Energy System Modelling and Energy Justice - Incompatible Concepts?

Session 1: Basics of Energy Modelling

Workshop @ Meccanica Feminale,
Stuttgart, 18.02 – 20.2.2025

Martha M. Hoffmann

Introduction

- Master degree „Regenerative energy systems“, Berlin Institute of Technology (TUB), Germany
- 2019-2022: Researcher, Reiner Lemoine Institut
- Since 2022: PhD Student, Reiner Lemoine Foundation

REINER LEMOINE STIFTUNG

REINER LEMOINE INSTITUT

Europa-Universität Flensburg

FOSSIL EXIT Research Group

Reiner Lemoine Institut

- Non-profit research institute, founded 2010 (Berlin)
- 100 % subsidiary of Reiner Lemoine-Foundation (RLS)
- Managing Directors:

  Dr. Kathrin Goldammer & Dr. Christine Kühnel
- ≈ 100 researchers and students
- Scientific research for an energy transition towards **100 % Renewable Energy**

Reiner Lemoine
Founder of the Reiner Lemoine-Foundation

Round of Introductions

- Name
- Study programme
- Bachelor / Master
- Expectations and wishes

Workshop Sessions

Day 1: Introduction to Energy Modelling			
10:00	11:30	Session 1	Basics of Energy Modelling
14:00	15:30	Session 2	Open Energy Models
16:00	17:30	Session 3	Oemof-Tutorial

Day 2: Introduction to Justice Concepts			
8:30	10:00	Session 4	Social aspects of energy systems
10:30	12:00	Session 5	Justice in energy systems
14:00	15:30	Session 6	Case Studies Development

Day 3: Co-Creation at the Intersection of Energy Modelling & Justice			
8:30	10:00	Session 7	Group Work on Case Studies
10:30	12:00	Session 8	Discussion of Case Studies

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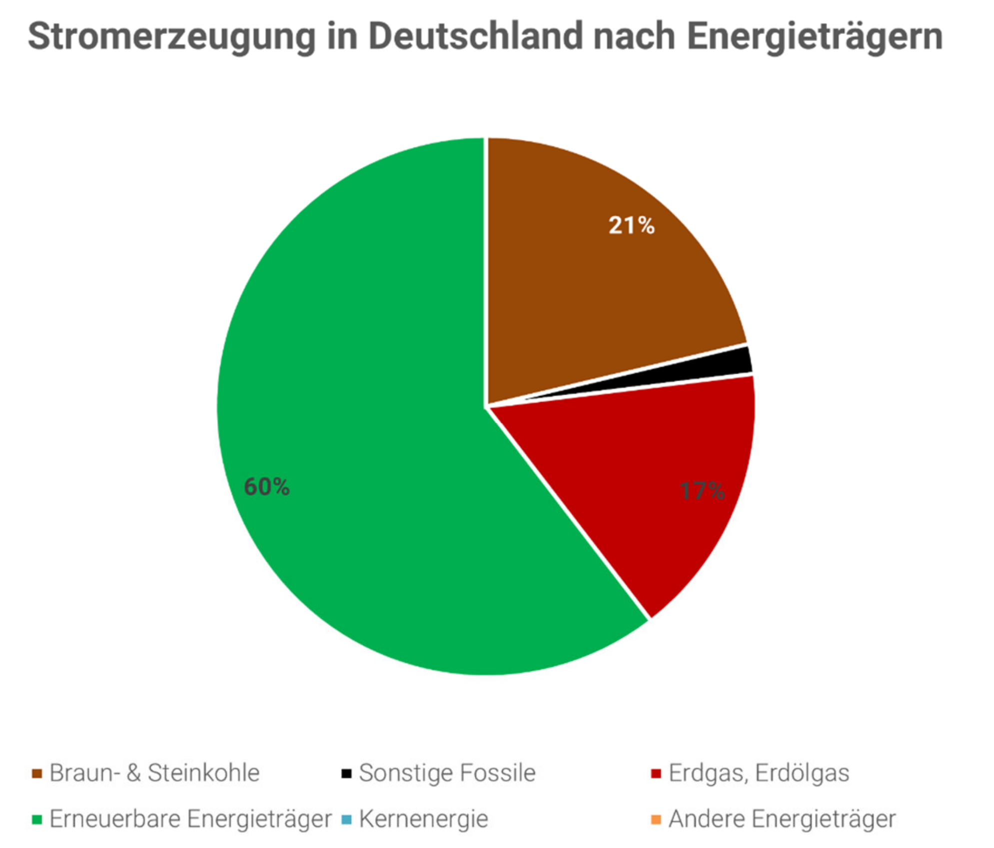
Agenda Session 1 – Basics of Energy Modelling

Time	Title
10:00	Settling in
10:10	Introductions & Expectations
10:25	Agenda
10:40	Time for Questions
10:45	Energy supply basics
10:55	Foundations of energy modelling
11:05	Experimental Use OpenPlan
11:25	Time for Questions
11:30	Pause

MH0

Electricity generation assets in Germany



- Paris agreement: 1.5 (2.0) degree global warming
- Klimate neutrality in Germany by 2045
- 2025: 60% of electricity generation from renewables in Germany!

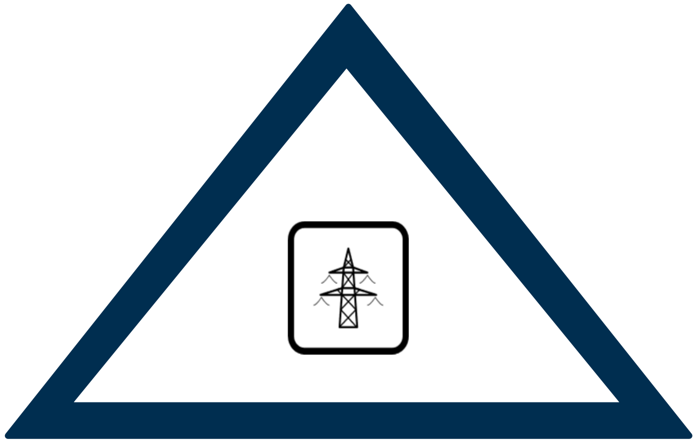
Burger, Bruno. 2025. 'Stromerzeugung in Deutschland Im Jahr 2024'. https://www.energy-charts.info/downloads/Stromerzeugung_2024.pdf .

Folie 8

MH0 Add categories or election check

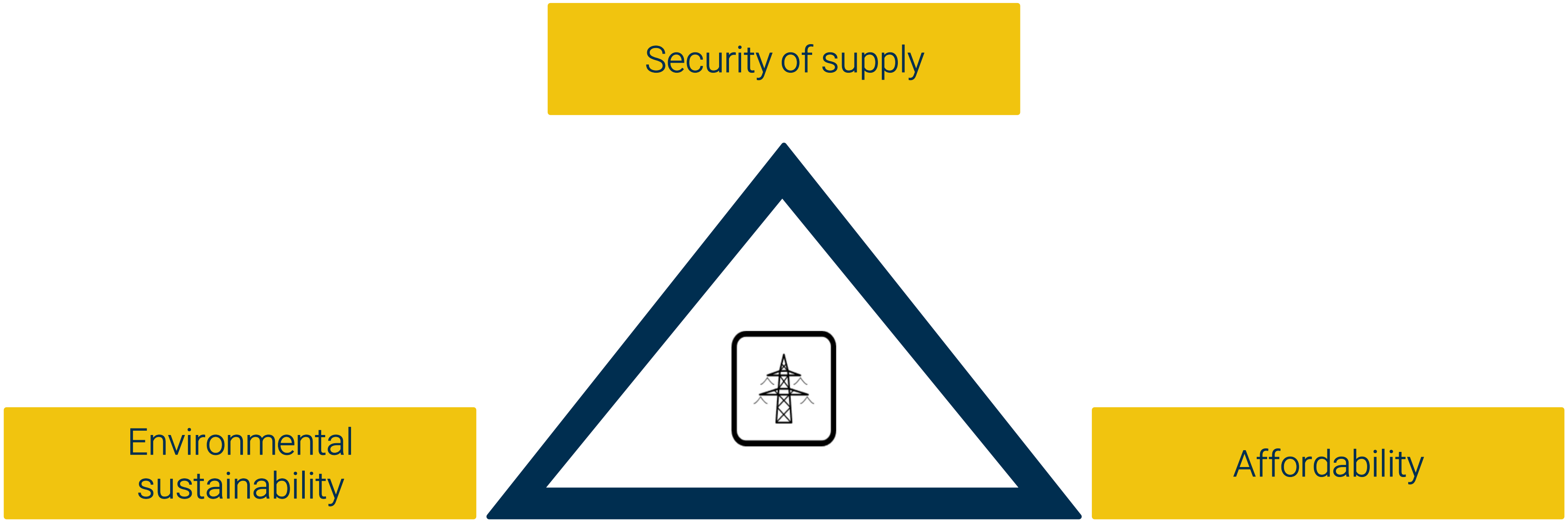
Martha Hoffmann; 2025-02-14T09:09:01.513

