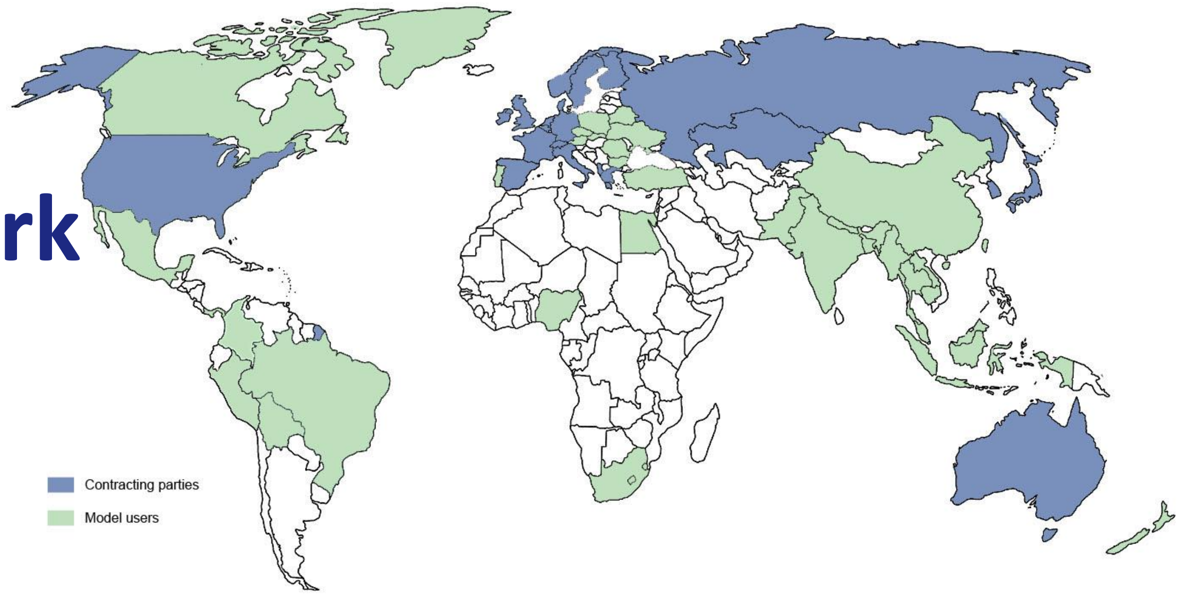
an occasion suitable for memorializing with a photograph.
"the phone is a great way to avoid missing a Kodak moment"

Definitions from Oxford Languages

- The new "Kodak moment" is that moment when you realize that customer end behaviour preferences changes so dramatically from your assumptions that it is too late to change

TIMES modelling framework

TIMES modelling framework



- TIMES is a **modelling tool** developed by ETSAP, implementing agreement of IEA
- Long-term optimisation models of the energy system
- Cost-optimal investments & operation to meet the future energy service demand at a least cost
- Used by individuals/ teams in 70 countries
- Successor and enhanced version of MARKAL
- Open-source code available on GitHub

Model users

Contracting parties

ETSAP etsap

The Energy Technology Systems Analysis Program

- Long Running Technology Collaboration Program of IEA
- Contracting parties in 20 countries and two private sector sponsors
- Bi-annual meetings, continuous model development and support
- https://iea-etsap.org/
- Annex XVI(2023-2025)
  - Aligning Energy Security with Zero Emission Energy Systems

Figure: IEA-ETSAP

TIMES models specifications

- Implemented in GAMS
- Solver: CPLEX or XPRESS
- User friendly interface for managing input and results; VEDA
- Distinguish code and input

