Energy System Modelling and Energy Justice - Incompatible Concepts?

Session 2:
Open Energy Modelling

Workshop @ Meccanica Feminale,
Stuttgart, 18.02 – 20.2.2025

Martha M. Hoffmann

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

MH0

Agenda Session 2 – Open Energy Models

Time	Title
14:00	Check-In
14:10	Open Energy Models
14:30	Example: Open Plan
14:40	Example: oemof
14:50	Jupiter Notebook oemof
15:20	Questions
15:30	Pause

Folie 3

MH0 Agenda does not fit anymore
Martha Hoffmann; 2025-02-14T19:05:07.310

Repetition: Questions regarding sessions

- What is an energy system model (ESM)?
- What are energy supply components?
- What data requirements exist for ESM?
- What are expected outputs of ESM?

Open Questions?

Components of an Energy System Model (ESM)

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

Inputs: Data requirements of model

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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

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

$$i \in \{WEA, PV, BHKW, Speicher\}$$
$$t \in \{1...8760\}$$

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	-

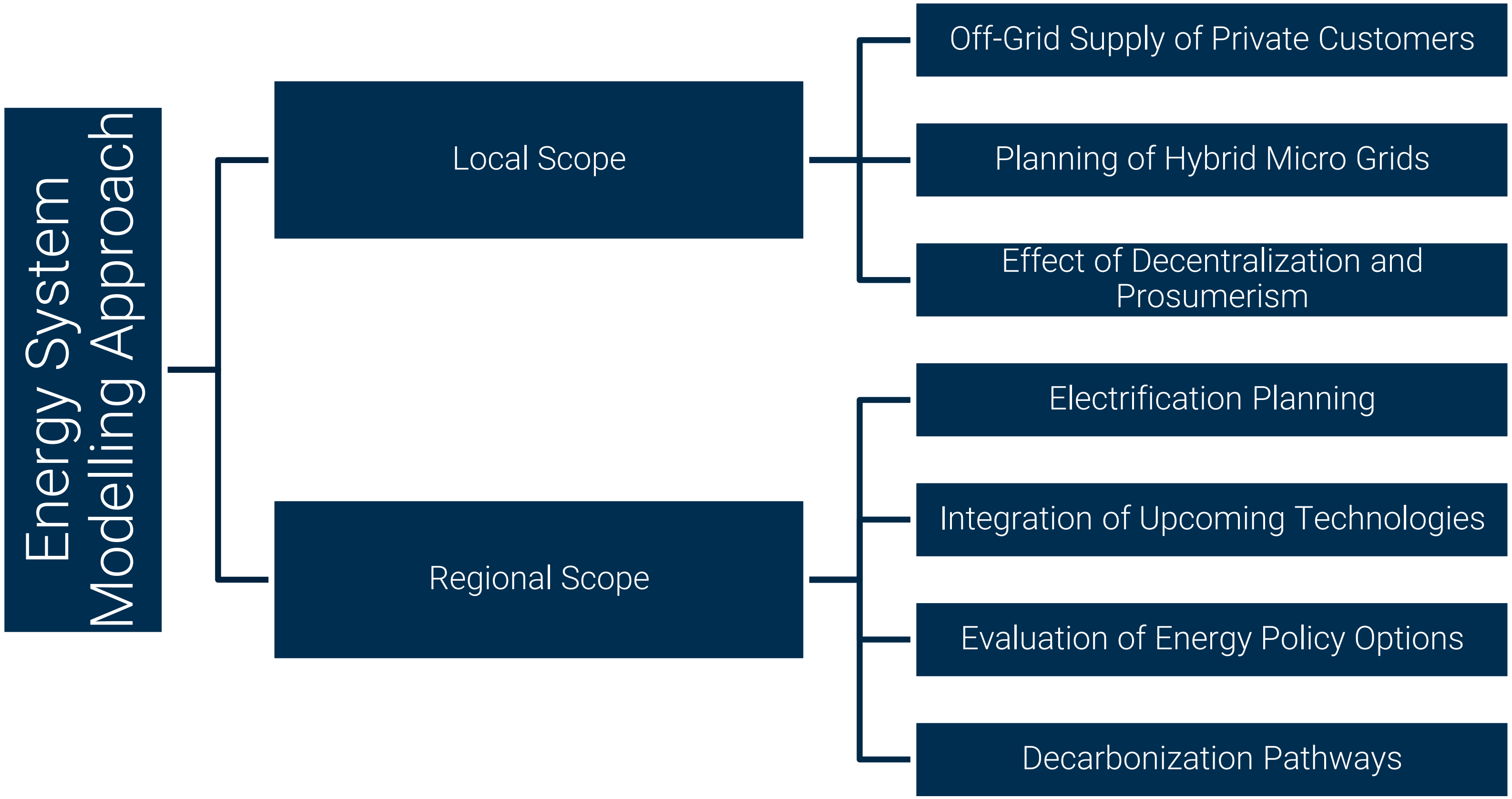
Outputs of ESM

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

Excercise: Use of Energy System Models

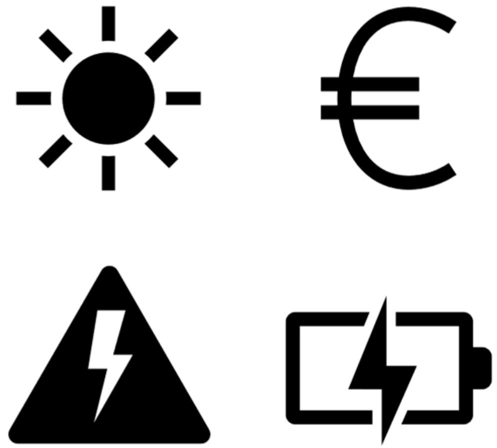
What can energy system models be used for?

Application of ESM - Overview



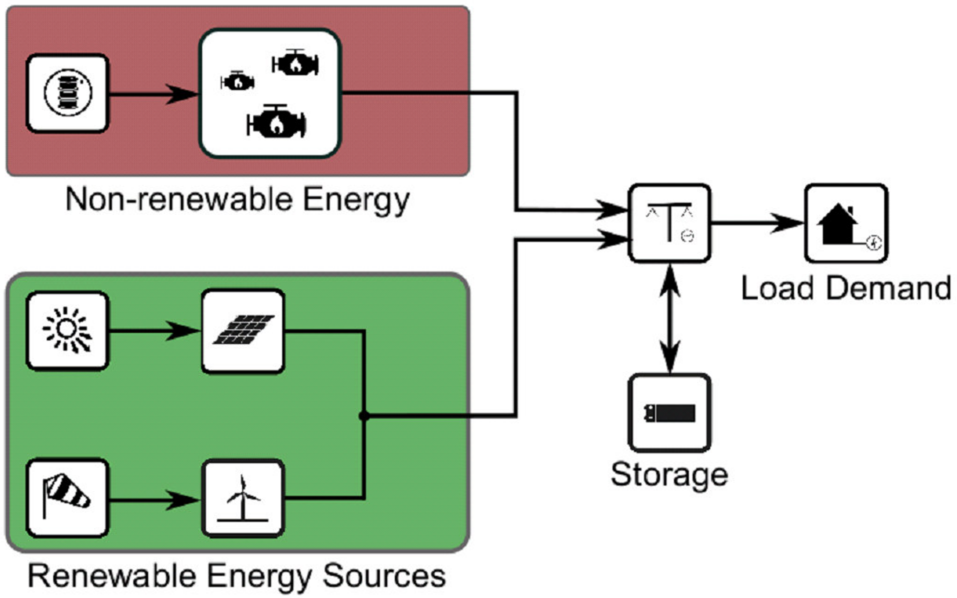
Off-Grid Supply of Private Customers

- Individual household level
- Cost-optimal supply of household:
  - Should a household invest into SHS, or battery storage?
  - What is the cheapest heating or cooling supply for a household?
  - Is supply from the national grid the cheapest option?
  - If there are blackouts, what are the backup capacities that a household should install?



