



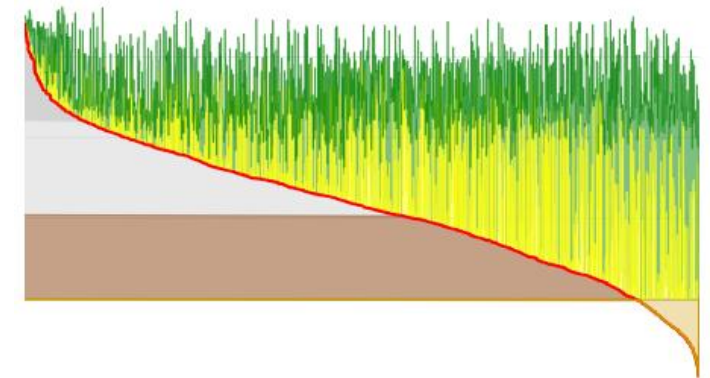
House of  
**Energy Markets  
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## EaSimPower – a novel web-based tool for teaching the interplay between technologies and markets in future electricity systems

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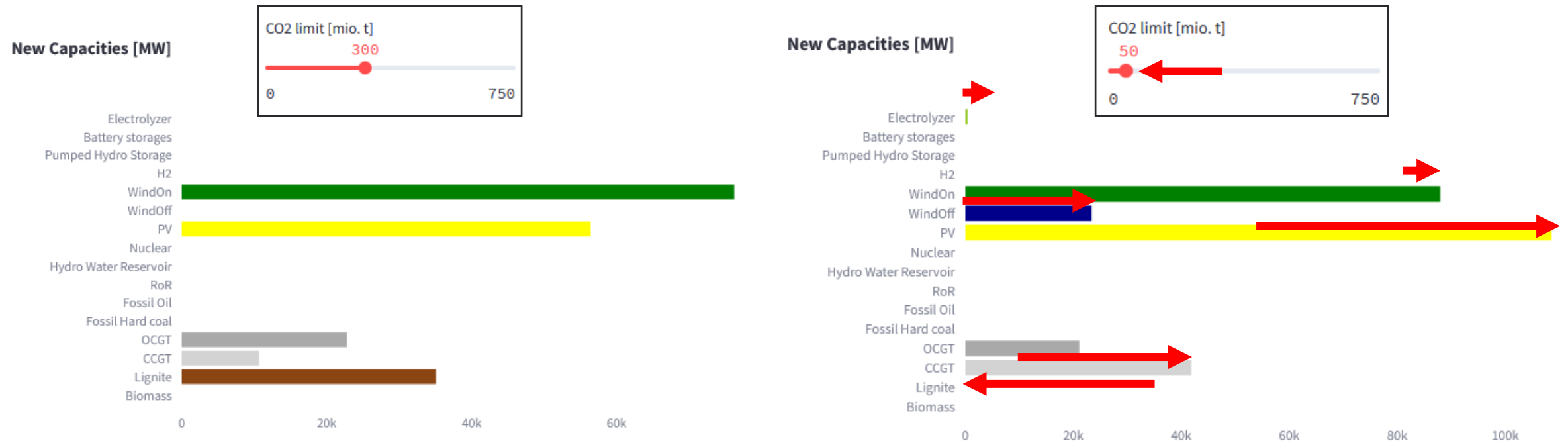
**Introduction** – Interactivity & multi-dimensionality in energy education – Model setup and implementation – Application studies – Outlook

- Future electricity markets will rely on a complex interplay between generation and storage technologies, demand side flexibilities, and dynamic price signals
  - Necessitates deeper understanding of how techno-economic characteristics of technologies interact in optimized power systems: Comprehensive education in this field is essential!
  - ***Bridging the gap between properties of theoretical models and their practical application.***
- Multiple existing tools for energy system analysis (e.g. TIMES, Calliope, PyPSA, EHDO), each with strengths, but limited suitability for educational use
- ***EaSimPower:***
  - Access to complex interdependencies by highlighting key features of primal and dual solutions in linear optimization
  - Web based platform that enables input adjustments and interactive analyses
  - Provides immediate visual feedback