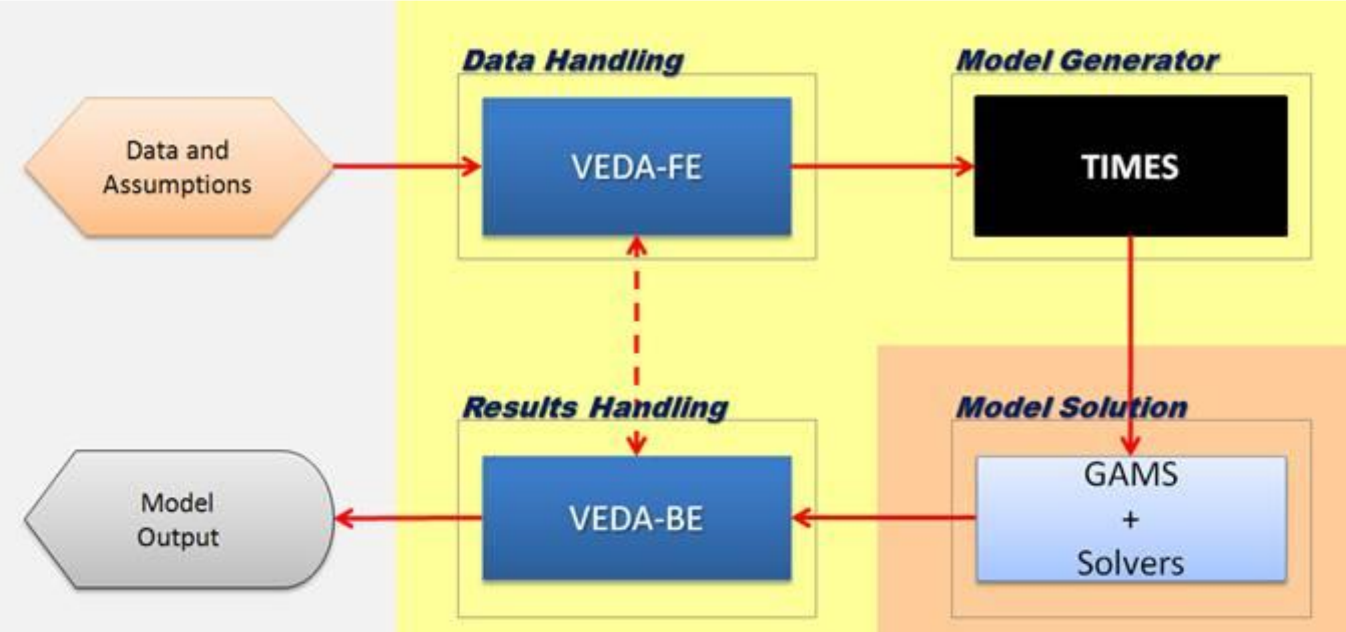


Figure: IEA-ETSAP

Example of TIMES energy system analysis

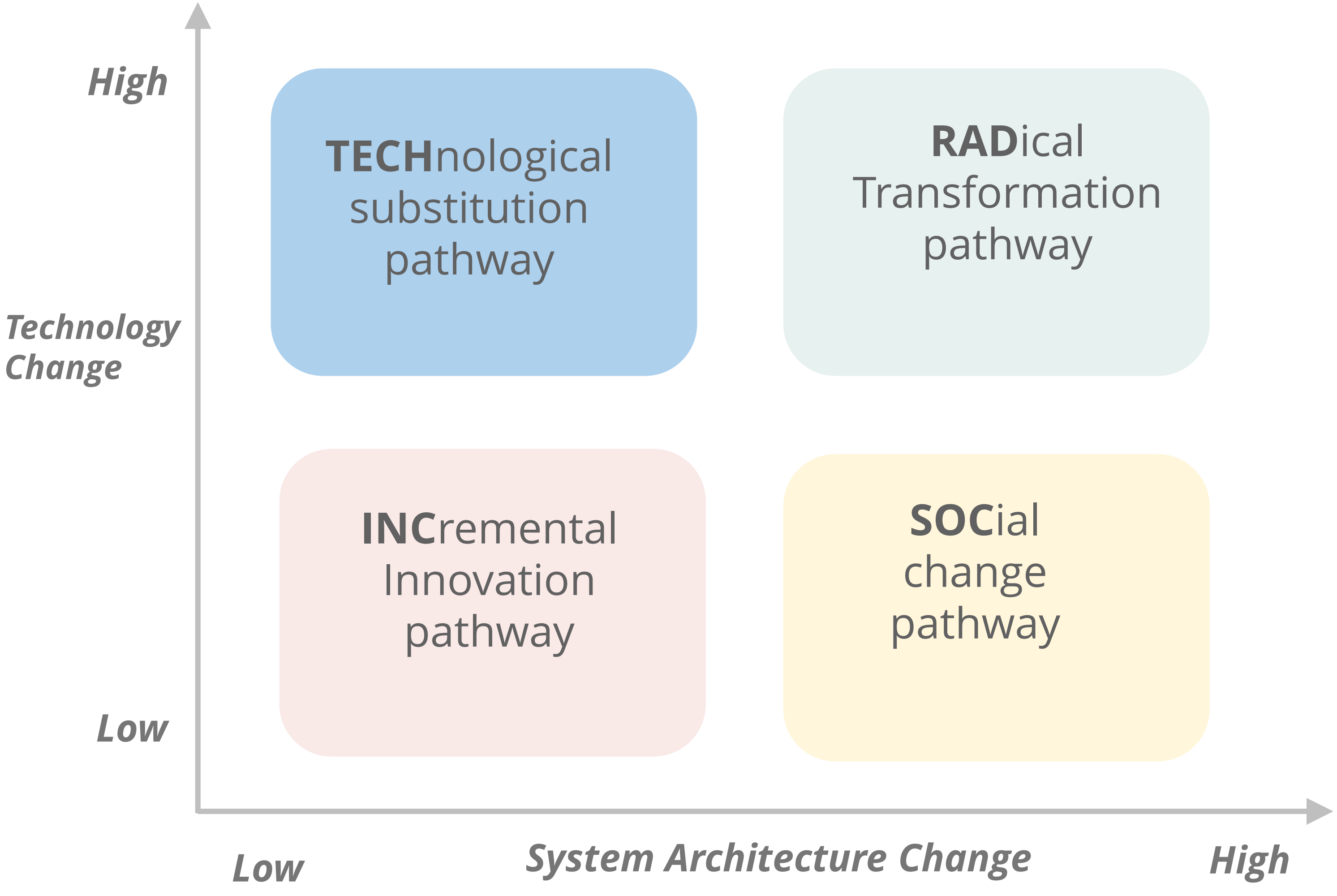
NTRANS
Norwegian Centre for Energy Transition Strategies

Forskningssenter for miljøvennlig energi

NTRANS Socio-technical pathways and scenario analysis

Kari Aamodt Espegren[a], Kristina Haaskjold[a], Eva Rosenberg[a], Sigrid Damman[b], Tuukka Mäkitie[b], Allan Dahl Andersen[c], Tomas Moe Skjølsvold[d] and Paolo Pisciella[e]

