The Mathematics of Energy Economics and Carbon Neutrality

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Background

- **PhD in Power Systems (2013)**
  Comillas Pontifical University, Spain
- **MSc in Computation for Design and Optimization (2008)**
  Massachusetts Institute of Technology, USA
- **Dipl.-Ing. Technical Mathematics (2008)**
  Graz University of Technology, Austria

Areas of Research I

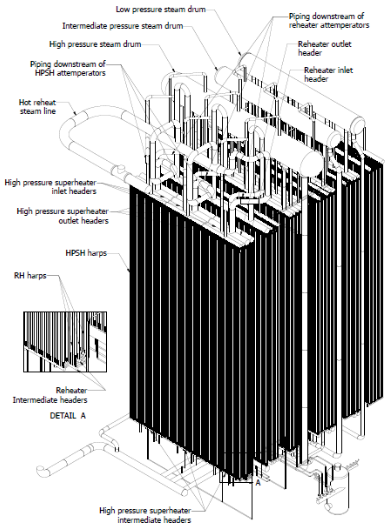
Energy System Modeling:

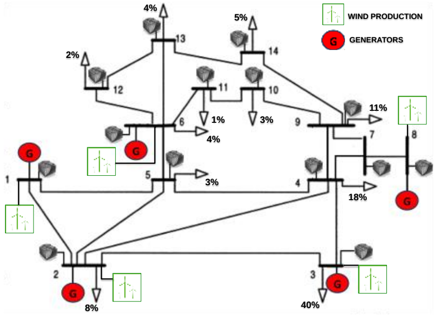
Transmission/Generation Expansion

Unit Commitment

Optimal Power Flow

Bilevel Programming





$$\forall i \begin{cases} \max_{x_i,q_i} & t(p(q_i,q_{-i})-\delta)q_i-\beta x_i \\ s.t. & \text{Second stage} \end{cases}$$

$$\forall i \begin{cases} \max_{x_i,q_i} & t(p(q_i,q_{-i})-\delta)q_i \\ s.t. & 0 \le q_i \le x_i \end{cases}$$

$$d = q_i + q_{-i},\ d = D_0 - \alpha p$$

Areas of Research II

Techno-Economic Analyses:
Energy Transition
Profitability in Electricity Markets

everis
an NTT DATA Company

klima energie fonds + Bundesministerium Klimaschutz, Umwelt, Energie, Mobilität, Innovation und Technologie

EOR

Fundación IBERDROLA

Data Science & Artificial Intelligence:
Fault detection in heat pumps
Prediction of cycle life

COMILLAS UNIVERSIDAD PONTIFICIA
ICAI ICADE CIHS

Energy Storage:
Allocation & Investment

European Commission

INNOMERICS

UAI UNIVERSIDAD ADOLFO IBÁÑEZ

NTNU Norwegian University of Science and Technology

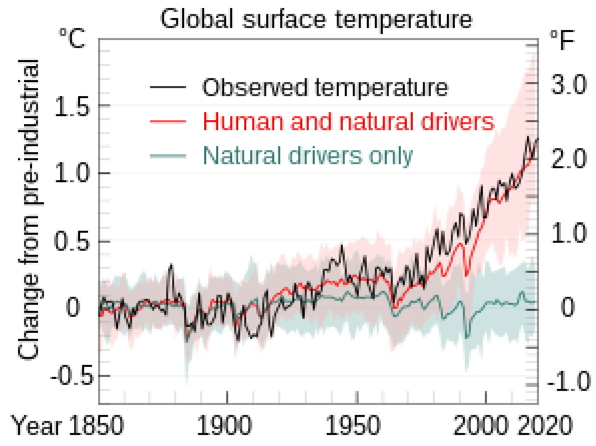
Agenda

- Motivation. Why do we care about energy system planning?
- Mathematical modeling and optimization as decision support tools
- Strategic generation expansion planning in liberalized electricity markets
- Conclusions

Source: https://www.instagram.com/p/CGtFYBOBl8l/

Why do we care about energy system planning?

There is this thing called **climate change**.



Source: https://en.wikipedia.org/wiki/Climate_change#/media/File:Global_Temperature_And_Forces_With_Fahrenheit.svg