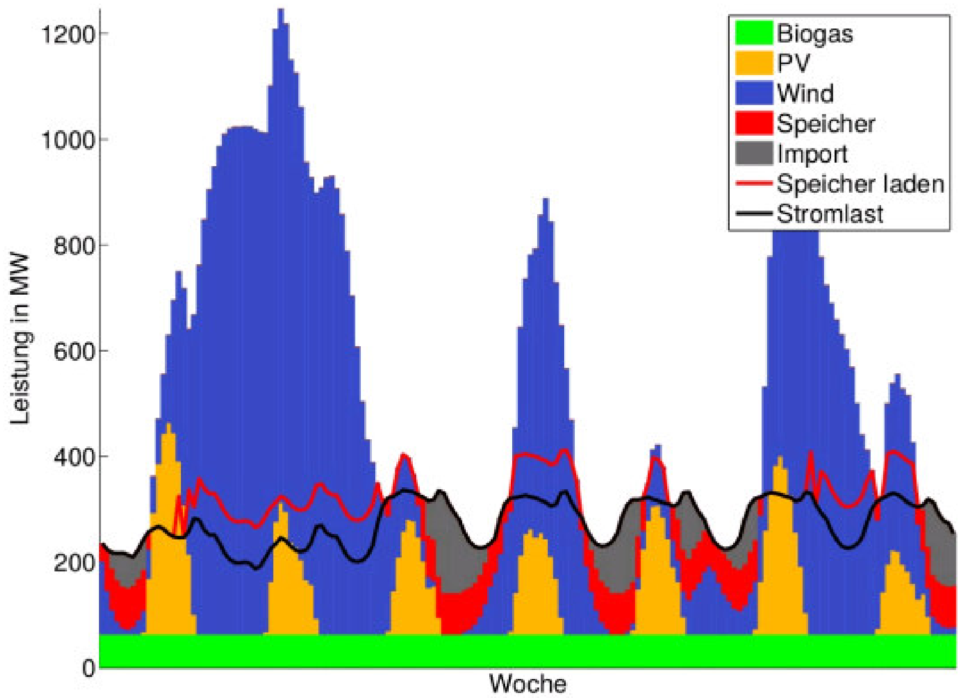
Planning of Hybrid Micro Grids (I)

- Sizing, optimization and dispatch of generator power and battery energy storage system
- Target of optimization:
  - Minimize total system cost
- Constraints:
  - Cover demand at each time increment
  - Share of Renewables min. 80 %



Planning of Hybrid Micro Grids (II)

- Sizing, optimization and dispatch of generator power and battery energy storage system
- Target of optimization:
  - Minimize total system cost
- Constraints:
  - Cover demand at each time increment
  - Share of Renewables min. 80 %



Effect of Decentralization and Prosumerism

- Past structure of electricity grid:
  - Large and dispatchable power plants
  - Plants located at strategic points in the grid
  - Top-down voltage levels, no flow from lower levels to higher levels
- Current trend:
  - Smaller, decentralized generation
  - Increasing share of non-dispatchable generation
  - Feed-in of small plants and prosumers into lower voltage grid

  → Necessity of grid topology adaption?

  → Flexibility options?

Electrification Planning

- Combines ESM with geographic information systems (GIS)
- Analysis of a great number of locations in a region
- Multi-staged electrification planning over a certain timespan (eg. decades)
- Determinates:
  - Which locations should be conneced to the national grid and when
  - Which locations should receive intermediate electrification solutions
  - Which locations are infeasible to connect to the national grid and should receive long-term off-grid supply solutions, eg. micro grids or SHS

Integration of Upcoming Technologies

- New technologies may support future energy systems
  - Decarbonization
  - Increased efficiency
  - Electrification of other sectors
  - Storage
- Examples: H2, Power-2-X, sector-coupling, electrification of transport sector
- ESM determines
  - If technologies are techno-economically feasible today
  - When technologies are expected to be integrated
  - The role of technologies in the future energy supply

Evaluation of Energy Policy Options

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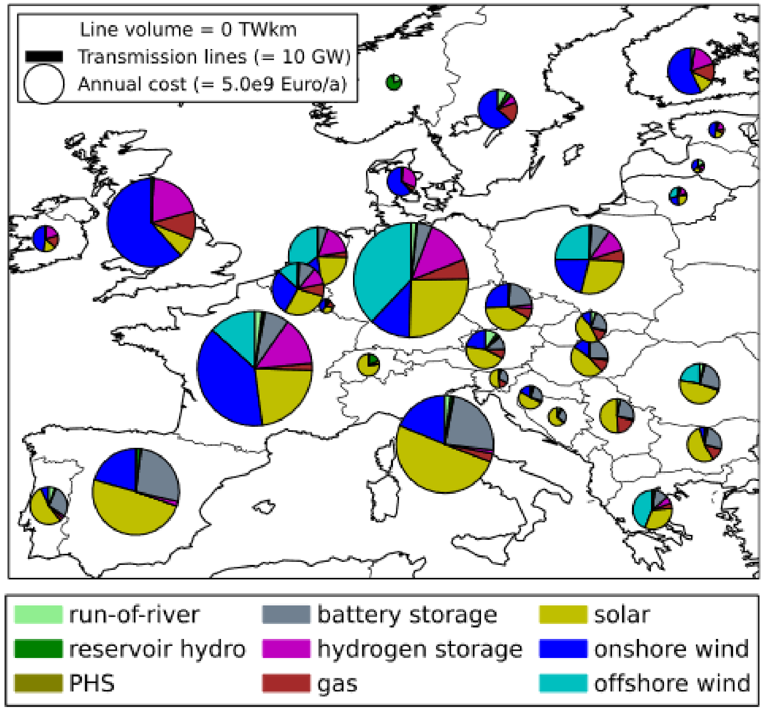
- Policy makers consider different policy options
- What are the impacts of the policies on the energy system?
- ESM can compare policy options
- Policy makers can choose the outcome that is favourable

Decarbonization Pathways

- Policy makers have certain goals
  - e.g. carbon emission reductions
  - need to know how to get there
- Multi-year and bird-eye view ESM
  - Large energy systems with a number of stakeholders
  - Not one-time investment considerations
  - Capacity building investigation
  - Determination of roadmaps and scenarios
  - Supports policy making by providing policy makers with options
- The specific policy decisions, ie. subsidy schemes or regulations are up to the decision makers



D.P. Schlachtberger, T. Brown, S. Schramm, M. Greiner (2017): *The benefits of cooperation in a highly renewable European electricity network*. Energy, https://doi.org/10.1016/j.energy.2017.06.004

Open Source (OS) Software

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- Closed source software acts as a blackbox → limits applicability
- OS meet scientific standards in software based research
  - Replicability, Accessability, Reproducability
- foster bottom-up approaches by reducing barriers associated with high license cost of proprietary software tools
- improve research quality & completeness & knowledge pooling due to collaborative modelling

openmod open energy modelling initiative

„ (…) models need to meet scientific standards as public acceptance becomes increasingly important"

Hilpert et. al[3)]

Exercise: Open Source Solutions

Have you ever used open source solutions?

Exercise: Open Source Solutions

Linux

Signal

Liebe Office

Have you ever used open source solutions?