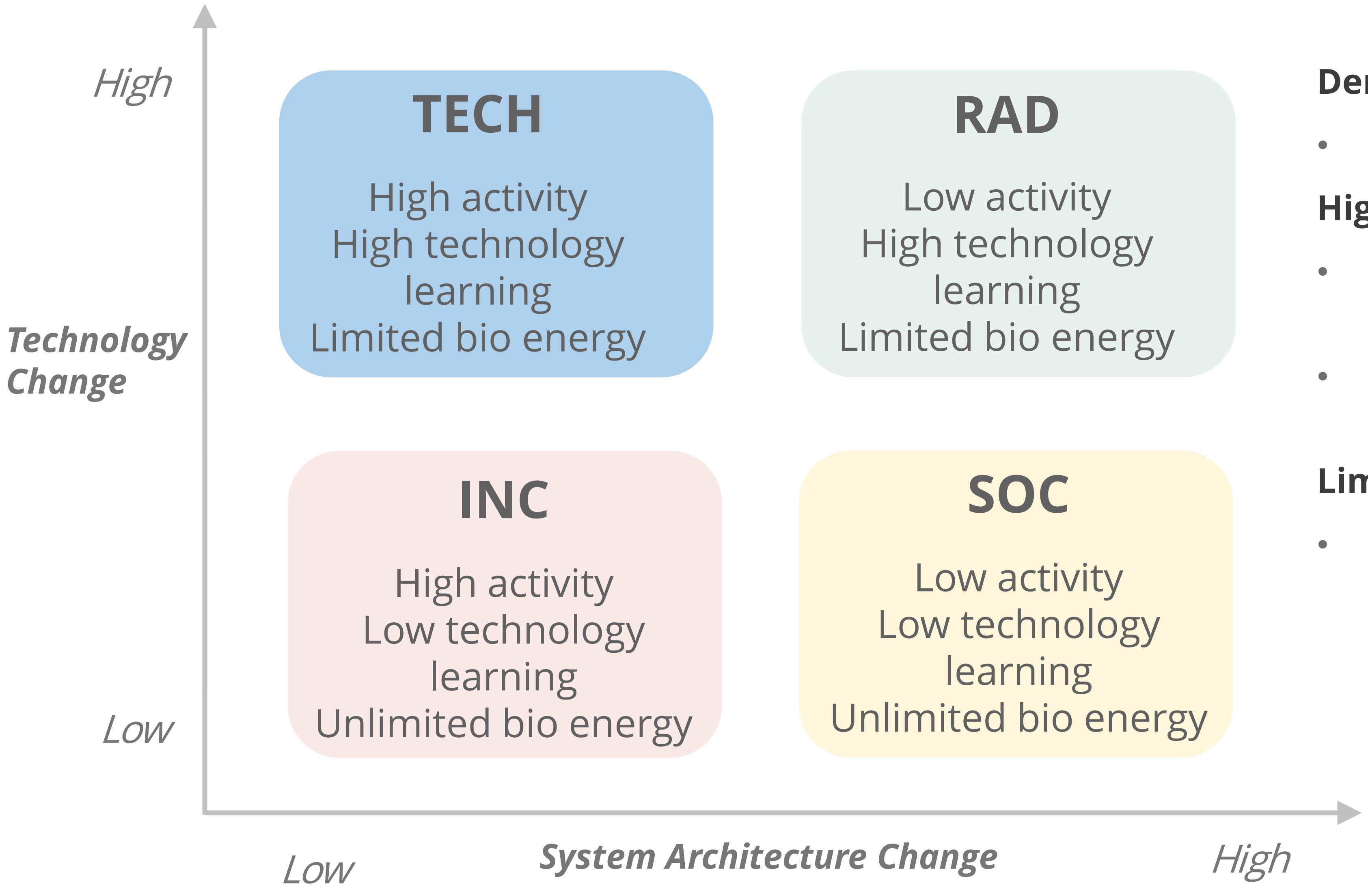
NTRANS socio-technical scenarios



The scenarios are described by:

- Activity levels of end-use sectors
- Onshore/offshore wind potential
- National/trade transmission
- Technology costs, potentials, maturity etc. e.g., for:
  - Battery electric transport
  - Hydrogen technologies
  - CCS
  - Blue hydrogen for export
- Cost/availability of bio energy
- End-use behaviour / rate

Main assumptions



Demand projection /activity levels

- High impact and uncertain

High technology learning

- Decreased cost of hydrogen and battery technologies
- High possible electrification and use of hydrogen