Energy trilemma - traditional targets of supply

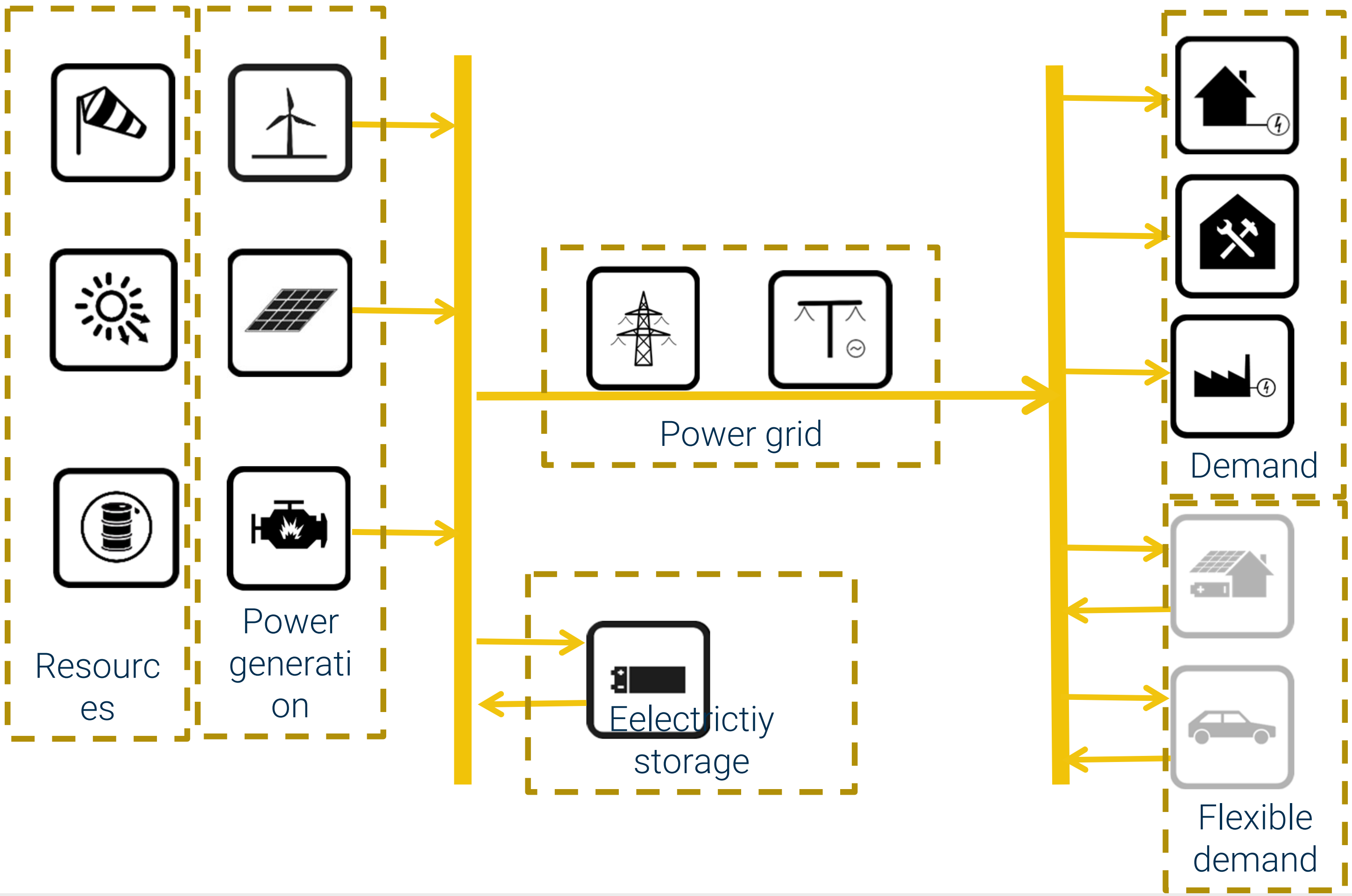


What are traditional targets of energy supply?

Energy trilemma - traditional targets of supply



What is an energy supply system?



Renewable Energy in Electricity Sector

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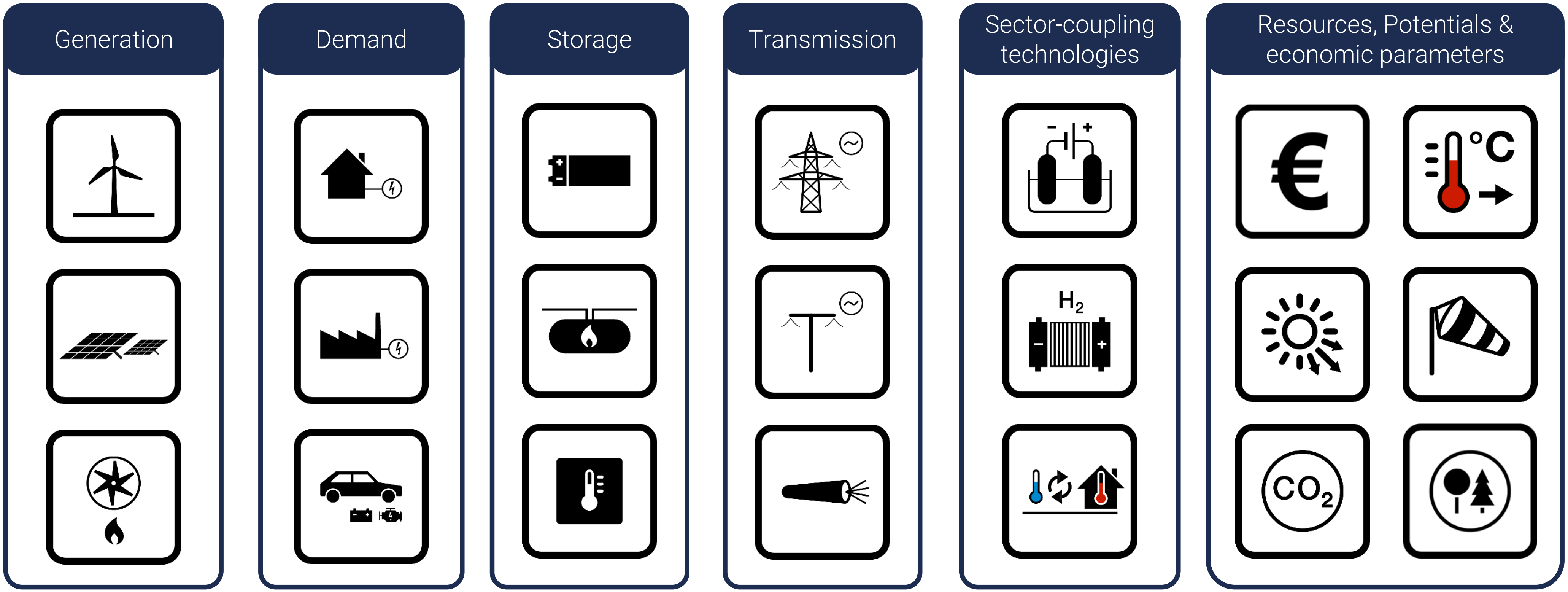
- Use of renewable energy holds the potential of…
  - Reducing GHG emissions
  - Reducing power generation costs

- Current electricity grid already combines:
  - Fossil-fuelled generation (gas, coal, nuclear)
  - Renewable energy (hydro, PV, wind)
  - Storage (mainly hydropower)

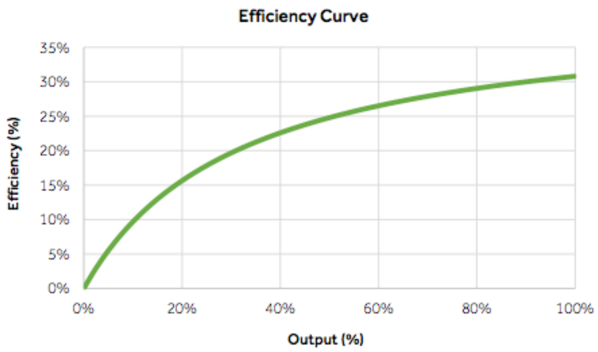
Components of energy systems



Diesel generator

Fuel = Diesel → Kinetic Energy → Electricity

- Conversion Principle: magnetic induction
- Fuel price: ??? ~ 0.6 USD/l
- Emissions: 3.1-3.5 kgCO2/l
- Flexible

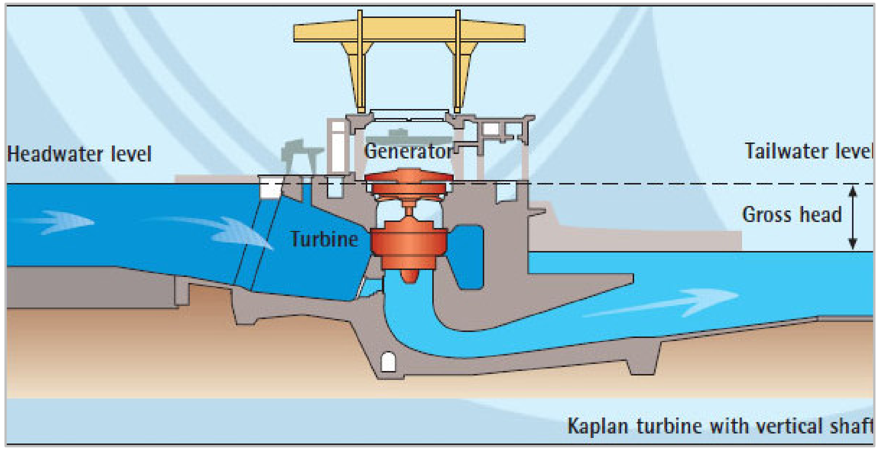


Source
DG: http://www.marine-dieselgenerator.com
Efficiency: Aqioun Energy

Hydro Power System

„Fuel“ = water flow → Electricity

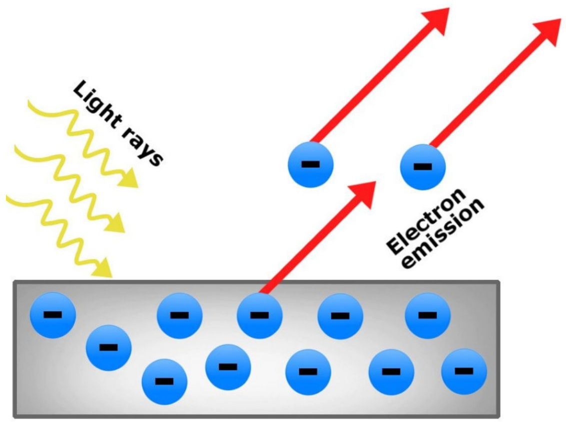
- Conversion Principle: potential energy to rotating energy
- Fuel price: 0 USD/unit
- Emissions: 0 kgCO_2/unit
- Dipatchable (with reservoir)
- Provides rotating mass