- Multi-dimensionality of the concepts is challenging
  - **Merit Order**: PP with lowest marginal costs are dispatched first
    - Relates to short-term market operations
    - Influences long-term investment decisions
  - **Peak load pricing**: balancing supply & demand during periods of high consumption
    - Understand operational and investment strategies
  - **Long-term market equilibrium**: simultaneously consider
    - Technical aspects
    - Economic principles: cost recovery, market pricing mechanisms
    - Policy instruments
    - Fuel cost variations
    - Capacity expansion constraints



- Traditional methods (static models, simplified case studies) may be weak to capture these interactions
- **EaSimPower** enables active exploration and manipulation of system parameters
  - Observing the **immediate effect of adjustments** (generation mix, costs, investments,...)
  - Highlighting underlying mathematics of cost minimization and constraint satisfaction



- **EaSimPower**: Python-based investment tool for a long-term equilibrium model for energy systems analysis
- Optimizes capacity investments and operational dispatch under user-defined parameters
- Providing insights into the interplay between technologies and markets in electricity systems

## Data Inputs

CO2 limit  
Fuel costs (gas, H2, coal, lignite, oil)  
Timestep length  
Demand timeseries  
RES input profiles (DE 2023)  
Emission factors  
Efficiencies  
Investment costs  
Typical lifespans  
Energy to power ratio

Adjustable via GUI

Adjustable via Input File

## Technologies

Battery storages  
Electrolyzer  
(Biomass)  
(RoR)  
(Hydro water reservoir)  
(Nuclear)  
Lignite  
CCGT  
OCGT  
Fossil hard coal  
Fossil oil  
PV  
WindOff  
WindOn  
H2  
Pumped hydro storage

## Results/Outputs

Total costs  
CO2 price  
Electricity prices  
Contribution margins  
Capacities  
Production  
Residual load curve  
Storage operation  
Curtailment  
H2 production

# Model formulation: most important constraints

$$\text{minimize! } C^{tot} = C^{op} + C^{inv} \quad (1)$$

Objective function: minimizing total costs

$$C^{op} = \sum_i y_{t,i} \cdot (c_i^{fuel}/\eta_i + c_i^{other}) \cdot \Delta t - \sum_{i \in J^{PtG}} y_{t,i}^{h2} \cdot p^{h2} \cdot \Delta t \quad (2)$$

Operational costs minus revenue for produced hydrogen

$$C^{inv} = \sum_i a_i \cdot K_i \cdot c_i^{inv} \quad (3)$$

Annualized investment costs

$$\text{s.t. } \left( \sum_i y_{t,i} - \sum_{i \in J^{Sto}} y_{t,i}^{ch} \right) \cdot \Delta t = D_t \cdot \Delta t, \quad \forall t \quad (4)$$

Load serving constraint

$$y_{t,i} - K_i \leq K_{0,i}, \quad \forall i \in J \quad (5)$$

Maximum capacity constraint

$$y_{t,i} + y_{t,i}^{ch} - K_i \leq K_{0,i}, \quad \forall i \in J^{Sto} \quad (6)$$

Maximum storage charging

$$y_{t,i}^{ch} - K_i \leq K_{0,i}, \quad \forall i \in J^{PtG} \quad (7)$$

Maximum electrolyzer capacity

$$y_{t,i}^{ch} \cdot \eta_i = y_{t,i}^{h2}, \quad \forall i \in J^{PtG} \quad (8)$$

PtG hydrogen production

$$y_{t,i} + y_{t,i}^{curr} = s_{t,r,i} \cdot (K_{0,i} + K_i), \quad \forall i \in J^{Res} \quad (9)$$

Renewable infeed constraint

$$l_{t,i} \leq (K_{0,i} + K_i) \cdot \gamma_i^{Sto}, \quad \forall i \in J^{Sto} \quad (10)$$

Maximum filling level restriction for storage power plants

$$l_{t+1,i} = l_{t,i} - (y_{t,i}/\eta_i - y_{t,i}^{ch} \eta_i) \cdot \Delta t, \quad \forall i \in J^{Sto} \quad (11)$$

Filling level restriction for other storages

$$l_{t+1,i} = l_{t,i} + (h_{t,i} - y_{t,i}) \cdot \Delta t, \quad \forall i \in J^{HyRes} \quad (12)$$

Filling level restriction for hydro reservoir

$$\sum_t \sum_i y_{t,i}/\eta_i \cdot \chi_i^{CO2} \cdot \Delta t \leq L^{CO2} \quad (13)$$