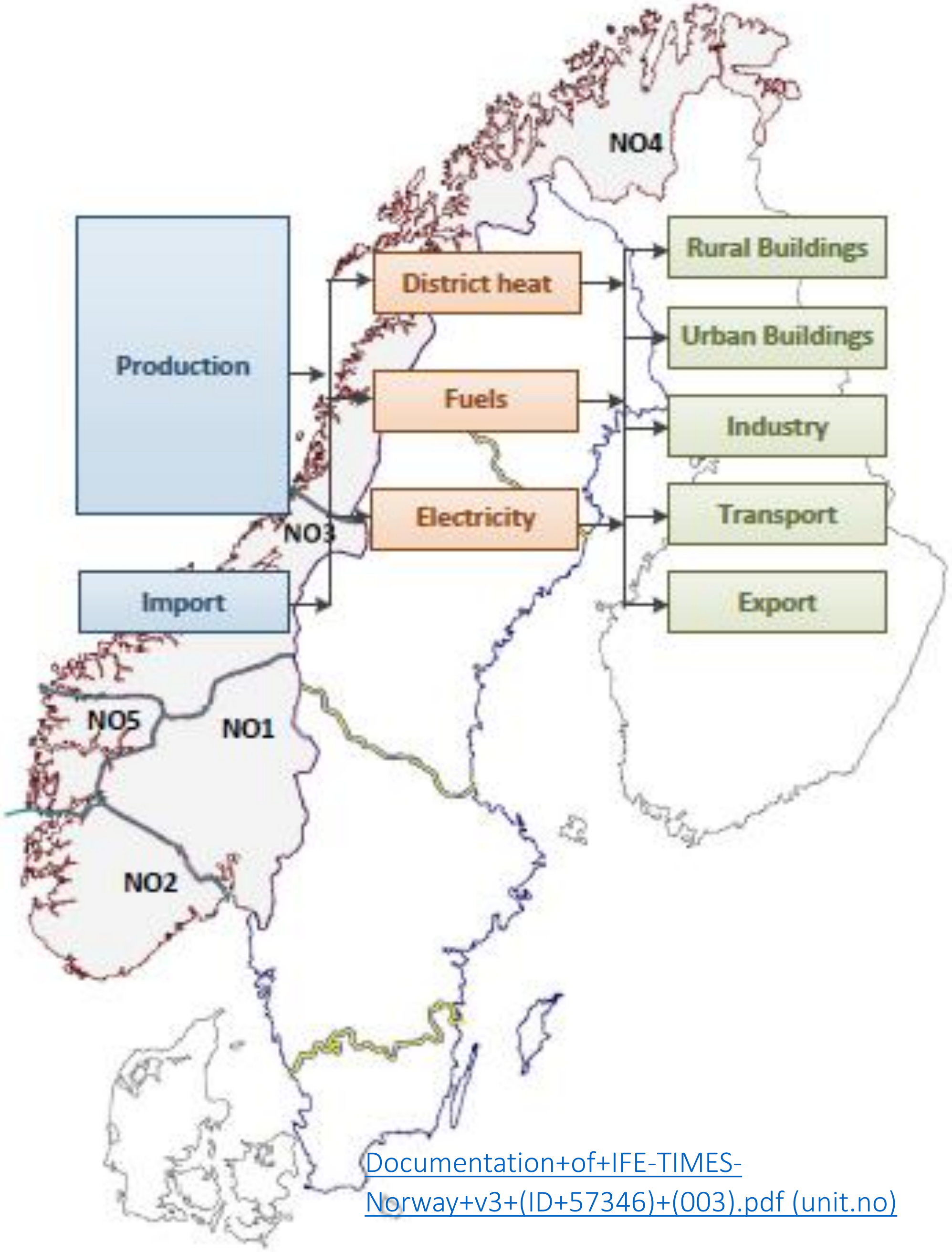
Limited bio energy

- Restricted to Norwegian resources

Forskningssenter for miljøvennlig energi

Energy system model
IFE-TIMES-Norway

- Long-term optimization model of the Norwegian energy system (2018-2060)
- Developed in collaboration with NVE
- Covers entire energy system, including end-use; buildings, industry & transport
  - Sector coupling
  - Competition and interplay of energy carriers & technologies
- High detail level of end use sectors
  - Buildings
  - Industry
  - Transport



Documentation+of+IFE-TIMES-Norway+v3+(ID+57346)+(003).pdf (unit.no)

Model input: Energy service demand

	Total				Electricity specific use			
	2020	INC	TECH	SOC & RAD	2020	INC	TECH	SOC & RAD
Aluminium	32	39	44	34	22	28	32	24
Other metals	16	20	20	16	5	6	6	5
Chemicals	20	23	23	20	8	10	10	8
Wood	17	17	17	17	4	4	4	4
Minerals	4	4	4	4	1	1	1	1
Light	10	10	13	10	4	4	5	4
Agri&Construction	4	4	5	4	3	3	4	3
Petro	69	28	28	-	9	9	9	-
New	1	20	46	1	1	20	46	1
H2 Export	-	-	100	-			5	
Total	**173**	**165**	**299**	**106**	**56**	**85**	**121**	**49**