Solar PV System

„Fuel“ = solar irradiance → Electricity

- Conversion Principle: photoelectric effect
- Fuel price: 0 USD/unit
- Emissions: 0 kgCO2/unit
- Volatile



Sources: scienceabc (l), Mascus Deutschland (r)

Wind Power System

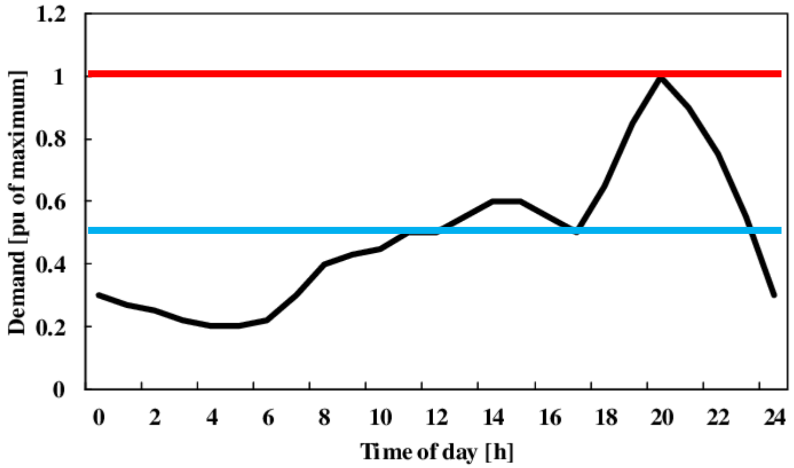
„Fuel“ = wind (air flow) → Electricity

- Conversion Principle: kinetic energy to rotating energy
- Fuel price: 0 USD/unit
- Emissions: 0 kgCO2/unit
- Volatile

Energy demand and load profiles

- Peak demand (kW, MW)
- Average demand (kW, MW)
- Daily energy demand (kWh, MWh)
- Load factor: A. demand/ P. demand

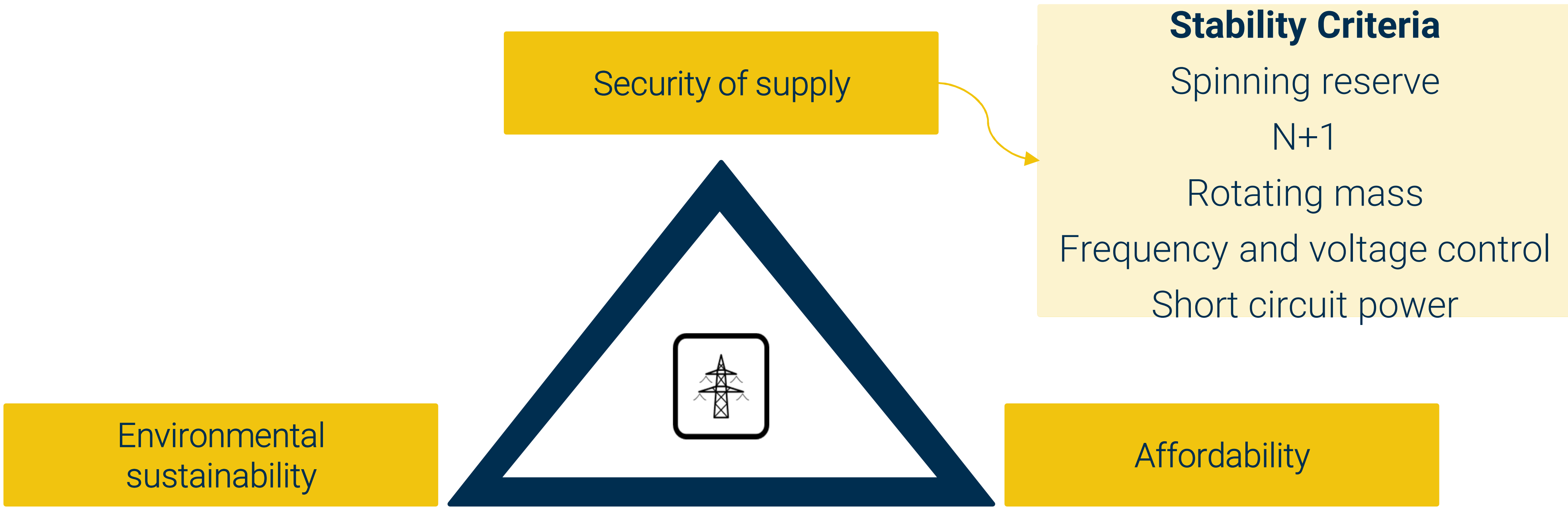
- Load profile: Temporal resolution
- Key for RE based systems



Challenges of electricity supply

- Dynamic load response challenge intensified by fluctuating renewable electricity production
- Intermittent generation and intermittent consumption
- Higher uncertainty leads to higher spinning reserve needs
- Generation and supply need to match on temporal and spatial scale

Energy trilemma - traditional targets of supply



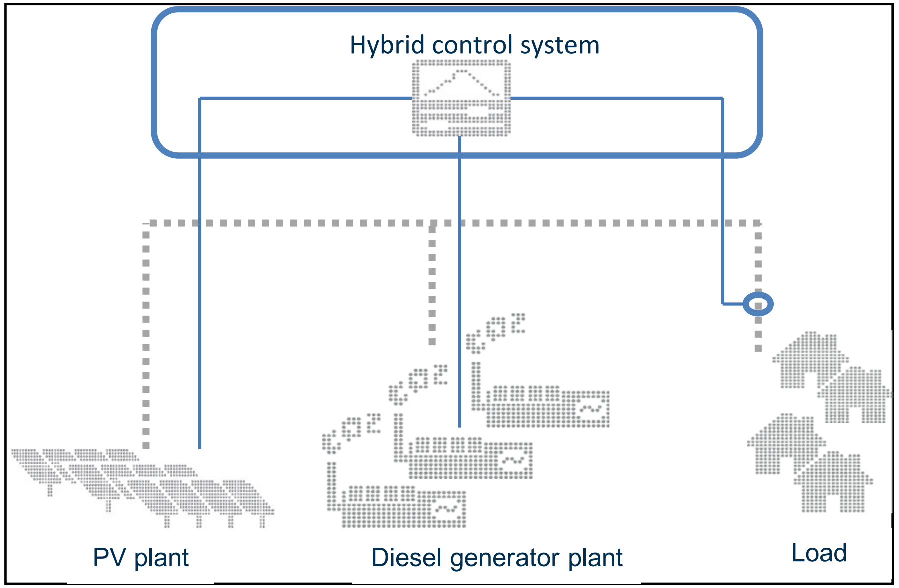
Energy management system (EMS)