GIMP

Corona-Warn-App

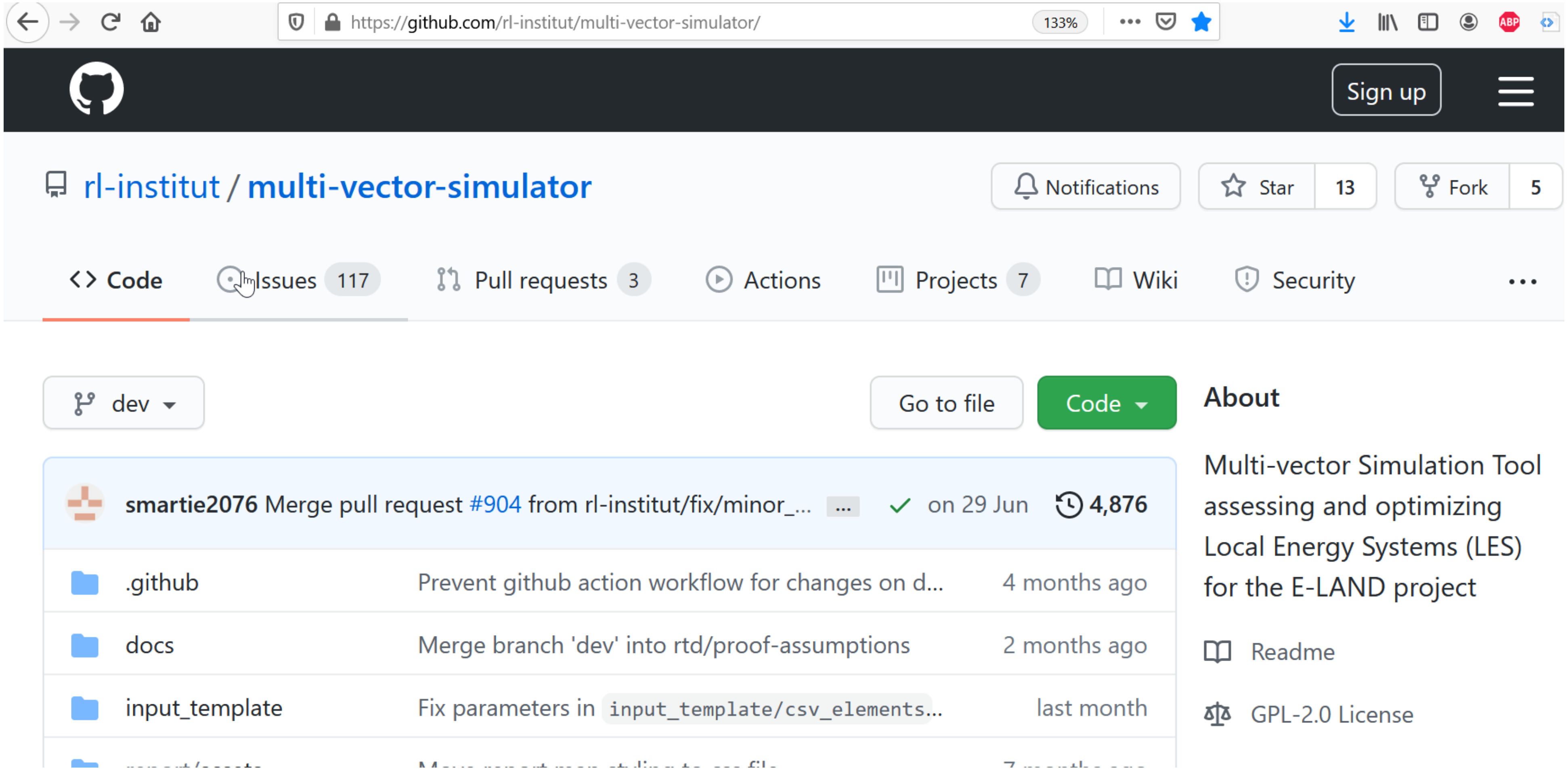
Python

Supporting colloborative development: GitHub

- Version control solution
  - History of changes
  - Reasoning behind changes
  - Public availability (can be disabled)
  - Authors
- Enables colloboration on programming projects
  - Discussion of issues
  - Validating proposed changes
  - Rights management
  - Projekt management

Further reading:
(1) Github: https://github.com/

Example of a GitHub repository



Examplary ESM Tools

- There are a large number of tools available:

Simplified Planning Tool (SPT)

iHOGA

TRNSYS

pyPSA

Open Energy Modelling Framework (oemof)

Multi-Vector Simulator

OSeMOSYS

Offgridders

HOMER

RETScreen

urbs

H2RES

Names in red: Tools discussed within this session

INSEL

Extensive overview over available simulation tools:

(1) Sinha S, Chandel SS (2014) Review of software tools for hybrid renewable energy systems. Renew Sustain Energy Rev 32:192–205

(2) Ringkjøb H-K, Haugan PM, Solbrekke IM (2018) A review of modelling tools for energy and electricity systems with large shares of variable renewables. Renew Sustain Energy Rev 96:440–459

(3) Connolly D, Lund H, Mathiesen BV, Leahy M (2010) A review of computer tools for analysing the integration of renewable energy into various energy systems. Appl Energy 87(4):1059–1082

Programming languages of ESM

Comparison of selected features for energy system modelling frameworks that are applied in Africa

Software	Version	Citation	Language	Free and open	Power flow	Transport model	LOPF[d]	SCLOPF[e]	Unit commitment	Sector-coupling	Pathway optimization[f]
Calliope	v0.6.8	[10]	Python	✓		✓			✓	✓	
Dispa-SET	v2.4	[11]	GAMS	✓		✓			✓		
GridPath	v0.14.1	[12]	Python	✓		✓	✓		✓		✓
LEAP	2020.1.63	[13]	NA[a]							✓	
LUT	2021	[14]	GNU[b]			✓	✓			✓	✓
NEMO	v1.7	[15]	Julia	✓	✓	✓	✓		✓		
OSeMOSYS	2022	[16]	GNU[c]	✓		✓				✓	✓
PLEXOS	9	[17]	NA[a]			✓	✓	✓	✓	✓	✓
PYPOWER	5.15.5	[18]	Python	✓	✓	✓	✓		✓		
PyPSA	v0.20.0	[3]	Python	✓	✓	✓	✓	✓	✓	✓	✓
SPLAT-MESSAGE	2022	[19]	GAMS			✓			✓	✓	
TIMES[g]	2022	[20]	GAMS			✓	✓		✓	✓	✓

[a] NA = no information available.
[b] Mix of GNU-Mathprog and Matlab.
[c] Available in GNU Mathprog, Python and GAMS.
[d] Linearized optimal power flow [3].
[e] Security constrained linearized optimal power flow [3].
[f] Includes myopic and perfect foresight optimizations over multiple years [21].
[g] Times is open source but not free as licensing for GAMS is required to operate the model.

Source: Parzen et al.,2023

Examplary Models: Homer

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- User interface
- Industry standard, often used for research
  - Often used as a comparison to open sourve tools
- Payed software with monthly/annual subscriptions for different modules
- Closed-source and therefore black box tool
  - No adaptations possible
  - Component models and dispatch rules not 100% clear

Logo: (CC) HOMER Energy by UL, https://www.homerenergy.com/

Examplary Models: *OSeMOSYS*

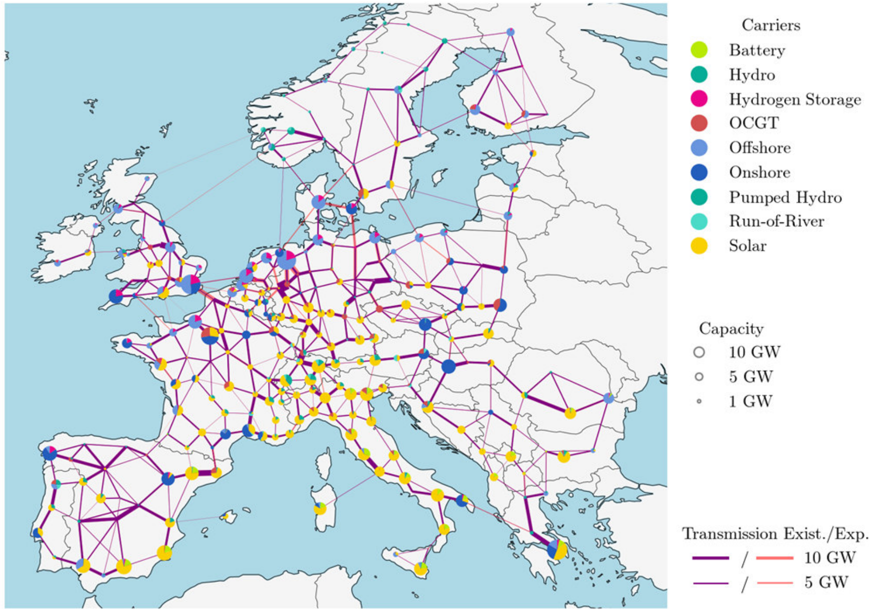
- Adressing developers, modellers, academics and policy makers
- Computes energy supply mix in the course of the evaluated period (decades)
  - Can cover sector-coupling
  - Various scales: Continents, countries, regions, villages
- Large number of publications

[1}

Further reading:
(1) OSeMOSYS: The Open Source Energy Modeling System, http://www.osemosys.org/
(2) Github repository of OSeMOSYS:: https://github.com/OSeMOSYS/OSeMOSYS
(3) M. Howells et al., OSeMOSYS: The Open Source Energy Modeling System: An introduction to its ethos, structure and development, Energy Policy, October 2011. http://www.sciencedirect.com/science/article/pii/S0301421511004897