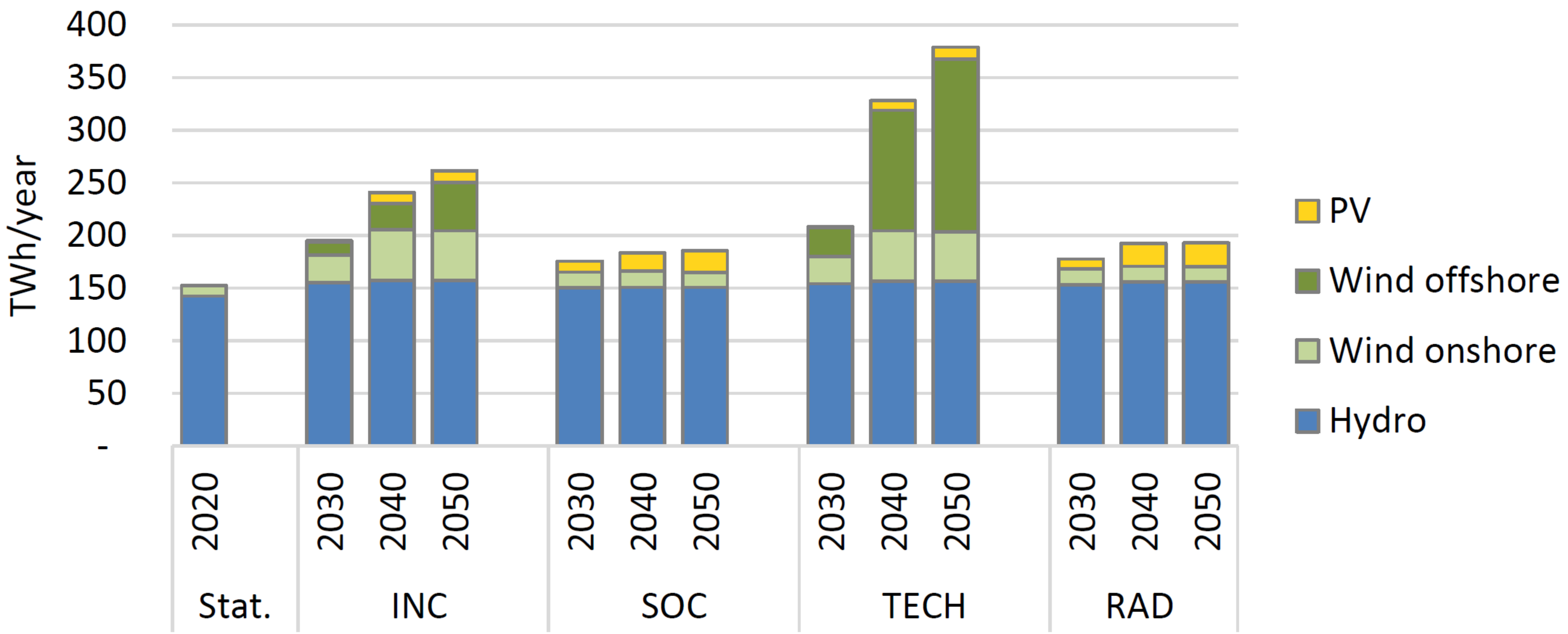
Model input: Energy service demand

Building type		End-use		INC & TECH		SOC & RAD	
			2020	2030	2050	2030	2050
Single-family	Existing	El.spec.	8.4	7.9	6.7	7.6	6.4
		Heat	32.8	30.5	24.8	26.0	18.8
		Total	41.1	38.4	31.4	33.7	25.2
	New	El.spec.	-	0.8	2.4	0.8	1.4
		Heat	-	2.0	4.8	1.7	2.7
		Total	-	2.9	7.2	2.5	4.1
Multi-family	Existing	El.spec.	1.8	1.7	1.6	1.7	1.5
		Heat	5.1	4.9	4.4	3.9	3.0
		Total	6.9	6.6	5.9	5.6	4.5
	New	El.spec.	-	0.5	1.5	0.4	2.1
		Heat	-	1.0	2.7	0.8	3.7
		Total	-	1.5	4.1	1.3	5.8
Non-residential	Existing	El.spec.	16.6	15.8	14.2	14.2	12.1
		Heat	15.3	14.4	12.7	10.7	7.6
		Total	31.9	30.1	26.9	24.9	19.6
	New	El.spec.	-	1.4	3.7	0.7	3.6
		Heat	-	0.9	2.0	0.5	1.8
		Total	-	2.3	5.8	1.2	5.4