Need for control and dispatch mechanism securing supply security

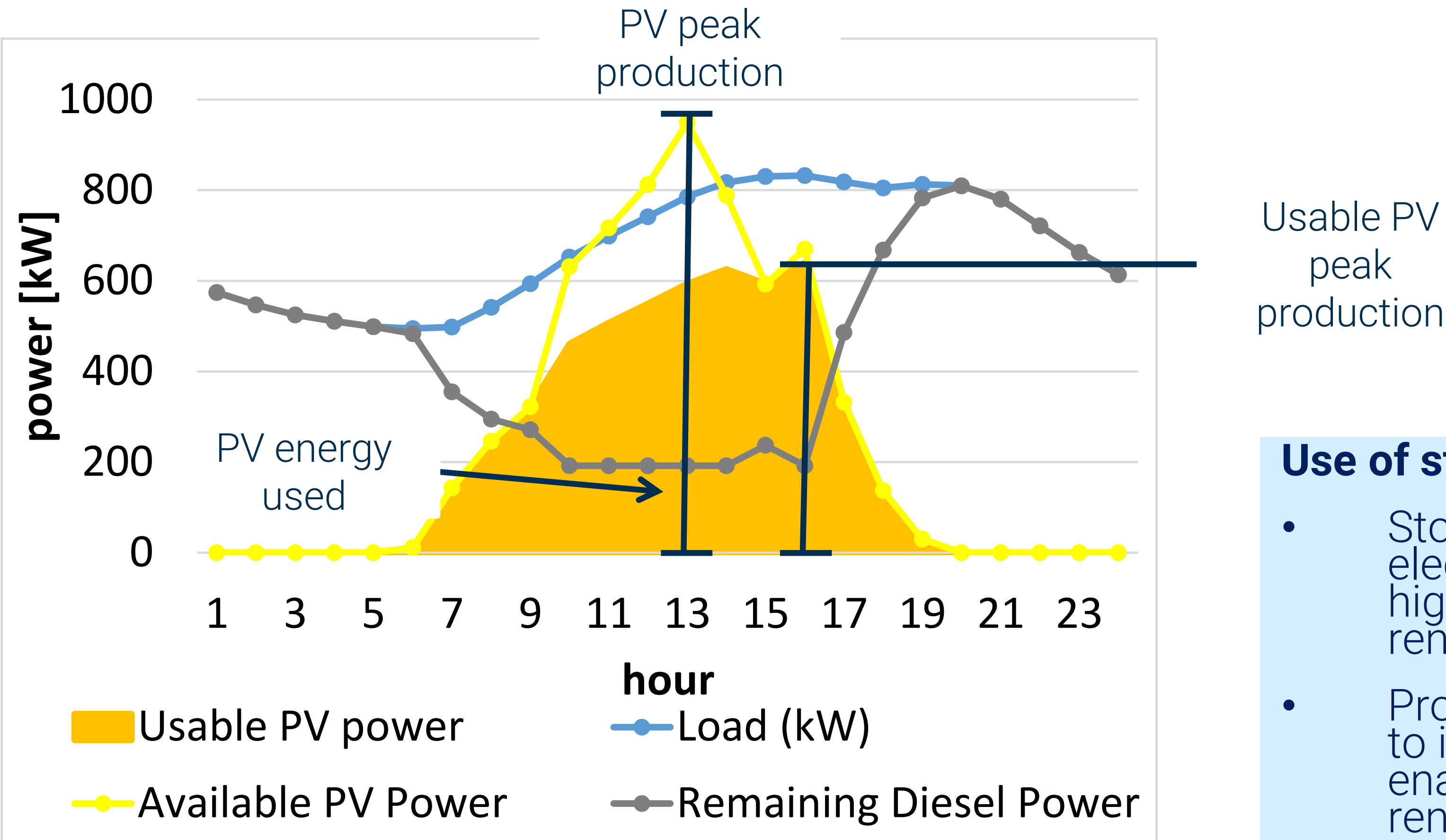
→ Energy management system

EMS tracks and manages…

- Electricity generation
- Demand
- Voltage and frequency
- Potential: forecasting



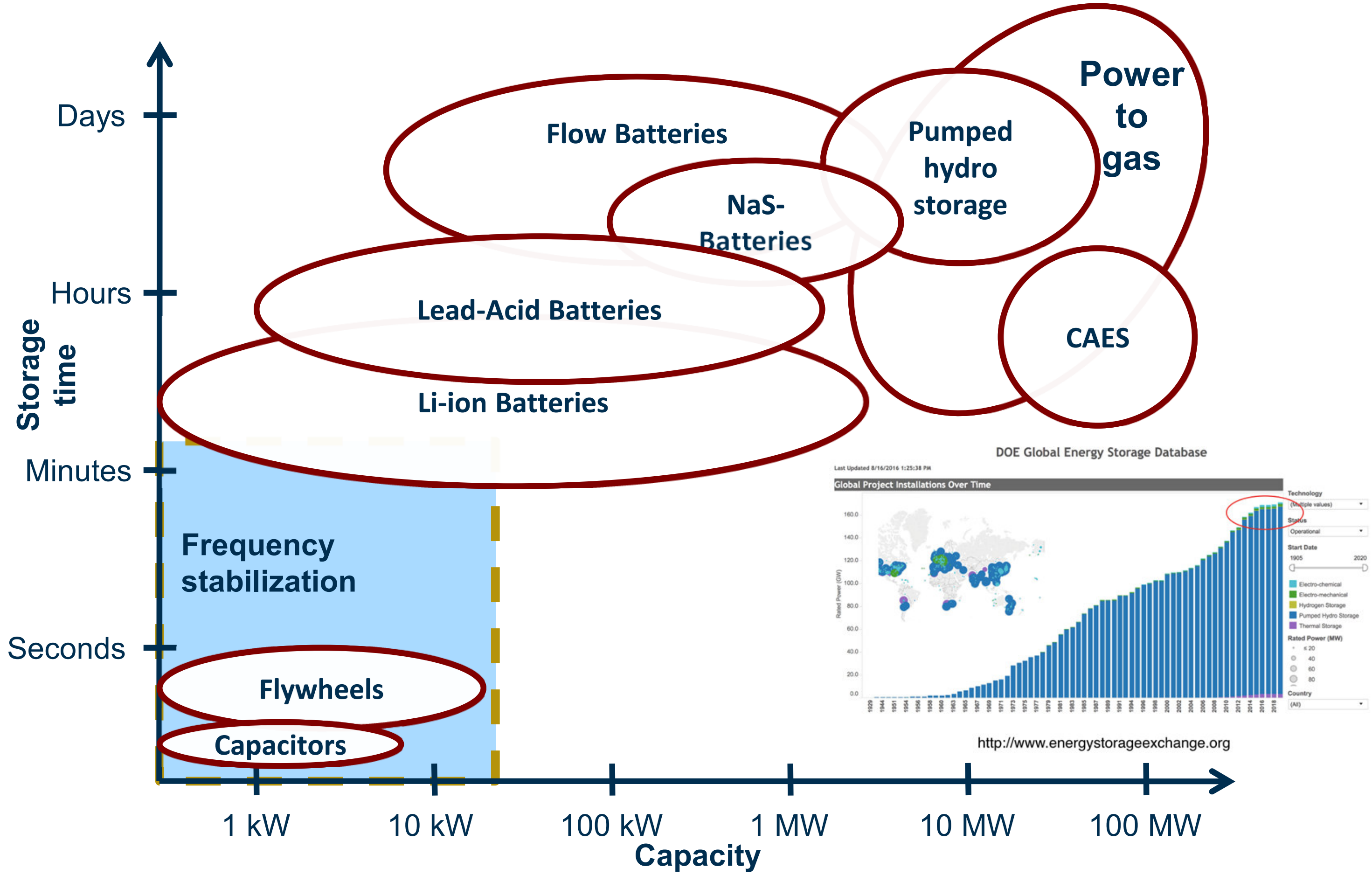
Usable PV production in PV-diesel systems

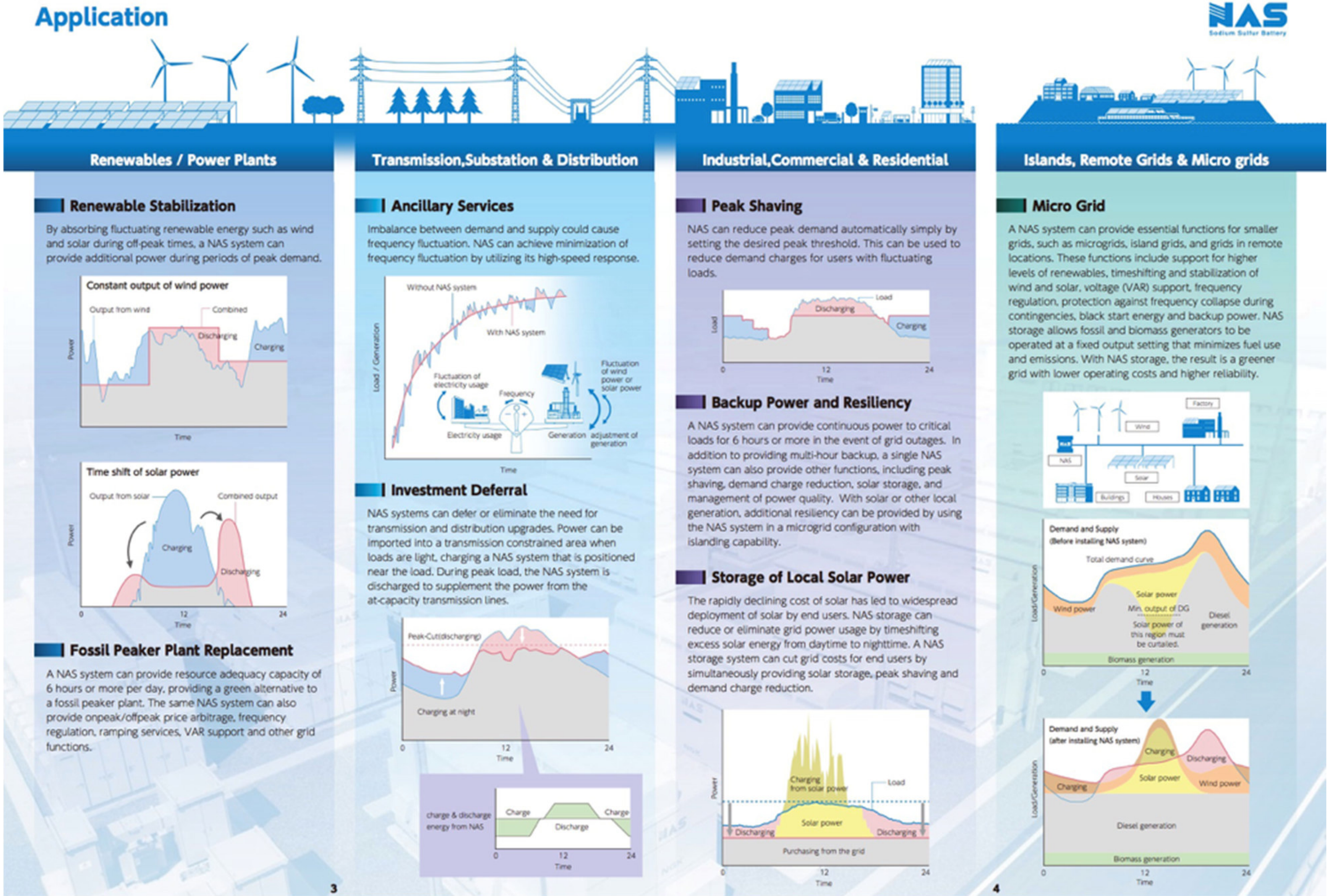


Use of storage:

- Storing and time shifting of electricity → enabling higher shares of renewables
- Providing ancillary services to improve grid quality and enable higher share of renewable energy

Storage Systems





Application

NAS
Sodium Sulfur Battery

Renewables / Power Plants

Renewable Stabilization

By absorbing fluctuating renewable energy such as wind and solar during off-peak times, a NAS system can provide additional power during periods of peak demand.