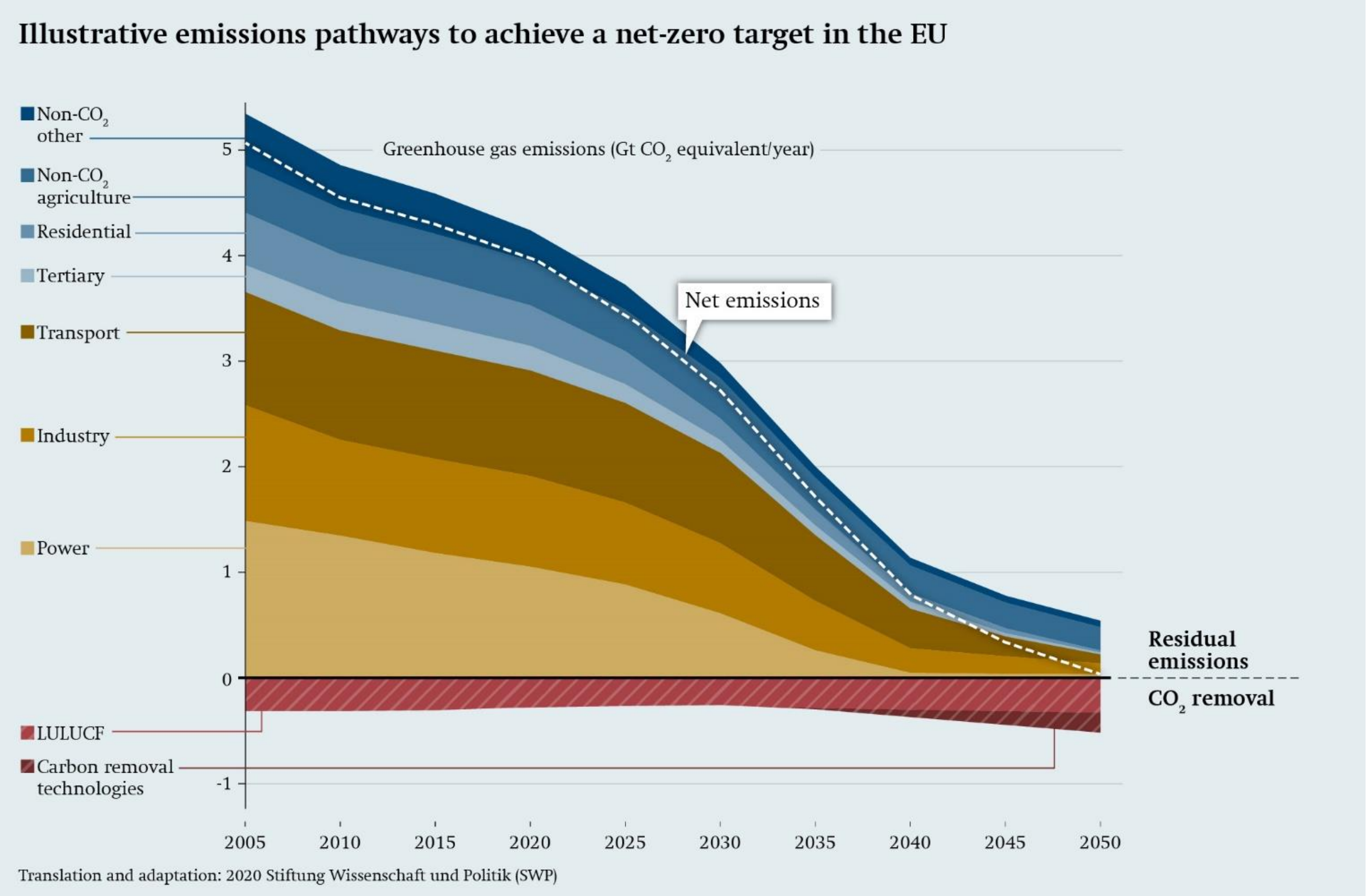
Source: https://www.dw.com/en/greece-wildfiresthousands-flee-island-of-evia-as-blazes-continue-to-ravage-lands/a-58794368

Source:https://www.premiumtimesng.com/news/top-news/473966-over-80-dead-dozens-missing-as-floods-hit-germany.html

Source: https://www.greenpeace.org/usa/warsaw-climate-talks-so-bad-us-looked-good/melting-ice-polar-bear-on-206311-jpg/