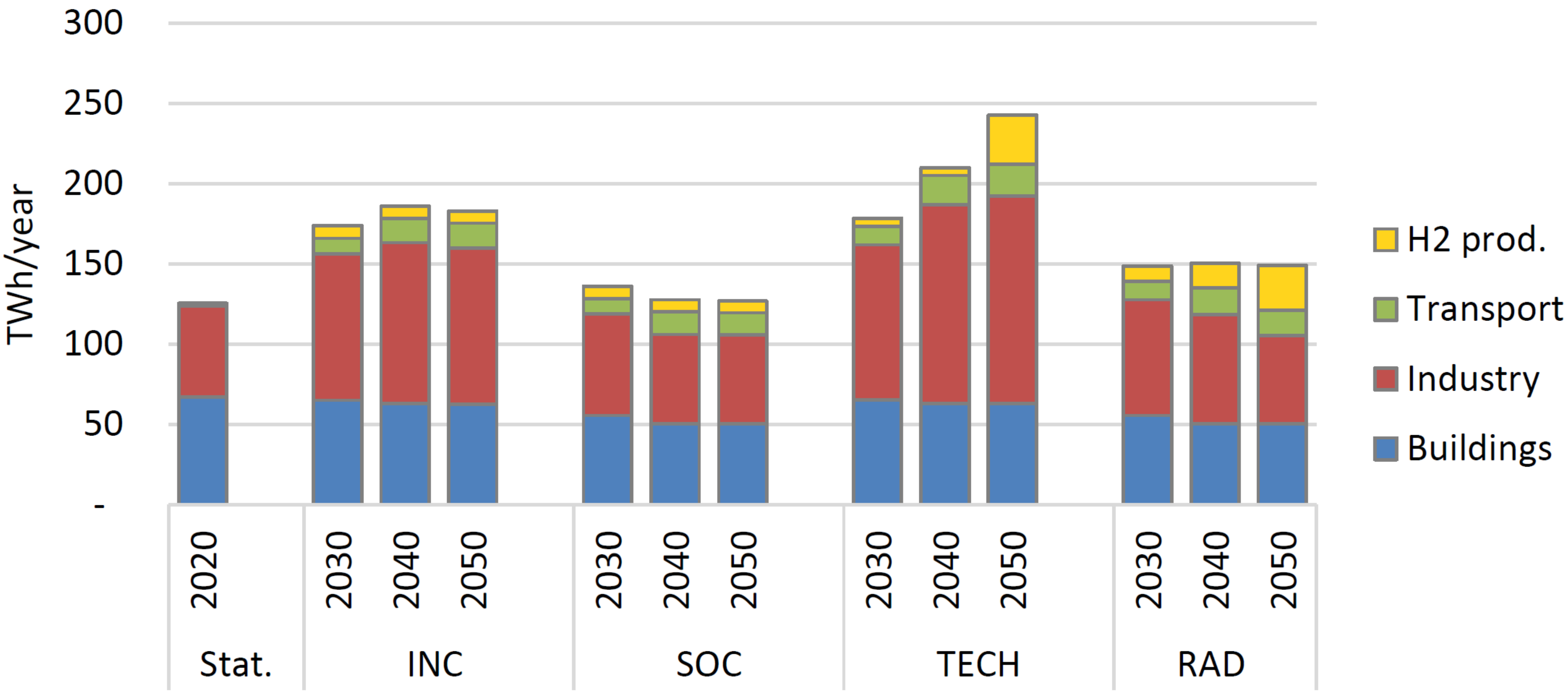
Model input: Energy service demand

		INC & TECH				SOC & RAD			
	2018	2020	2030	2050	2050 vs. 2018	2020	2030	2050	2050 vs. 2018
Road transport (billion-vehicle-km)	**45.1**	**46.3**	**52.5**	**61.7**	**137 %**	**45.1**	**45.2**	**40.8**	**90 %**
Cars	35.1	36.0	40.1	45.1	128 %	35.1	35.1	31.6	90 %
Vans	7.3	7.6	9.4	12.7	174 %	7.3	7.3	6.6	90 %
Small trucks	0.51	0.49	0.41	0.37	72 %	0.51	0.51	0.46	90 %
Large trucks, short distance	0.77	0.82	1.02	1.44	186 %	0.77	0.77	0.70	90 %
Large trucks, long distance	0.77	0.82	1.02	1.44	186 %	0.77	0.77	0.70	90 %
Buses	0.57	0.58	0.60	0.62	108 %	0.59	0.65	0.73	114 %
Non-road transport (TWh)	**21.6**	**21.9**	**23.0**	**24.6**	**114 %**	21.6	22.2	22.3	103 %
Air	4.9	4.9	5.1	5.3	109 %	4.9	4.9	4.4	90 %
Passenger ships	3.5	3.5	3.6	3.5	101 %	3.5	4.0	4.5	128 %
Fishing ships	2.7	2.8	3.0	3.2	116 %	2.7	2.7	2.7	100 %
Other ships	4.7	4.8	5.1	5.4	116 %	4.7	4.7	4.7	100 %
Rail	0.7	0.8	0.9	1.2	163 %	0.7	0.8	0.9	128 %
Other mobile transport	5.1	5.2	5.4	6.0	117 %	5.1	5.1	5.1	100 %