Fossil Peaker Plant Replacement

A NAS system can provide resource adequacy capacity of 6 hours or more per day, providing a green alternative to a fossil peaker plant. The same NAS system can also provide onpeak/offpeak price arbitrage, frequency regulation, ramping services, VAR support and other grid functions.

3

Transmission,Substation & Distribution

Ancillary Services

Imbalance between demand and supply could cause frequency fluctuation. NAS can achieve minimization of frequency fluctuation by utilizing its high-speed response.

Investment Deferral

NAS systems can defer or eliminate the need for transmission and distribution upgrades. Power can be imported into a transmission constrained area when loads are light, charging a NAS system that is positioned near the load. During peak load, the NAS system is discharged to supplement the power from the at-capacity transmission lines.

Industrial,Commercial & Residential

Peak Shaving

NAS can reduce peak demand automatically simply by setting the desired peak threshold. This can be used to reduce demand charges for users with fluctuating loads.

Backup Power and Resiliency

A NAS system can provide continuous power to critical loads for 6 hours or more in the event of grid outages. In addition to providing multi-hour backup, a single NAS system can also provide other functions, including peak shaving, demand charge reduction, solar storage, and management of power quality. With solar or other local generation, additional resiliency can be provided by using the NAS system in a microgrid configuration with islanding capability.

Storage of Local Solar Power

The rapidly declining cost of solar has led to widespread deployment of solar by end users. NAS storage can reduce or eliminate grid power usage by timeshifting excess solar energy from daytime to nighttime. A NAS storage system can cut grid costs for end users by simultaneously providing solar storage, peak shaving and demand charge reduction.

4

Islands, Remote Grids & Micro grids

Micro Grid

A NAS system can provide essential functions for smaller grids, such as microgrids, island grids, and grids in remote locations. These functions include support for higher levels of renewables, timeshifting and stabilization of wind and solar, voltage (VAR) support, frequency regulation, protection against frequency collapse during contingencies, black start energy and backup power. NAS storage allows fossil and biomass generators to be operated at a fixed output setting that minimizes fuel use and emissions. With NAS storage, the result is a greener grid with lower operating costs and higher reliability.

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NGK Insulators Inc.

Energy supply planning

Energy supply should optimally fulfill all demand and stability requirements

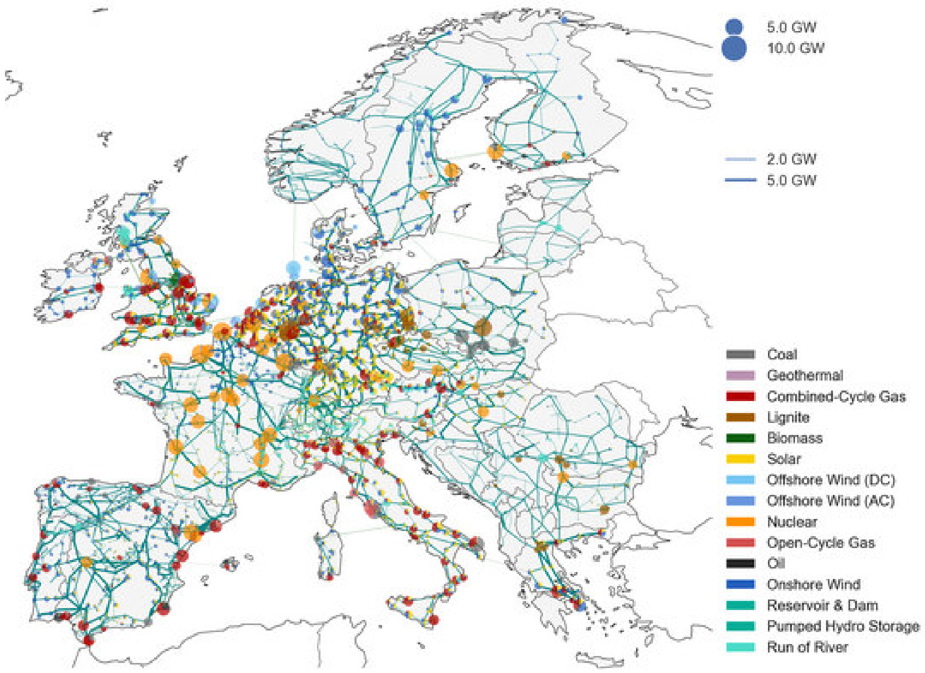
Planning is needed for appropriate demand, generation, capacity and dispatch.

Complexity increases with renewables and decentralization of supply and demand!

Energy system models needed!

What is Energy Modelling?

- Computational representations of energy systems to analyze, simulate, predict or simulate outcomes based on certain assumptions
- Simplification of real (complicated) conditions and are sensitive to applied input parameters/data

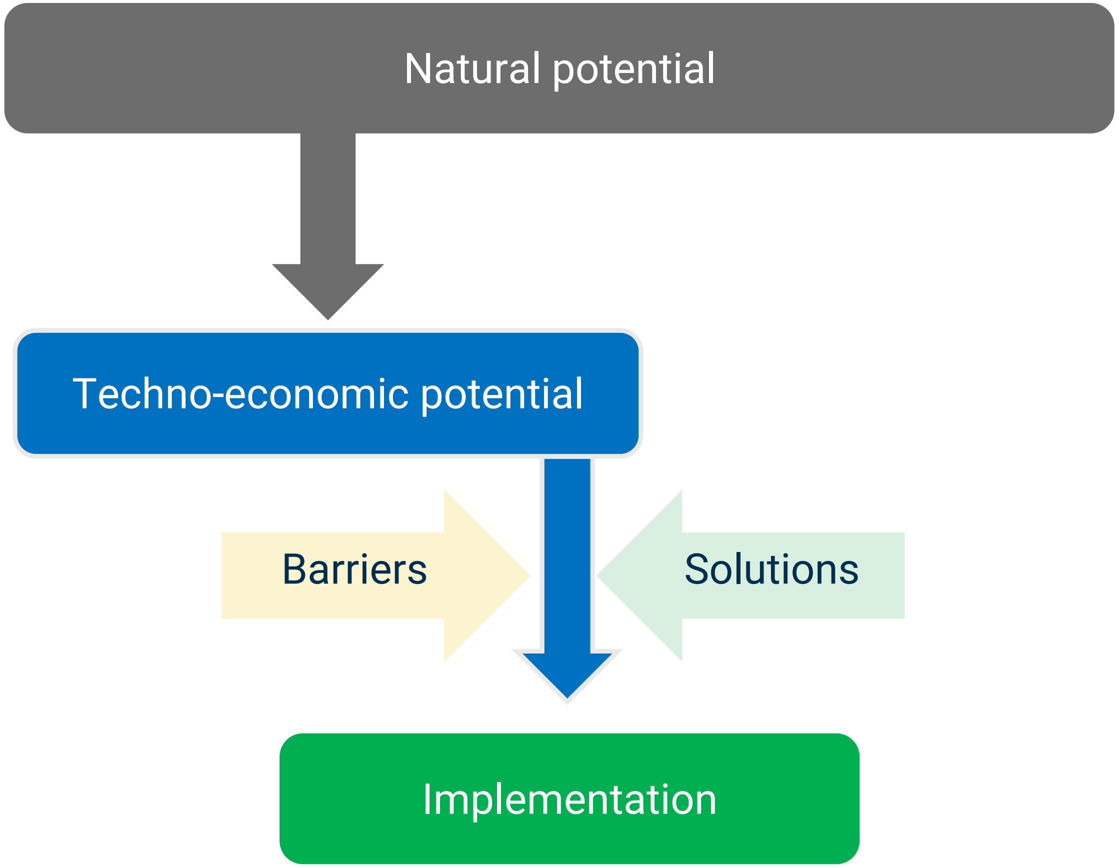


Sketch of PyPSA-Eur an open model dataset of the European energy system.
Source: https://pypsa-eur.readthedocs.io/en/latest/

Purpose of Energy Modelling

- Inform and support stakeholder / policy decisions:
  - Energy needs
  - Energy costs
  - Infrastructure requirements