PyPSA

- *Python for Power System Analysis*
- Designed for simulating and optimizing modern power systems
  → Static power flows, Economic Dispatch, Linear optimal power, Capacity expansion planning, Modelling-to-Generate-Alternatives
- Active, large, global user group
- Requires python knowledge
- Country or regionwide studies



https://pypsa.readthedocs.io

PyPSA-Earth

- Open-source tool for data management and optimization
- Provides policymakers, companies, and researchers with shared platform for a wide range of macro-energy system analyses
- PyPSA meets earth initiative focuses on activities outside of Europe
- Further information and documentation: https://pypsa-meets-earth.github.io/

Examplary Models: oemof

- *oemof* = Open Energy Modelling Framework
- Includes many libraries for energy system modelling
- oemof-solph – single-layer model
- Requires programming skills (python)
- Versatile definition of own energy system models

Further reading:
(1) Hilpert S, Kaldemeyer C, Krien U, Günther S, Wingenbach C, Plessmann G (2018) The open energy modelling framework (oemof)—a new approach to facilitate open science in energy system modelling. Energy Strategy Rev 22:16–25

What is the main idea behind *oemof*?

oemof ['ø:mɔf]
open energy modelling framework

- Is a community-driven open-Source modelling framework initiated by:

ZENTRUM FÜR NACHHALTIGE ENERGIESYSTEME
HOCHSCHULE | EUROPA-UNIVERSITÄT FLENSBURG

REINER LEMOINE INSTITUT

OTTO VON GUERICKE UNIVERSITÄT MAGDEBURG

- Python packages specifically developed for energy system modelling
- Model individual requirements/aspects in research projects

Further reading:

(1) Hilpert S, Kaldemeyer C, Krien U, Günther S, Wingenbach C, Plessmann G (2018) The open energy modelling framework (oemof)—a new approach to facilitate open science in energy system modelling. Energy Strategy Rev 22:16–25

Packages of *oemof*

- *oemof-solph* – Energy model generator
- *TESPy* – Modelling of thermal engineering systems
- *feedinlib* – PV potential
- *demandlib* – Head and power demand profiles
- *oemof-thermal* – Thermal energy components
- *DHNx* – District heating optimization
- *cydets* – Cycle detection
- …and some more programming-related packages

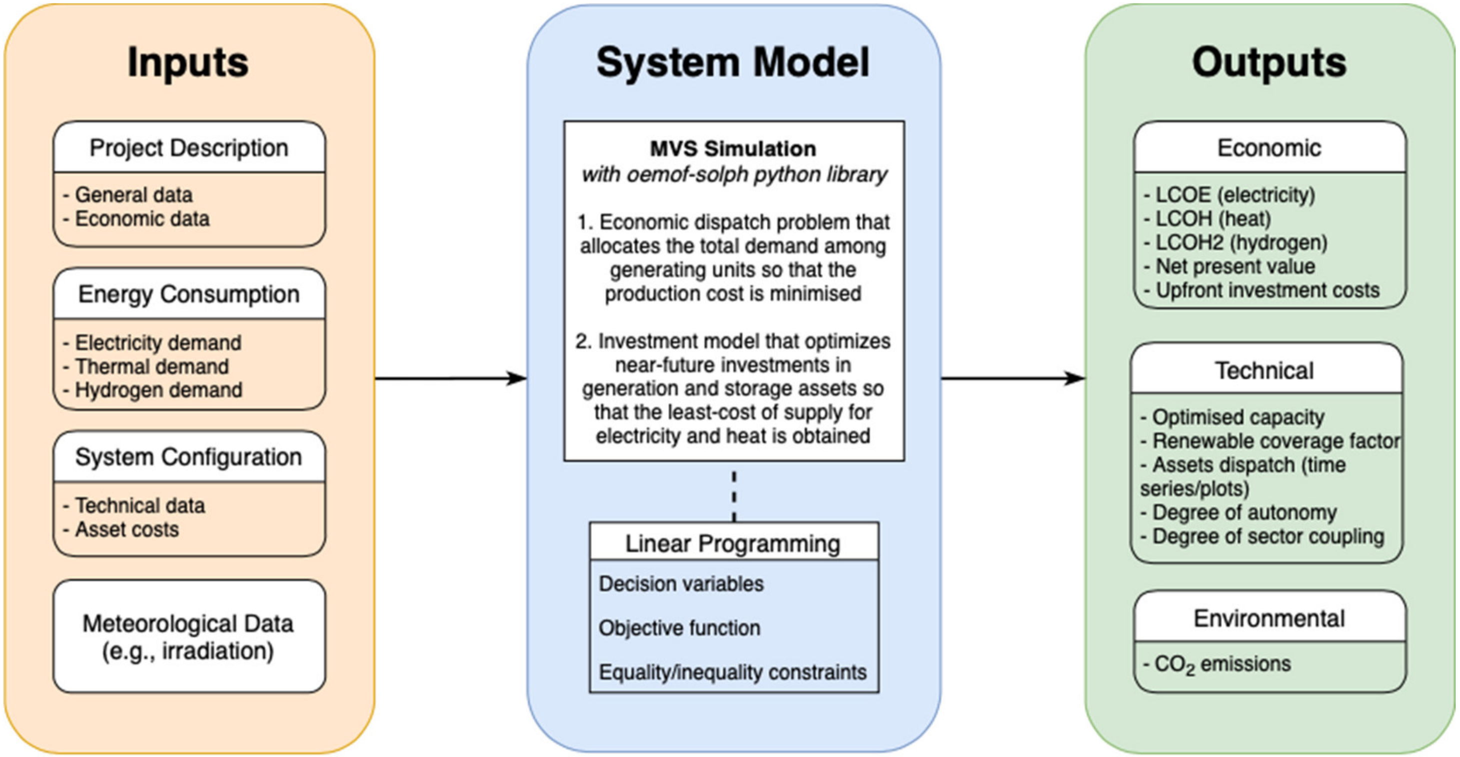
Further reading:
(1) Oemof repositories: https://github.com/orgs/oemof/repositories?q=&type=&language=&sort=stargazers

open_plan tool

- The open_plan project develops a cross-sectoral open planning tool with a graphical user interface based on the multi-vector-simulator and oemof with a special focus on energy cells.
- The development takes place in close cooperation with the stakeholders.
- 10/2021: Release of the open_plan tool (version 1.0)
- End of 2022: Release of the open_plan tool (version 2.0)
- Work on project proposals for open plan 3.0

- https://open-plan-tool.org
- https://open-plan.rl-institut.de

Generalizable Model Steps



- Github reprository of the MVS: https://github.com/rl-institut/multi-vector-simulator
- Manual of the MVS: https://multi-vector-simulator.readthedocs.io