CO2 emission constraint

Formulated in *python*  
Using *linopy* (modeling)  
and *HiGHS* (solver)

- Implemented as browser-based tool & client server architecture
  - Seamless user experience & low entry barrier
- *Streamlit* GUI: users select their desired input parameters
- Interface is structured in 3 main tabs
  - **Model**: with its inputs and outputs
  - **Documentation**: of all sets, variables, parameters, obj. function, constraints
  - **About**: the research group & background information
- Can be tailored to different educational levels
  - Undergraduate version: Simplified, focuses on market equilibria and dispatch
  - Graduate version: Advanced, includes storage and sector coupling
- Outputs are provided in visually engaging formats
  - Bar charts, pie charts, time-series for e.g. generation and prices, duration curves
  - Can be downloaded as Excel-files

# Presenting the Model-Page

Introduction – Interactivity & multi-dimensionality in energy education – **Model setup and implementation (IV/V)** – Application studies – Outlook

Spaces EWL EWLStreamLit like 0 Running Logs

App Files Community Settings

Model Documentation About

## Settings from file

Download Excel Template

Upload own Excel File

Drag and drop file here  
Limit 200MB per file

Browse files

Run model with uploaded Excel values

## Manual settings from GUI

CO2 limit [mio. t] 200

Fossil Gas Price [EUR/MWh] 40

H2 Price [EUR/MWh] 100

Fossil Hard Coal Price [EUR/MWh] 37

Fossil Lignite Price [EUR/MWh] 8

Fossil Oil Price [EUR/MWh] 60

Technologies for investment

- Lignite ×
- CCGT ×
- OCGT ×
- Fossil Hard coal ×
- Fossil Oil ×
- PV ×
- WindOff ×
- WindOn ×
- H2 ×
- Pumped Hydro S... ×
- Battery storages ×
- Electrolyzer ×

Timestep length [h] 6

Run model with manual values from the GUI

# Presenting the Documentation-Page

Introduction – Interactivity & multi-dimensionality in energy education – **Model setup and implementation (V/V)** – Application studies – Outlook

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Model **Documentation** About

## Mathematical model formulation

This page provides details on the mathematical formulation & constraints of the energy system optimization model.

## Objective function and constraints

### Objective function

Minimization of total costs

$$\min C^{tot} = C^{op} + C^{inv}$$

Operational costs minus revenue for produced hydrogen:

$$C^{op} = \sum_i y_{t,i} \cdot \left( \frac{c_i^{fuel}}{\eta_i} + c_i^{other} \right) \cdot \Delta t - \sum_{i \in \mathcal{I}^{Res}} y_{t,i}^{h2} \cdot p^{h2} \cdot \Delta t$$

Investment costs constraint:

$$C^{inv} = \sum_i a_i \cdot K_i \cdot c_i^{inv}$$

### Constraints

Load-serving constraint:

$$\left( \sum_i y_{t,i} - \sum_i y_{t,i}^{ch} \right) \cdot \Delta t = D_t \cdot \Delta t, \quad \forall t \in \mathcal{T}$$

Maximum capacity constraint:

$$y_{t,i} - K_i \leq K_{0,i}, \quad \forall i \in \mathcal{I}$$

Capacity limits for investment:

### Symbols

We use capital and lowercase letters for variables and parameters. Superscripts are used for further description. Subscripts represent sets.

### Sets

- $\mathcal{T}$ : Set of time steps
- $\mathcal{I}$ : Set of technologies
- $\mathcal{I}^{Sto}$ : Set of storage technologies
- $\mathcal{I}^{Conv}$ : Set of conversion technologies
- $\mathcal{I}^{PtG}$ : Set of power-to-gas technologies
- $\mathcal{I}^{Res}$ : Set of renewable energy sources
- $\mathcal{I}^{HyRes}$ : Set of hydro reservoir technologies
- $\mathcal{I}^{no\_invest}$ : Set of technologies without investment

### Variables

- $C^{tot}$ : Total costs (objective function)
- $C^{op}$ : Operational costs
- $C^{inv}$ : Investment costs
- $K_i$ : Installed capacity of technology  $i$
- $y_{t,i}$ : Electricity production of technology  $i$  at time  $t$
- $y_{t,i}^{ch}$ : Electricity consumption for charging storage of technology  $i$  at time  $t$

EN

A tool designated for better understanding of mathematical optimization in the context of energy economics. Be eager!