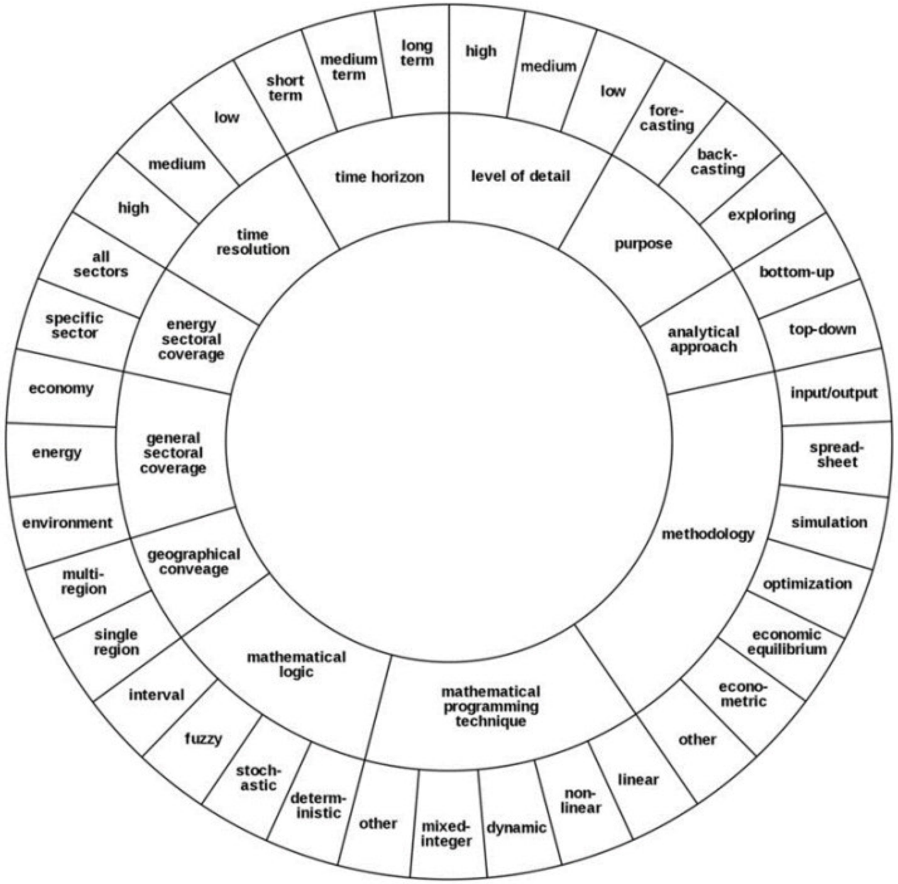
- Key categories:
  - Impact assessments
  - Long-term energy planning



Energy Model Classification I: Characteristics

Energy models can vary greatly, depending on their subject matter. Typically, the defining parameters will be:

- Geographical scale
- Sectors of the economy
- Timeframe
- Mathematical approaches
- and many more…



An example of model classification, Energy Planning and Modelling A Guide for Energy Planners and Policymakers 2022. Source: GIZ_EnergyModellingGuidebook_2022.pdf

Energy Model Classification II: Types

Agent-Based Models (ABM)	Macroeconomic Models (CGE, ...)	Microeconomic Models	Data Analysis	Energy System Models (ESM)
• Focused on individual agents • Behavioural decisions • Example: PV update depending on incentive schemes	• Focus on economy at large, • Including broad impacts like employment, GDP or wellfare • Example: CO2 taxing and employment effects	• Focussed on policy impacts on household level • Benefit and/or burden relative to specific group • Example: CO2 prices on heat	• Geospatial analysis • Correlations • Example: Histroical correlation between PV adoption and socio-economic background	• Representation of energy systems for planning • Dispatch optimization • Capacity and infrastructure planning • Example: Micro grid planning

Components of an Energy System Model (ESM)

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Demand that needs to be supplied

Definition of selected technologies available to fulfill demand

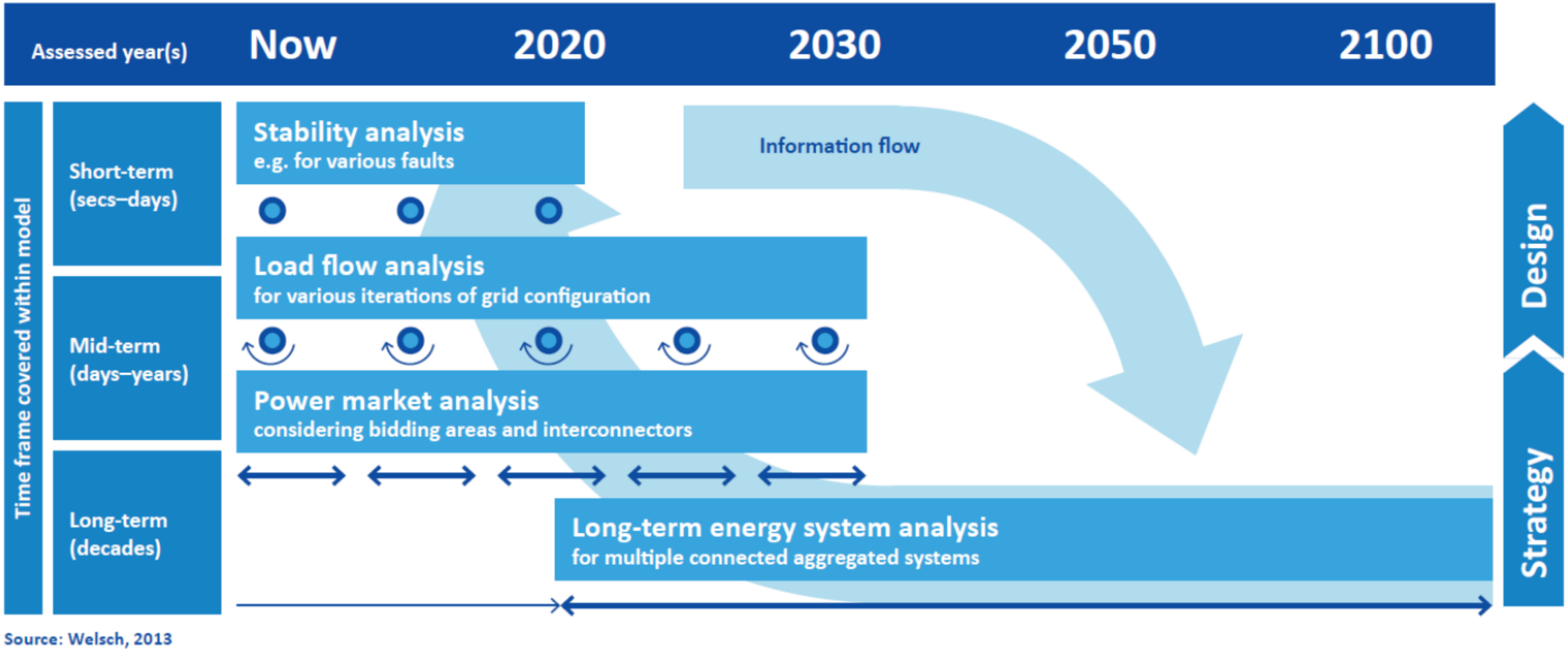
Objective function (eg. minimize annual supply costs)

Model represents real-life system under a number of simplifying assumptions

- Component models
- Economic assumptions
- Dispatch strategies

ESM Characteristics I: Timeframes

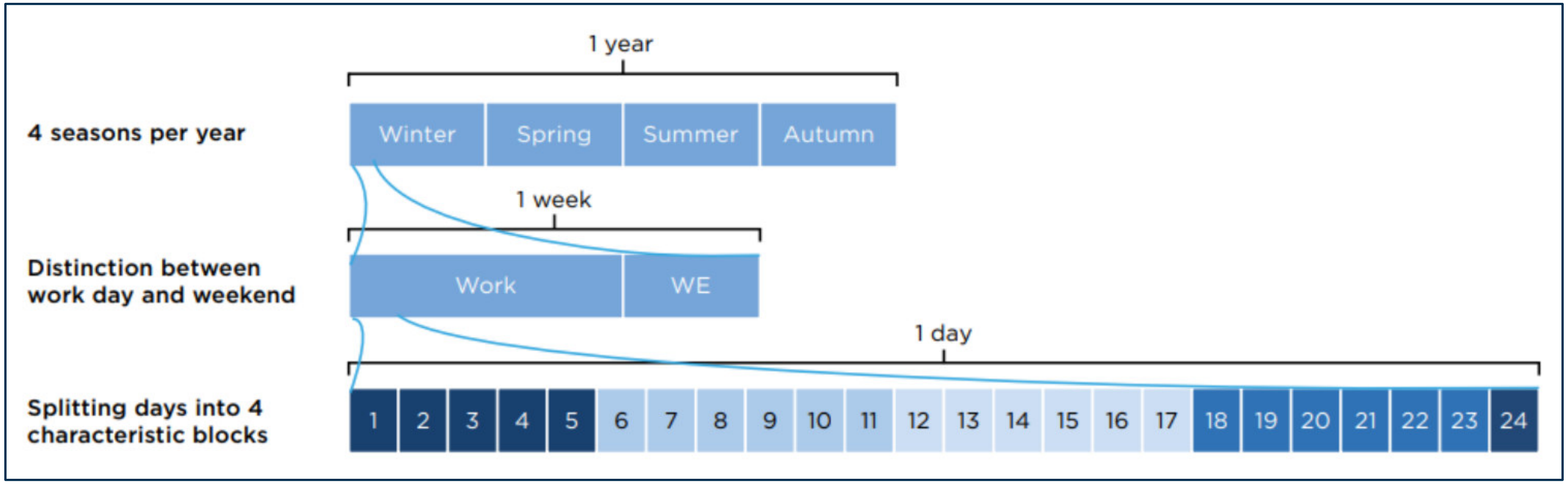
Timeframes are subject to the analytical objectives!