Data processing tools

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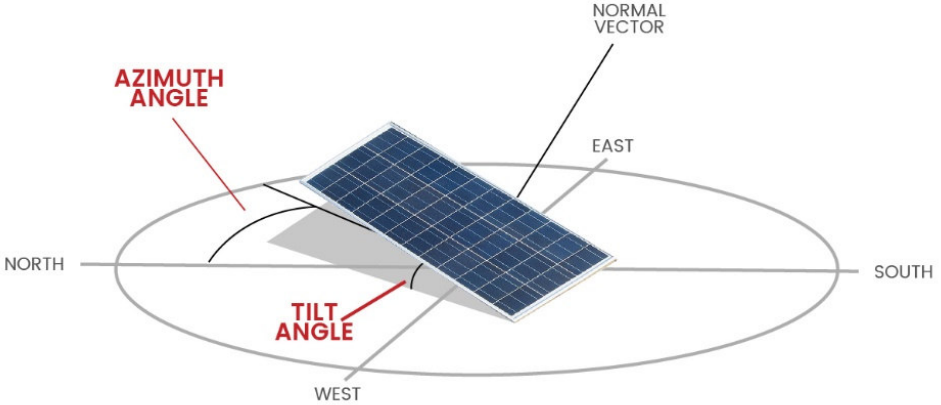
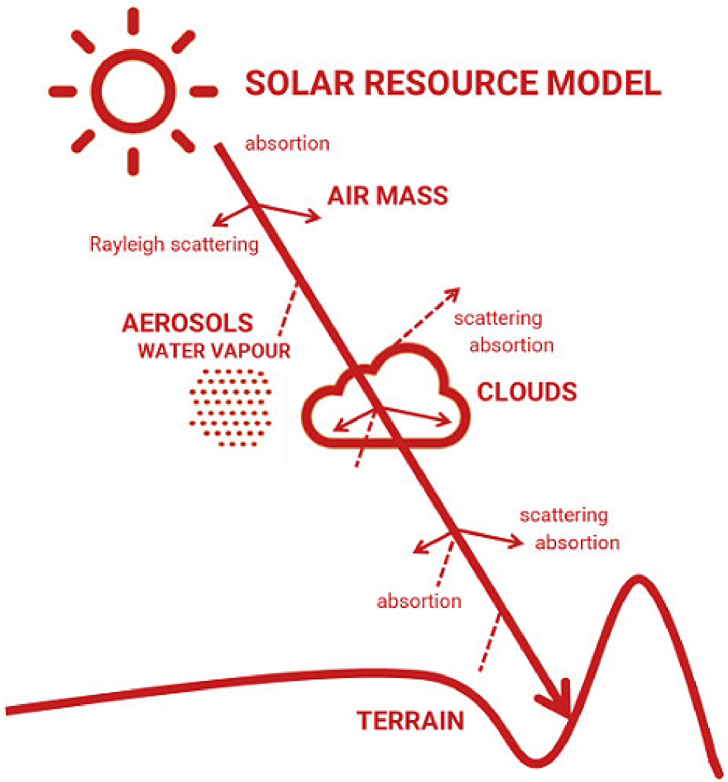
- Resource data as well as infrastructure data often available in larger datasets
  - Commercial tools like ArcGIS, freeware and open-source tools like QGIS provide User-Interface
  - More advanced programing tools like R and Python allow geospatial operations as well

Retrieving renewable potential (I): PV

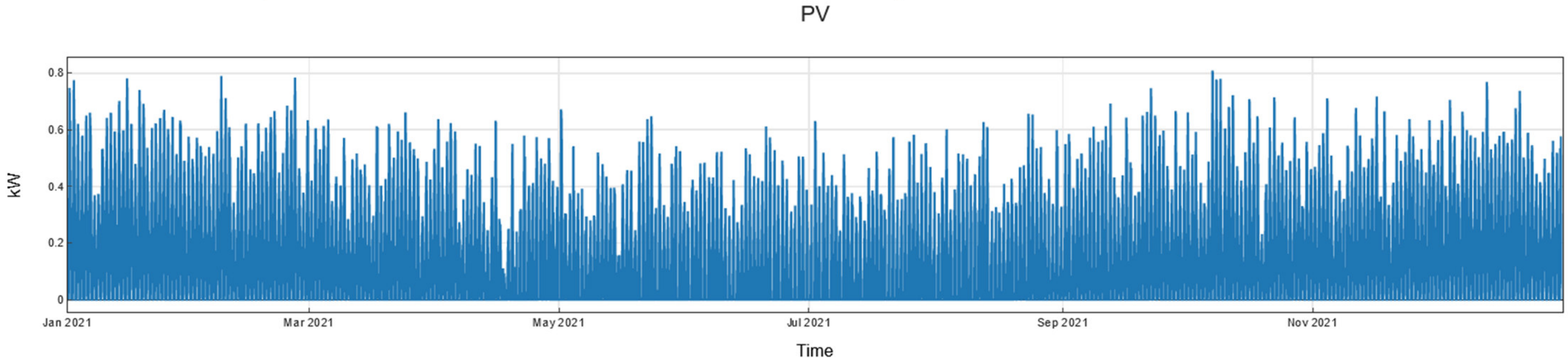
- Can be calculated based on:
  - solar radiation (considering the clear sky index)
  - ambient temperature (impact on module efficiency)
  - standard module efficiency (considering cable losses, inverter losses etc.)
- Solar panel position plays a role in output





Retrieving renewable potential (I): PV

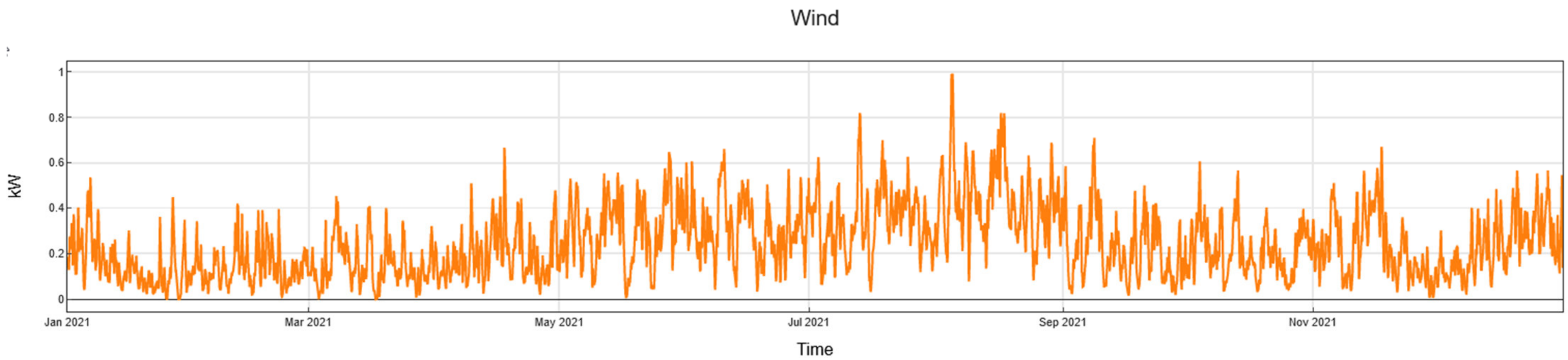
- PV potential
  - Python package: pvlib, feedinlib, atlite
  - Example for webtool: Renewables.ninja



Further info:
(1) Pvlib GitHub repository:. https://github.com/pvlib/pvlib-python
(2) Feedinlib GitHub repository: https://github.com/oemof/feedinlib
(3) Atlite GitHub reprository: https://github.com/PyPSA/atlite
(4) Renewables.ninja (2021) https://www.renewables.ninja/

Retrieving renewable potential (II): Wind

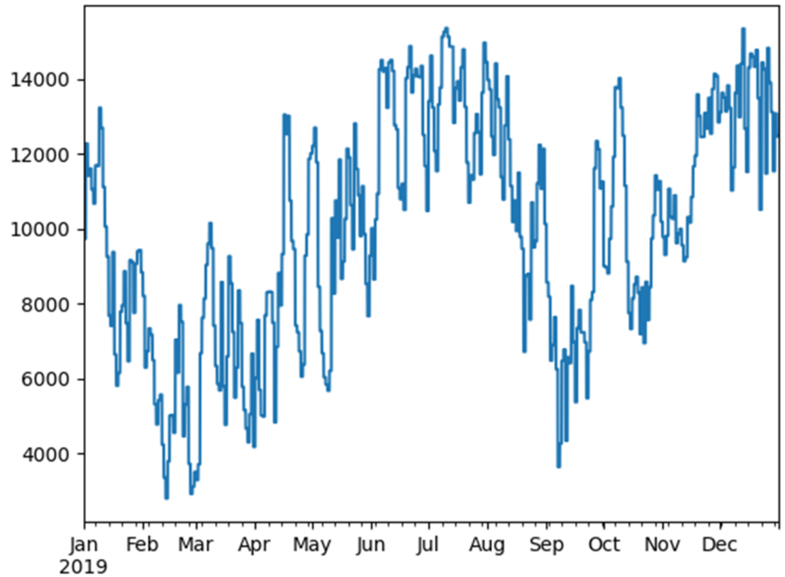
- Wind potential
  - Python package: windpowerlib, atlite
  - Example for webtool: Renewables.ninja



Further info:
(1) Windpowerlib GitHub repository: https://github.com/wind-python/windpowerlib
(2) Atlite GitHub reprository: https://github.com/PyPSA/atlite
(3) Renewables.ninja (2021) https://www.renewables.ninja/