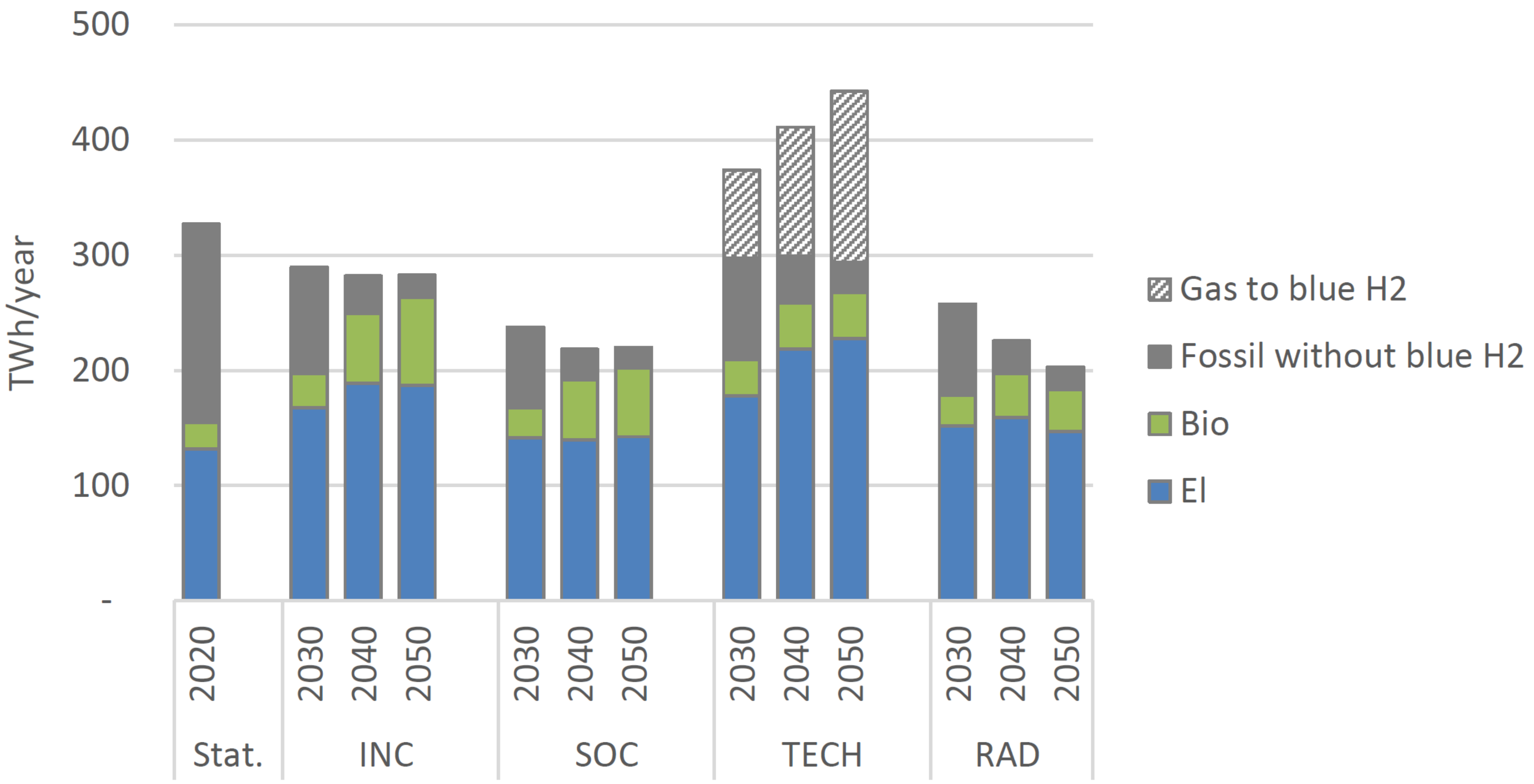
Model results: Electricity generation



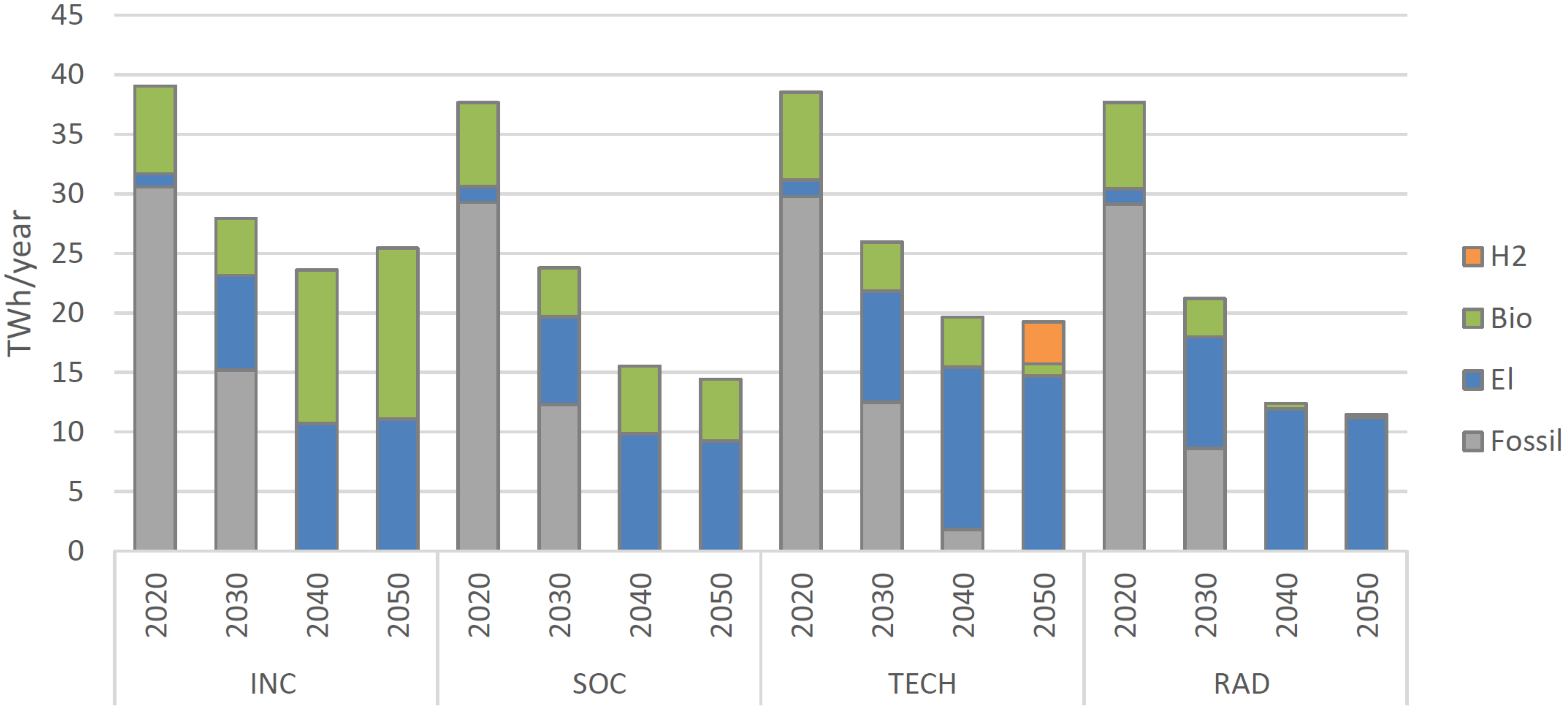
Model results: Electricity use



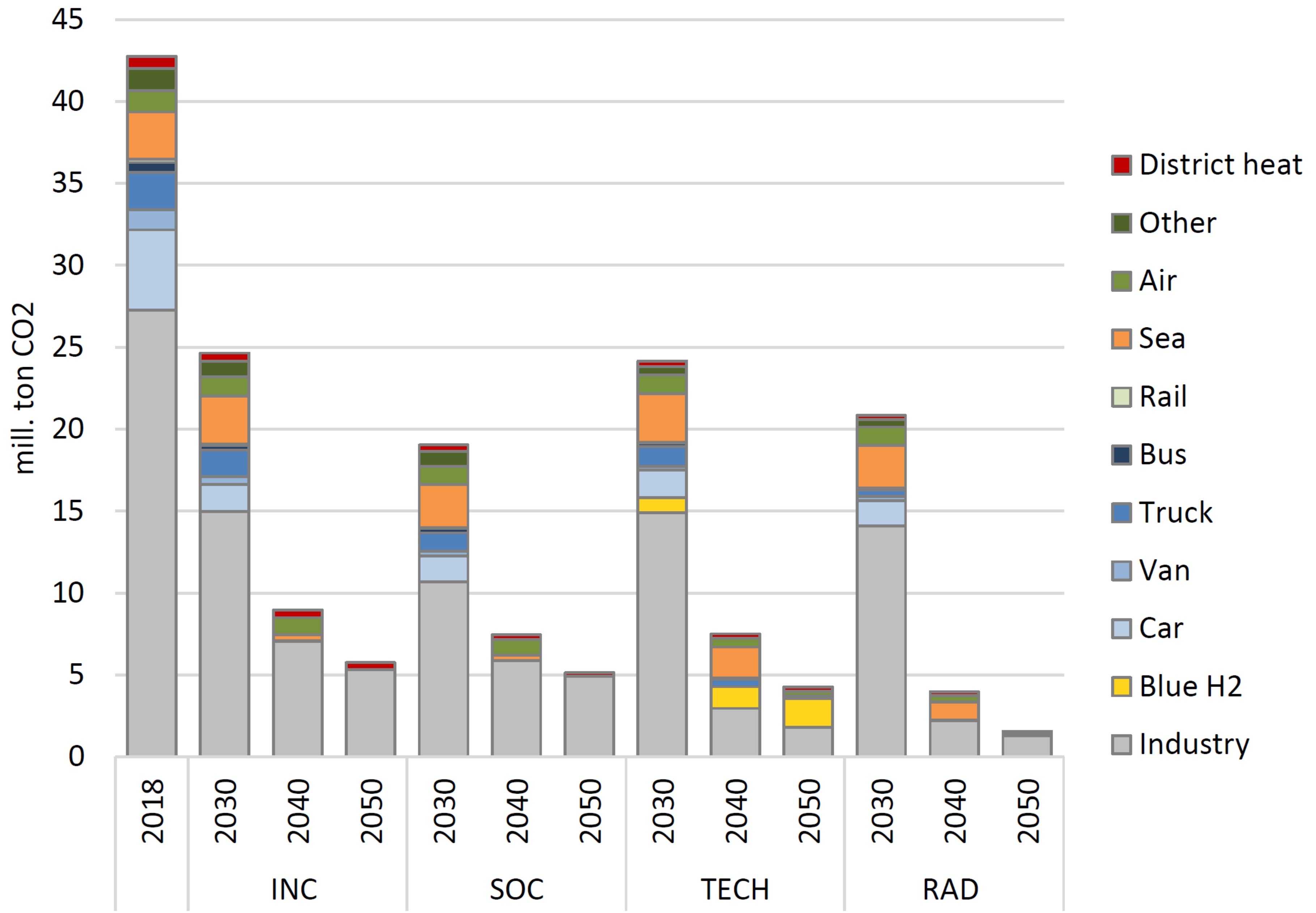
Model results: Final energy demand



Model results: Final energy demand-Road transport

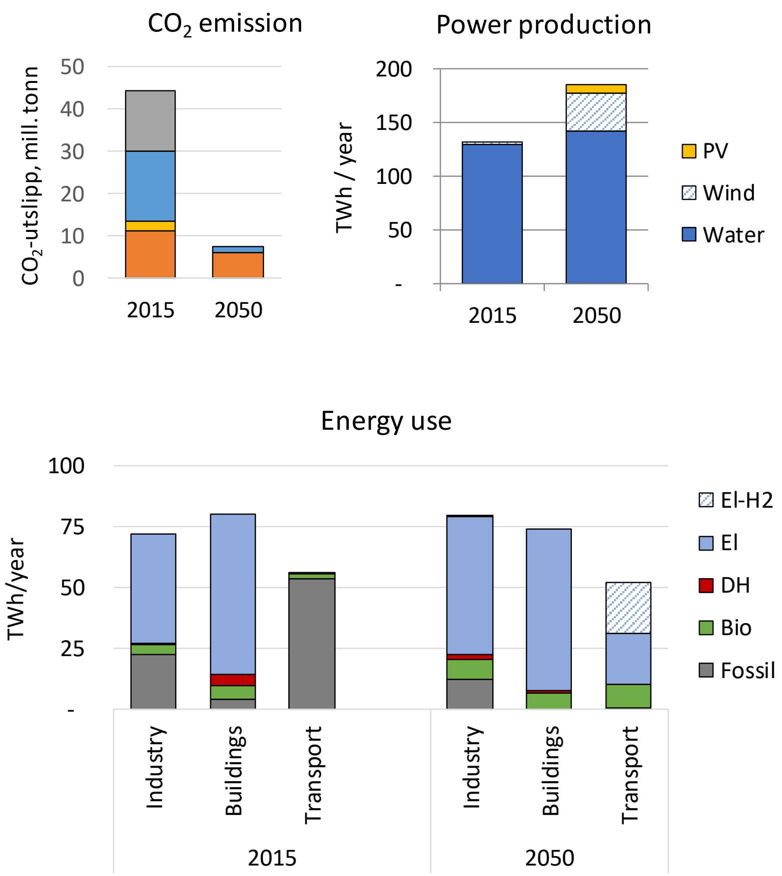


Model results: CO2 emissions



Questions for reflections

- What is a long-term energy system models and why can they be valuable?
- What are the objective function, decision variables and typical constraints?
- What are uncertain parameters of long-term energy system models?



Questions for reflections

- What have you learned today?
- What has been interesting?
- What is unclear?

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Final remarks/ summary

- A successful energy transition requires a holistic understanding of the energy system
- The future energy system is more integrated than the system of today
- Long-term energy system model, including TIMES models
  - captures interaction between energy services, end-use technologies, infrastructure and energy supply
  - provides least-cost solutions for investment and operation of the energy system to meet future demand for energy services