Time horizon by type of analysis, Energy Planning and Modelling A Guide for Energy Planners and Policymakers 2022. Source: [GIZ_EnergyModellingGuidebook_2022.pdf]

ESM Characteristics II: Time slices

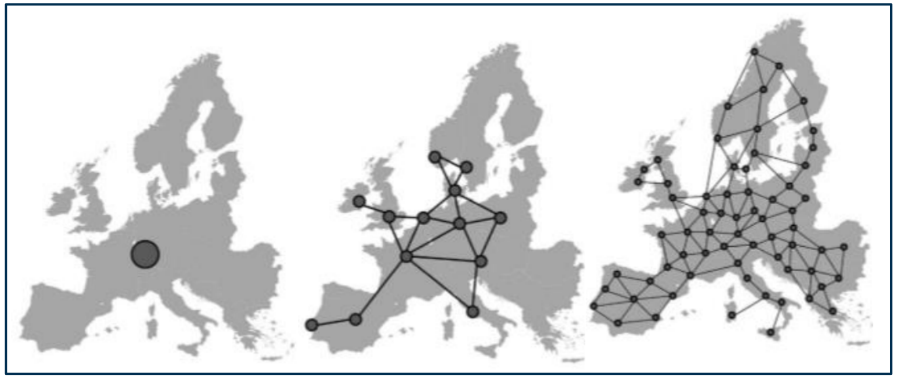
- Models often utilize time slices to avoid distorting reality through averaging (example: energy demand in summer and winter should not be summarized in a single value)



Example of representation of time slices, Energy Planning and Modelling A Guide for Energy Planners and Policymakers 2022.
Source: GIZ_EnergyModellingGuidebook_2022.pdf

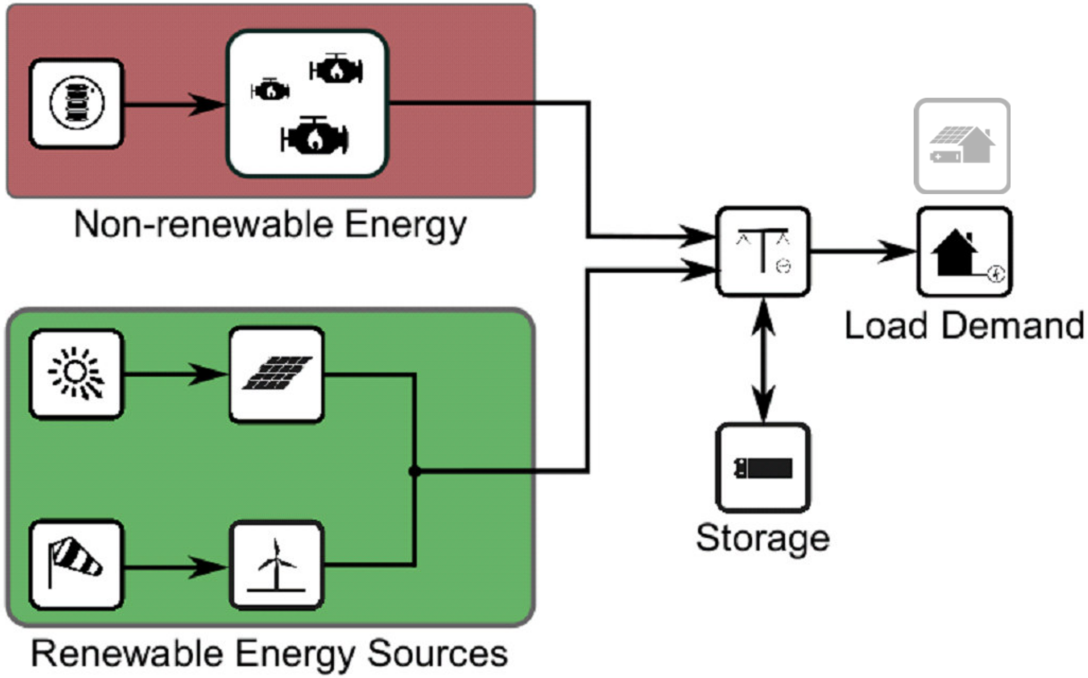
ESM Characteristics III: Geographical Scope

- Energy models can represent energy systems at a local, regional or global level
- Different purposes require different levels of simplification, which is typically achieved through nodes
- Depending on the goal, districts, cities, or entire regions can be summarized into a single node



Single node and multi-node representation, Energy Planning and Modelling A Guide for Energy Planners and Policymakers 2022. Source: GIZ_EnergyModellingGuidebook_2022.pdf

Case study example: Micro Grid



What do we need to represent this case study?

Basic steps of energy system modelling

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- Define energy supply system
- Implement components into model
- Collect input data
- Calculate scenarios / optimize component sizes or operational strategies
- Derive recommendations

Inputs: Data requirements of model

Load profiles for each time step

Timeseries of renewable generation potential

Economic parameters

Fix and variable cost of the system components, weighted average cost of capital, project lifetime

Technical parameters

Generators: Efficiencies or fuel curve, min/max runtime, min/max loading (if possible)

Battery storage system: minimum state of charge, input/output efficiencies, C-rate

Objective Function: Minimized Annuity

Minimize annual energy supply costs

- Decision variables: Asset capacities and their dispatch

$$\min \sum_i \underbrace{\left(Capex(i) * CRF(i) + Opex_{fix}(i)\right) * P_{inst}(i)}_{\text{Costs of components}} + \underbrace{\sum_i \sum_t Opex_{var}(i) * E_{gen}(i,t)}_{\text{Costs of dispatch}}$$

$i \in \{WEA, PV, BHKW, Speicher\}$

$t \in \{1 \ldots 8760\}$

Capex	Capital expenditure	EUR/kW
CRF	Capital recovery factor	-
$Opex_{fix}$	Fixed operational expenditure	EUR/(kW*a)
$Opex_{var}$	Variable operational expenditure	EUR/kWh
P_{inst}	Capacity of component	kW
E_{gen}	Generated electricity per timestep	kWh
i	Index of system components	-
t	Index of time steps	-

Potential technological constraints

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Maximum potentials for installation (e.g. space restrictions)

Minimal renewable share

Minimal degree of autonomy

Maximum Backup power

Maximum Emissions

Outputs of ESM

Technical	Economical	Others
• Optimal capacities • Dispatch of assets • Aggregated energy flows • Peak power • Renewable factor • Autonomy • Excess generation	• Total cost of energy system • Levelized cost of energy • Payback period, Return-of-Investment,…	• CO2-Emissions • Subsequent tariffs • Environmental indicators • Social indicators

Outputs of ESM: LCOE

LCOE = Levelized cost of electricity = €/kWh

- Important, but not only relevant indicator of optimal system sizing and operation
- Annual cost of energy system devided by supplied demand
- Not directly optimized for
- Dependent on system boundaries and provided economical details

Scenario calculation / optimization

Scenarios		Results				
Name	Components	Capacities	Investment costs total [USD]	LCOE [USD/kWh]	RE-share [%]	GHG emissions [Mtons/year]
Diesel-only	Diesel plant	2.4 MW	0	0.32	0	11
Wind-diesel	Diesel plant Wind farm	2.4 MW 3.6 MW	5.4 Million	0.27	35%	7.1
PV-battery-diesel	Diesel plant PV Battery storage	2.4 MW 4 MW 1.5 MWh	6.35 Million	0.28	39%	6.3

Webtool: open_plan tool

- Cross-sectoral open planning tool with a graphical user interface
  - based on the multi-vector-simulator and oemof
  - special focus on energy cells
- The development takes place in close cooperation with the stakeholders
- https://open-plan-tool.org, https://open-plan.rl-institut.de

Register for open_plan

Welcome to the open-plan-tool

Do you not have an account yet? **Sign up**

Forgot your password? **Reset Password**

https://open-plan.rl-institut.de/en/

Webtool OpenPlan – Excercise I

1. Log in to Open Plan
2. Everyone chooses a scenario
3. Run the default scenario without capacity optimization
4. Look at the results
5. Find Levelized cost of Electricity

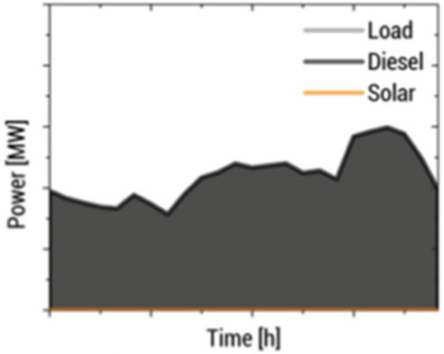
How expensive is each kWh electricity if only supplied by diesel generator?

Webtool OpenPlan – Excercise II

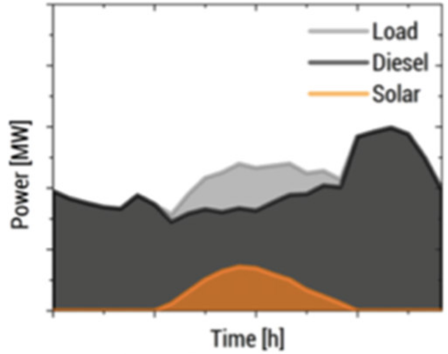
1. Create a new scenario
2. Remove storages from energy system
3. Create multiple scenarios with different renewable share constraints (25%, 50%, 75%)
4. Optimize capacity and dispatch
5. Look at the LCOE of the different scenarios
6. Does a renewable constraint of 100% work?

Discuss the behaviour of LCOE relative to the obtained renewable share!