Retrieving renewable potential (III): Hydropower

- Hydropower potential
  - Python package (under development): hydropowerlib
  - If existent, long-term measurements of steam velocity are of great value for planning run-off-the-river plants



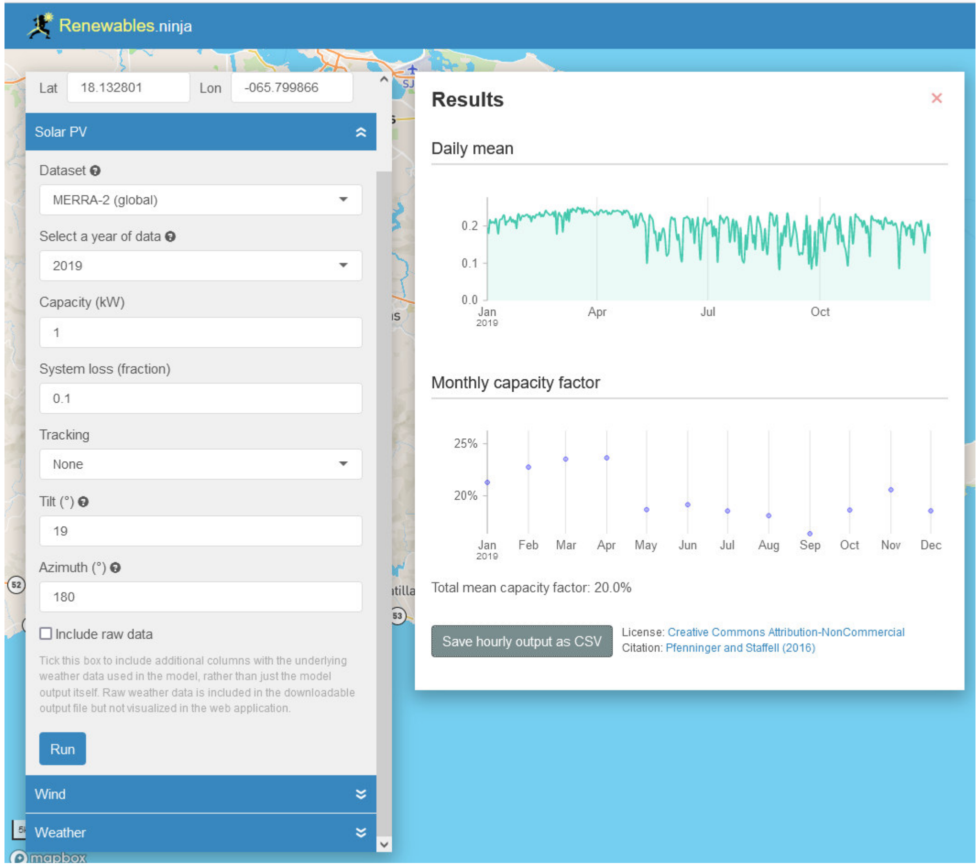
Own depiction, estimated hydropower generation potential based on measurements

Further info:
(1) Hydropowerlib GitHub repository: https://github.com/hydro-python/hydropowerlib

Excercise: Renewable Ninjas

https://www.renewables.ninja/

Do solar or wind ressources hold more annual generation potential per kWp installed.in Stuttgart?



Learning to use pvlib

Broad selection of tutorials and jupyter notebooks available:

pvlib-python / docs / **tutorials** /

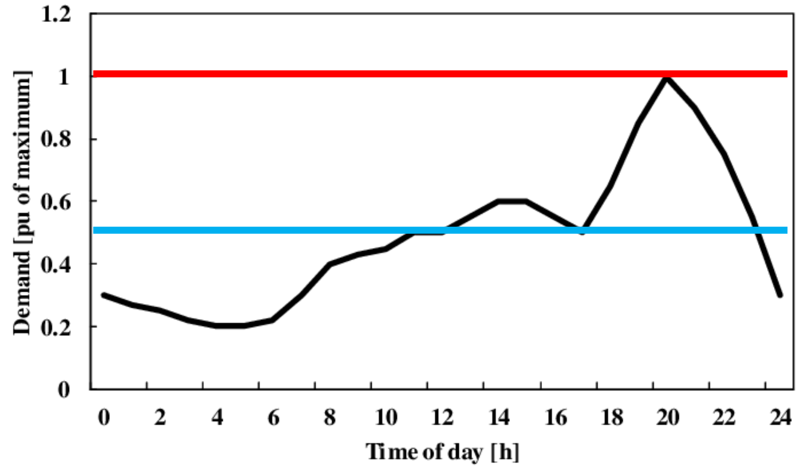
3 people Perform dayofyear-based calculations according to UTC, not local time (... d45790a · 5 months ago History

Name	Last commit message	Last commit date
..		
atmosphere.ipynb	Update tutorial notebooks for compat with current pvlib (#999)	5 years ago
irradiance.ipynb	Perform dayofyear-based calculations according to UTC, not local time (...	5 months ago
pvsystem.ipynb	remove pvsystem.systemdef (#1008)	5 years ago
solarposition.ipynb	more asv tests for solar position, fix fuentes asv bug (#1059)	5 years ago
tmy.ipynb	Update tutorial notebooks for compat with current pvlib (#999)	5 years ago
tmy_and_diffuse_irrad_models.ipynb	Update tutorial notebooks for compat with current pvlib (#999)	5 years ago
tmy_to_power.ipynb	Update tutorial notebooks for compat with current pvlib (#999)	5 years ago
tracking.ipynb	Update tutorial notebooks for compat with current pvlib (#999)	5 years ago

https://github.com/pvlib/pvlib-python/tree/main/docs/tutorials

Energy demand and load profiles

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



- Programming tools aiding demand estimation:
  - demandlib
  - RAMP

Demand estimation approaches

- Customer types
  - Households
  - Enterprises / Agriculture
  - Community Services
- Methodological approaches
  - Historical data
  - Normative approaches (e.g. Decent Living Standards)
  - Engineering approaches
    - “Hand drawn” load curves based on literature
    - Stochastic modelling (e.g. RAMP)
    - Appliance / energy services aggregation (no load curves drawn)

Demand assessment (I): *demandlib*

- Estimation of demand profiles for larger project sites (several households)
  - Electricity and heat demand profiles and
- Based on standard consumption profiles
  - Detailes consumer types: Residential, different types of public and commercial buildings
  - Database: Germany, 1999, the *BDEW* (Bundesverband der Energie- und Wasserwirtschaft e. V.)
- Only data requirement: Annual demand of each customer type

  → Scales standard load profiles to local realities

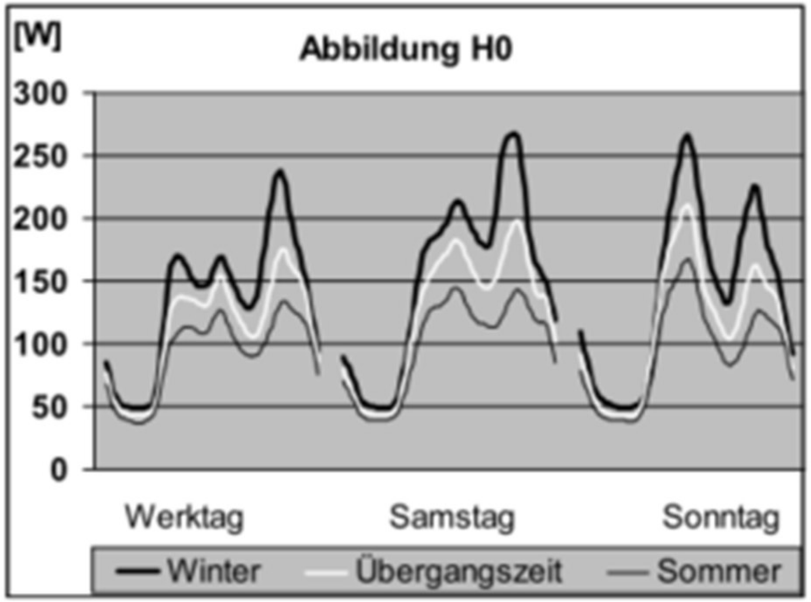
  → Differentiates between weekdays, weekends, holidays