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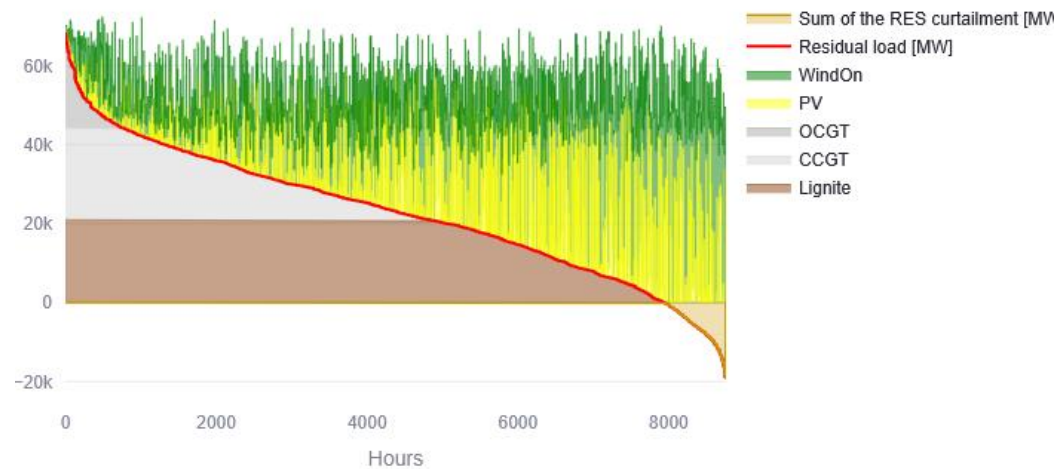
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# Application study I: Effects of reduced emission budget

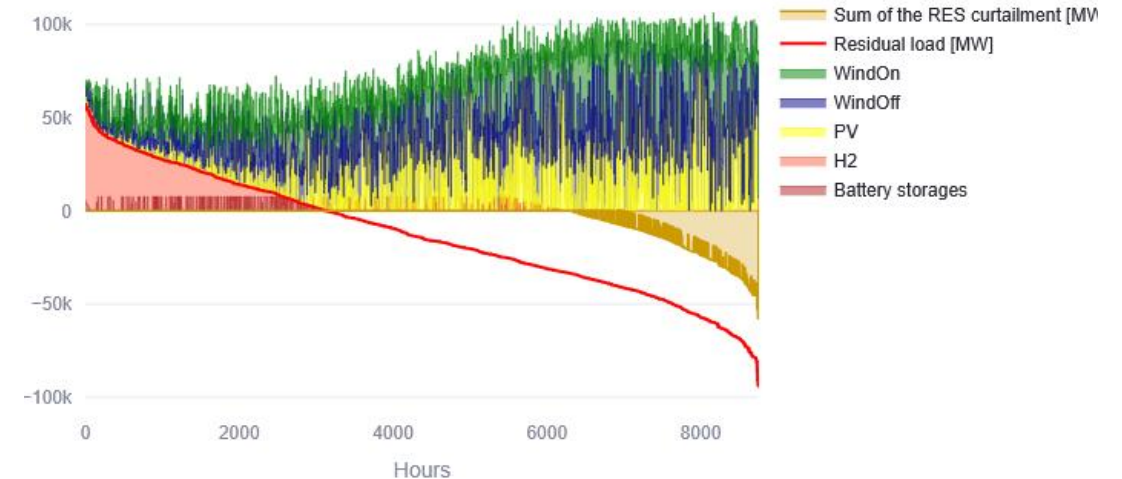
Introduction – Interactivity & multi-dimensionality in energy education – Model setup and implementation – **Application studies (I/IV)** – Outlook

- “Standard setting”: CO<sub>2</sub> limit of 200 mio t
  - 90 GW of installed wind and PV capacity
  - 30 % of total generation from lignite, 15 % gas
- Total costs: € 30.19 bn.
- “Zero-emission scenario”
  - Fossil technologies are excluded
  - Strong investment in RES
  - Deployment of H<sub>2</sub> power plants, storage capacities & electrolyzers
- Total costs: € 50.86 bn.