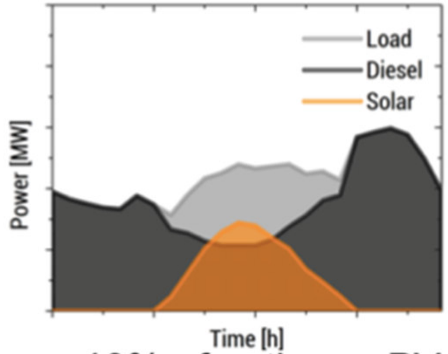
Impact of energy demand and load profile on RE



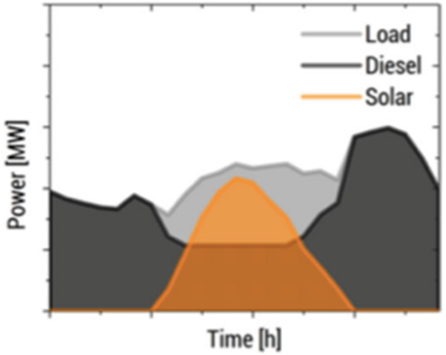
0% of optimum PV
LCOE = 0.360 $/kWh



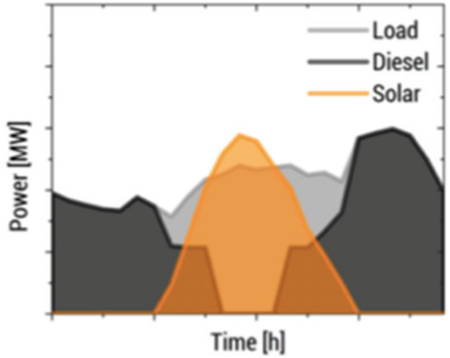
20% of optimum PV
LCOE = 0.350 $/kWh



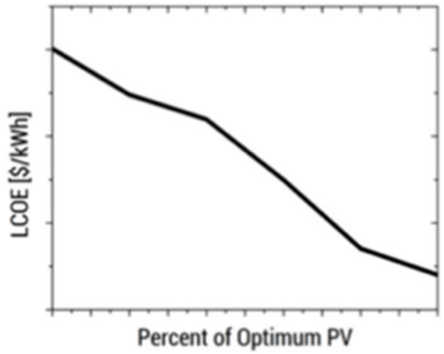
40% of optimum PV
LCOE = 0.344 $/kWh



60% of optimum PV
LCOE = 0.330 $/kWh

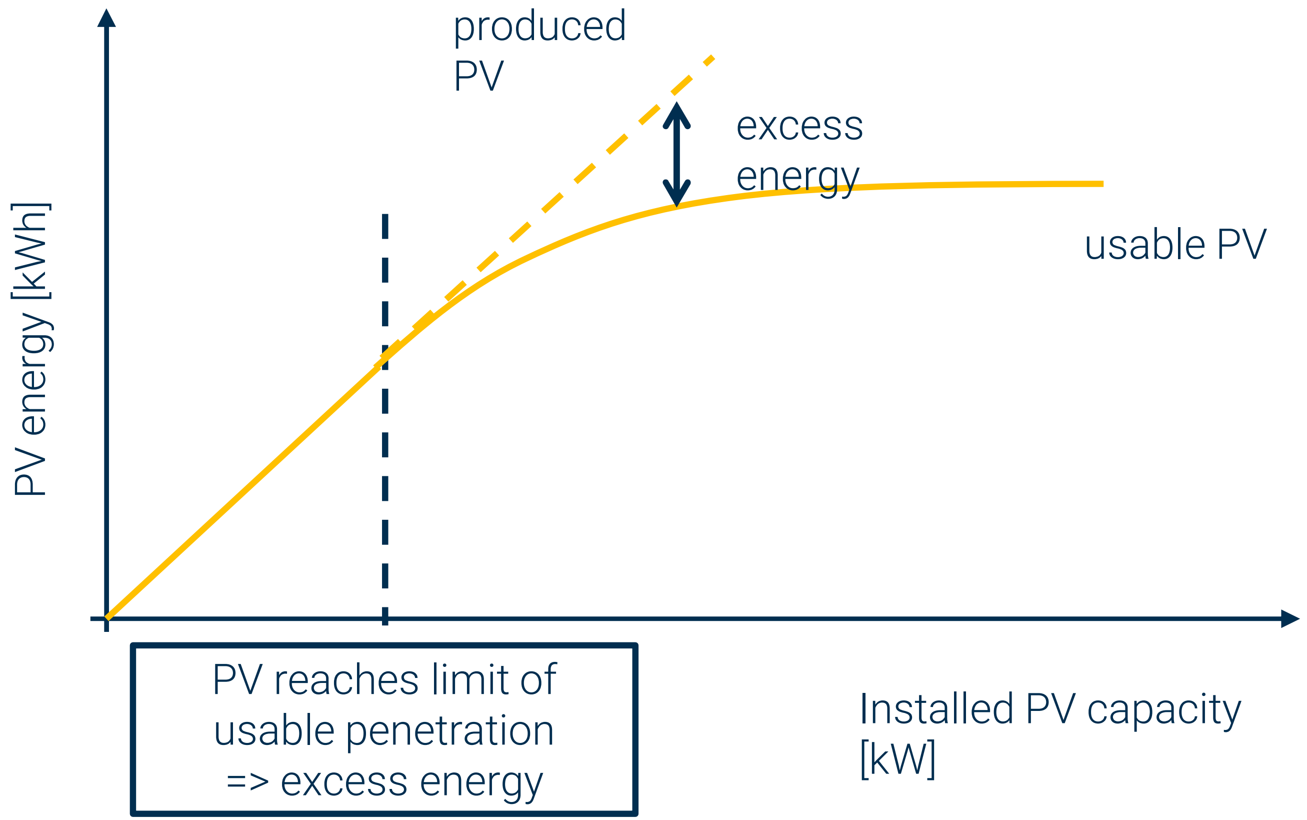


80% of optimum PV
LCOE = 0.314 $/kWh



Increasing Solar PV
Decreasing LCOE

Effect of excess energy

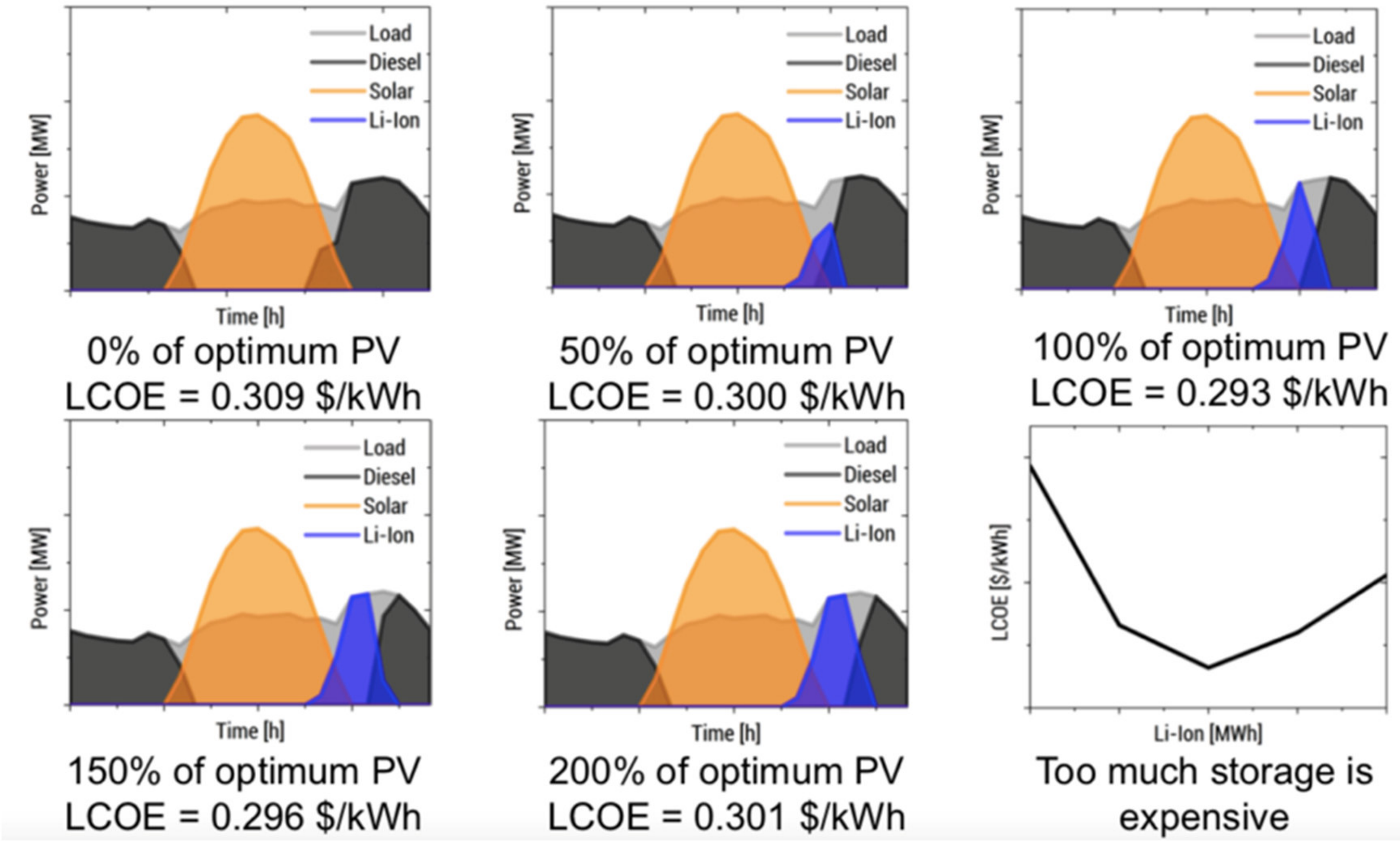


Webtool OpenPlan – Excercise III

1. Add a storage unit to the scenarios of excercise III
2. Create multiple scenarios with different renewable share constraints (25%, 50%, 75%)
3. Optimize capacity and dispatch
4. Look at the LCOE of the different scenarios
5. Does a renewable constraint of 100% work?

Discuss the LCOE!

Impact of energy demand and load profile on RE



Learnig Outcomes of this Session

- Energy trilemma
- Energy supply assets
  - Dispatchable and non-dispatchable
- Energy model types
- Energy system models
  - Components
  - Input Data
  - Output data
- First experience with energy modelling through openPlan

Thank you for your participation ☺

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