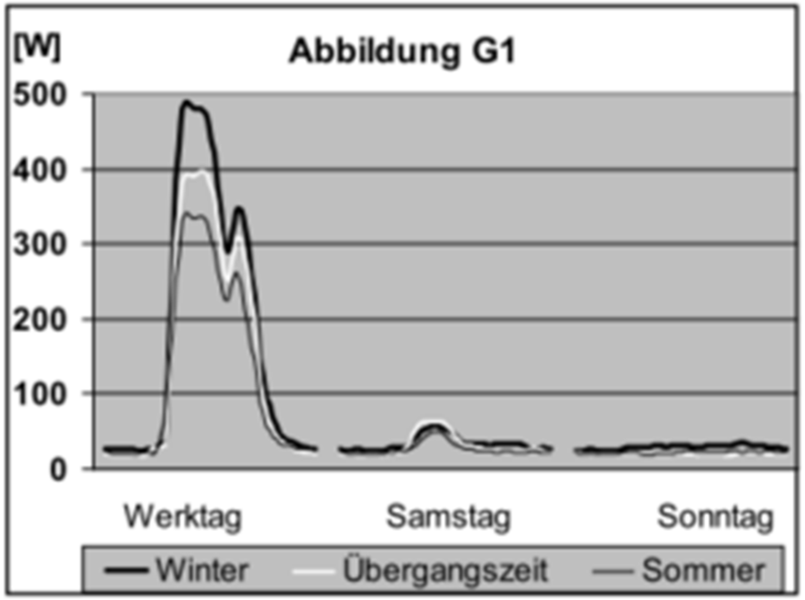
  → Possible to include personalized seasons

Examplary BDEW load profiles (electricity)

Households

Commercial, only





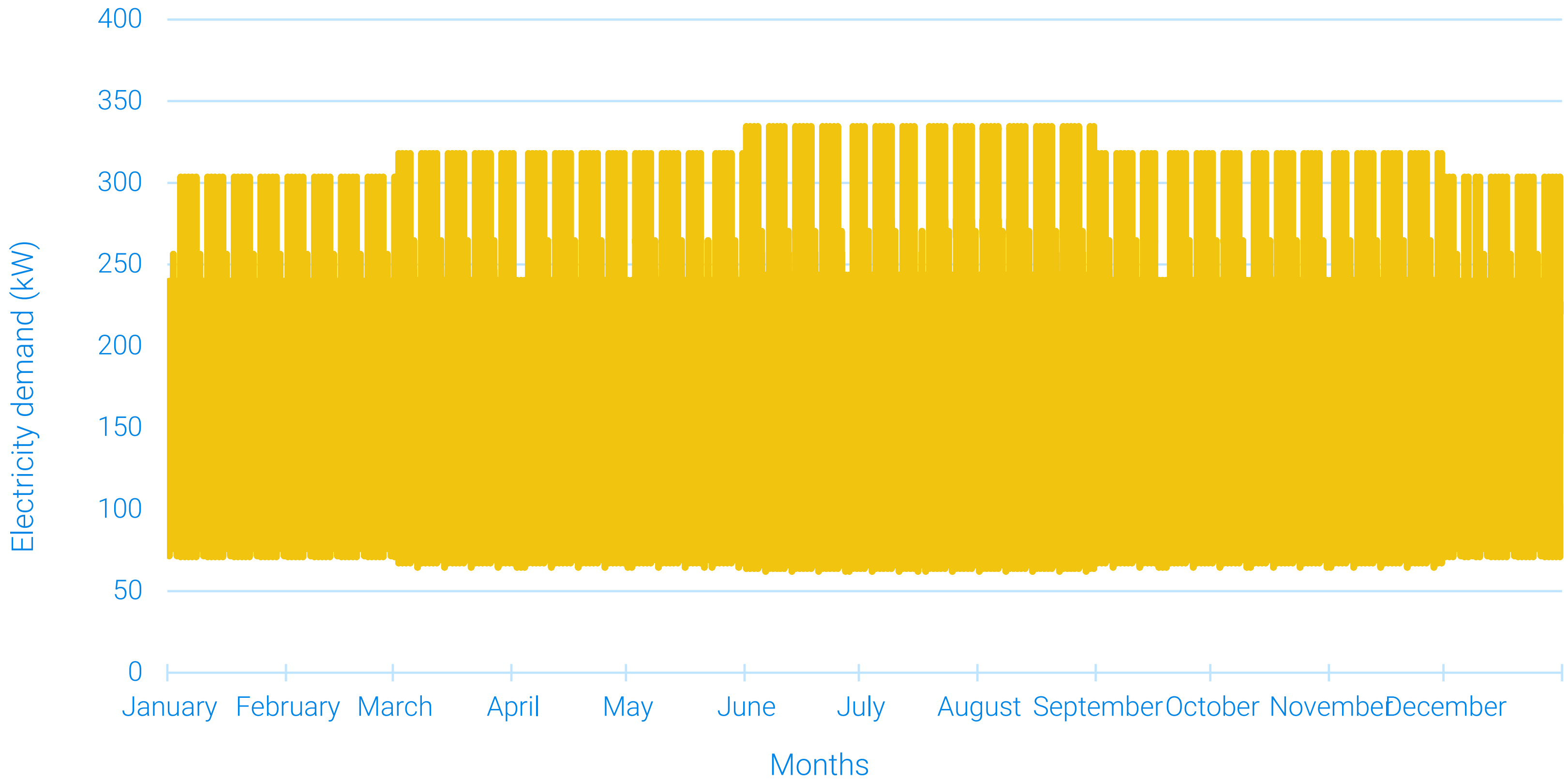
Weekday Saturday Sunday

Weekday Saturday Sunday

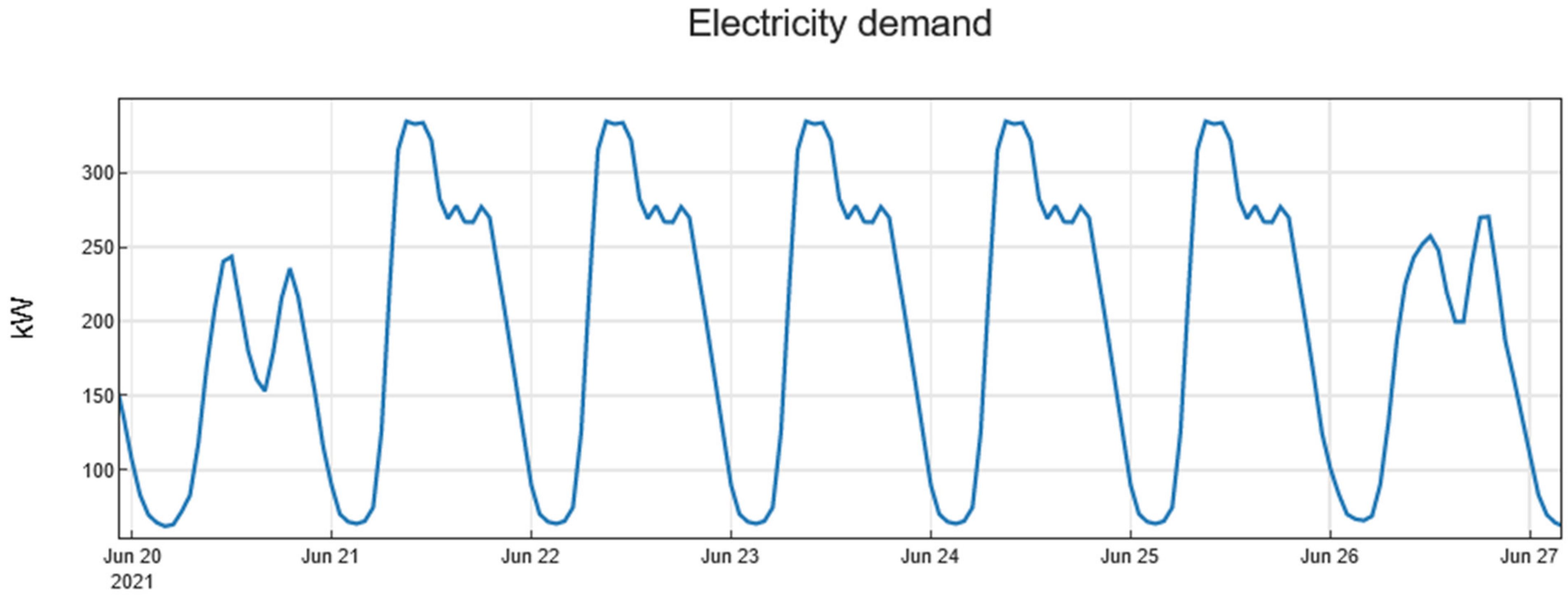
Images from:

(1) Fünfgeld, C., & Tiedermann, R. (2000). Anwendung der repräsentativen Lastprofile: Step by step.