Residual load duration curve and stacked production [MW]



Residual load duration curve and stacked production [MW]

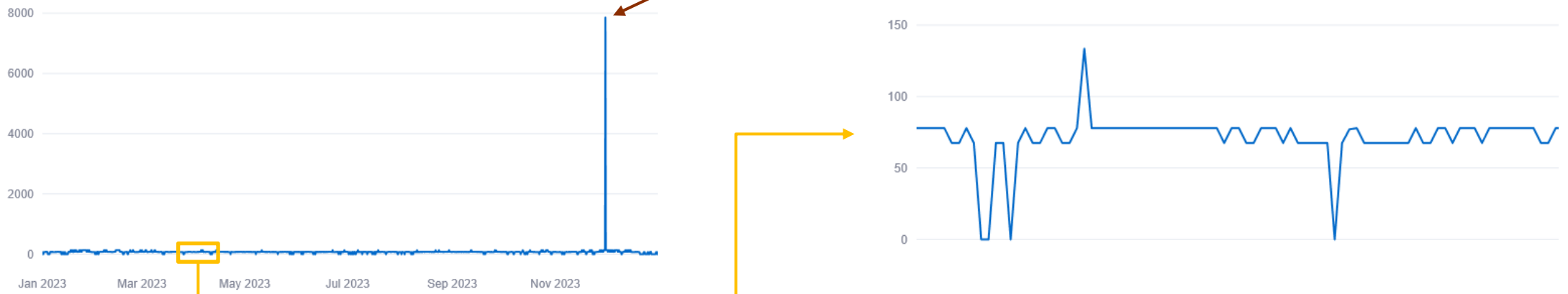


# Application study II: Price peaks in long-term deterministic models

Introduction – Interactivity & multi-dimensionality in energy education – Model setup and implementation – **Application studies (II/IV)** – Outlook

- Prices in equilibrium are derived based on long-term marginal costs (variable & annualized investment)
- Marginal costs > variable costs: only in periods when capacity is scarce & additional generation is needed
- In deterministic model: 1 period of maximal residual demand where marginal costs are extremely high
  - marginal generation unit must be installed to meet the demand in just this one period – price includes all annualized investments

Electricity prices [EUR/MWh]



# Application study II: price for peak load technology

Introduction – Interactivity & multi-dimensionality in energy education – Model setup and implementation – **Application studies (III/IV)** – Outlook

- Using EaSimPower In- and Outputs, learners can exemplify that every power plant (type) recovers its full costs in equilibrium\*

\*small deviations by rounding

- OCGT is peak technology. Has to recover full costs of

Investment costs p.u.	Lifetime	Annuity factor	Annual investment costs p.u.	Capacity	Annual investment costs
575 EUR/kW	30 years	0.08059	46,337 EUR/MW/a	21,108 MW	<b>978,085,238 EUR</b>
Given in Input file	Given in input file	$a_i = \frac{r \cdot (1+r)^{\text{lifetime}_i}}{(1+r)^{\text{lifetime}_i} - 1}$ $r=0.07$	$AF * 1000 * \text{InvCost\_pu}$	Given in output file	$Cap \cdot an\_InvCost$

- Price peak: This power plant recovers its full costs in one modeling timestep

Production	Price	Variable costs	Diff	Revenue	$\Delta t * \text{revenue}$
21,108 MWh	7,908 EUR/MWh	185.33 EUR/MWh	7,722 EUR/MWh	163,016,691 EUR	<b>978,100,47 EUR</b>
See next slide: merge production and prices and sort (desc)		Fuel costs: 45 EUR/MWh Efficiency: 0.45 Emission factor: 0.275 CO2 price: 94.66	$price - varCosts$	$production \cdot diff$	Since we are modeling in a 6 hour resolution

- **EaSimPower is designed to strike the balance between simple didactic examples and a fully realistic model!**
  - **Bridges the gap between theory and practical applications in energy systems**
  - **Web-based, intuitive tool for hands-on learning**
  - **Provides real-time feedback and lowers technical barriers**
  
- Possible extensions
  - Higher spatial resolution → multiple regions
  - Incorporate power flow (grid constraints)
  - Differentiate technology classes
    - By cost, efficiency,...
  - Stochastic scenarios for multiple years
  
- Limitations
  - Assumes perfect foresight (no uncertainty)
  - Assumes perfect coordination
  - Limited representation of technology heterogeneity
  - Ignores heterogeneity of investor behavior
  - Greenfield instead of brownfield approach
  - Simplified market and policy interactions

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# Thank you for your attention!

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