Demandlib output (I) – Annual profile



Demandlib output (II) – Weekly profile



Demand assessment (II): *RAMP*

- Can be used for small customer pools (eg. single households, villages)
- Requires knowledge about
  - Used assets and their power
  - Utilization patterns (duration, time of use)
- Creates randomized demand profiles
- Requires lots of input data and computational time

→ Results in very good approximations for villages

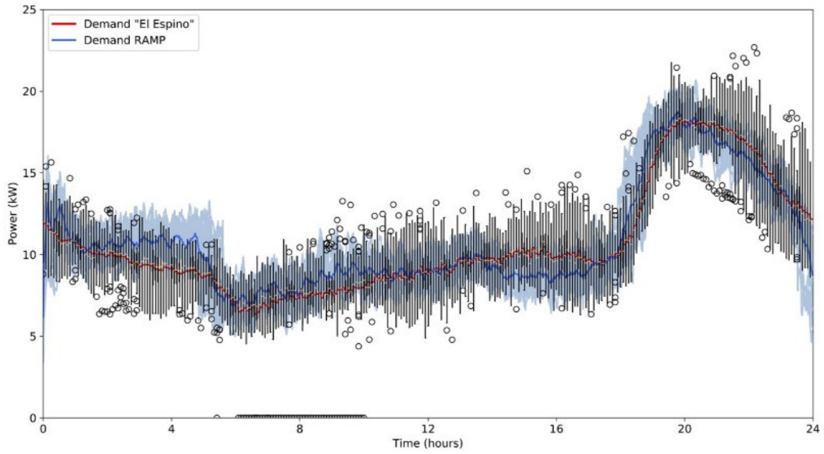


Image adapted from: https://github.com/RAMP-project/RAMP

Further reading:

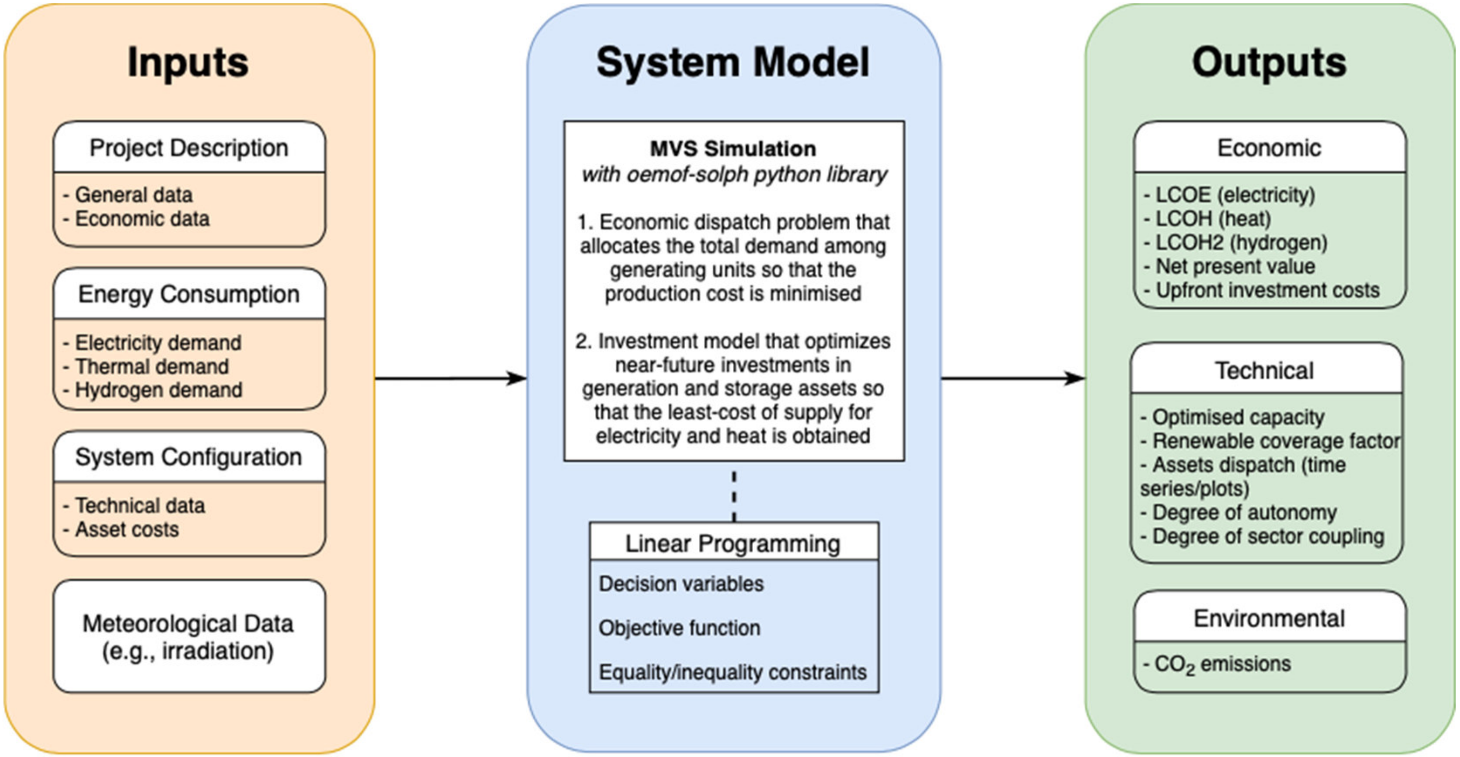
(1) RAMP GitHub repository: https://github.com/RAMP-project/RAMP
(2) F. Lombardi, S. Balderrama, S. Quoilin, E. Colombo, Generating high-resolution multi-energy load profiles for remote areas with an open-source stochastic model, Energy, 2019, https://doi.org/10.1016/j.energy.2019.04.097.

Excercise: Demand estimation

1. What are the main electric devices that you use?
2. What is the wattage of these devices?
3. Think of an examplary day. At which hours do you use each of the assets?
4. Create your personalized demand curve.
5. Create a demand curve for 15 minute intervals.

What is your personal demand curve?

Generalizable Model Steps



- Github reprository of the MVS: https://github.com/rl-institut/multi-vector-simulator
- Manual of the MVS: https://multi-vector-simulator.readthedocs.io

Potential technological constraints

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

Minimal renewable share

Minimal degree of autonomy

Maximum Backup power

Maximum Emissions

Excercise: Mathematical expessions

- Demand is always covered by generation
- Minimum renewable share
- Maximum emissions
- Maximum backup power
- Minimal degree of autonomy
- Maximum installation potential (eg. Space restrictions)
- Net.zero energy constraint

Note down how you can express the conditions mathematically.

ESM Solvers

A set of equations fully describes the energy system model as a whole

Linear Problem (LP) / Mixed Integer (Linear) Problem (MI(L)P) consists of :

- Target function
- Set of constraints and balances
- Equation system that describes whole ESM

Solver searches on the edges of the solutions space for the optimal solution

Identifies „optimal solution“

- At that point where the objective value does only marginally decrease
- At a threshold close to the theoretical mimimum of the objective value

Available solvers: CBC, GLPK, Gurobi, …

Perfect foresight

- Problem of solvers ability to forsee future:
  - Demand peaks
  - Renewable generation dips
  - Blackouts

  → pre-emptive battery charging behaviour or capacity sizing

  → Focal difference to real-world deployment!

  → Forecasting is important for Energy Management Systems (EMS).
  Here lies a potential application of machine learning algorithms, ie. KI

Learnig Outcomes of this Session

- Energy System Modelling Applications
- Open Source Software
- Examplary Energy System Models
- Accessing renewable resource data
- Generating demand profiles
- Translating constraints into mathematical expressions

Thank you for your participation ☺

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