Decarbonization in Europe

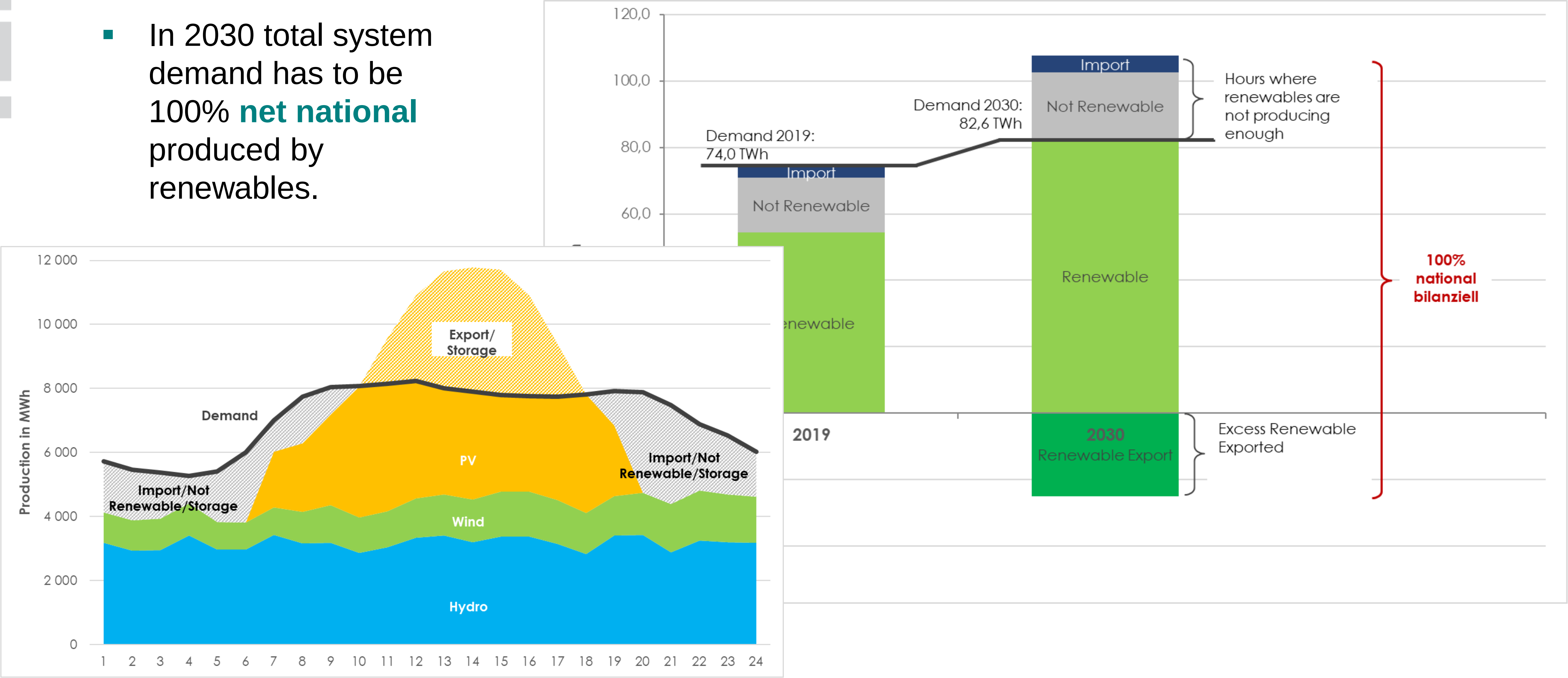
- How do we define **climate neutrality** in Europe.
- We want to achieve it **until 2050** (European Commission).
- Over sectors: Electricity, Industry, Transport, etc.



Source: https://www.swp-berlin.org/en/publication/eu-climate-policy-unconventional-mitigation

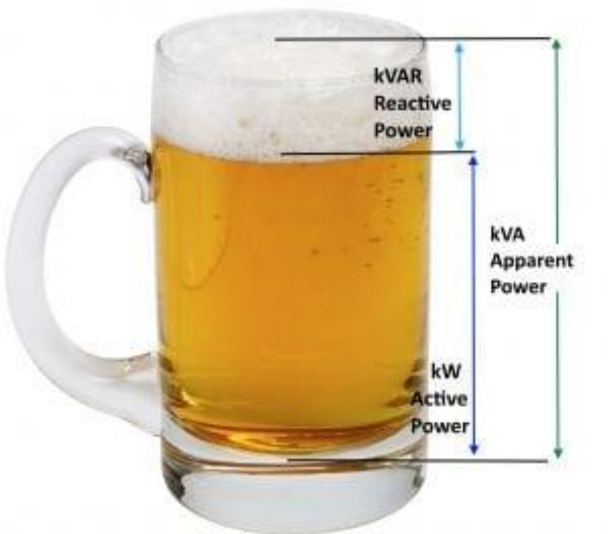
Climate neutrality in Austria: Renewable Expansion Law

- In 2030 total system demand has to be 100% **net national** produced by renewables.

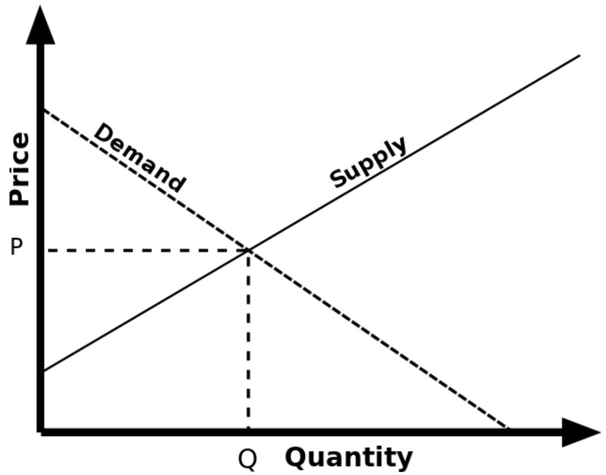


Challenges of decarbonization

Source: https://wolfhill.blog/2014/02/24/bitter-cold-anti-wynnewind-turbine-protest-at-queens-park/



Source: https://blog.se.com/energy-management-energy-efficiency/2018/01/22/can-learn-power-pint-beer/



Source: https://commons.wikimedia.org/wiki/File:Simple_supply_and_demand.svg

- **Social** (e.g. not in my backyard)
- **Technical** (e.g. reactive power, system inertia)
- **Economic** (e.g. profitability)

Modeling and optimization can serve as **decision support tool**.

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Modeling and optimization as decision support tools

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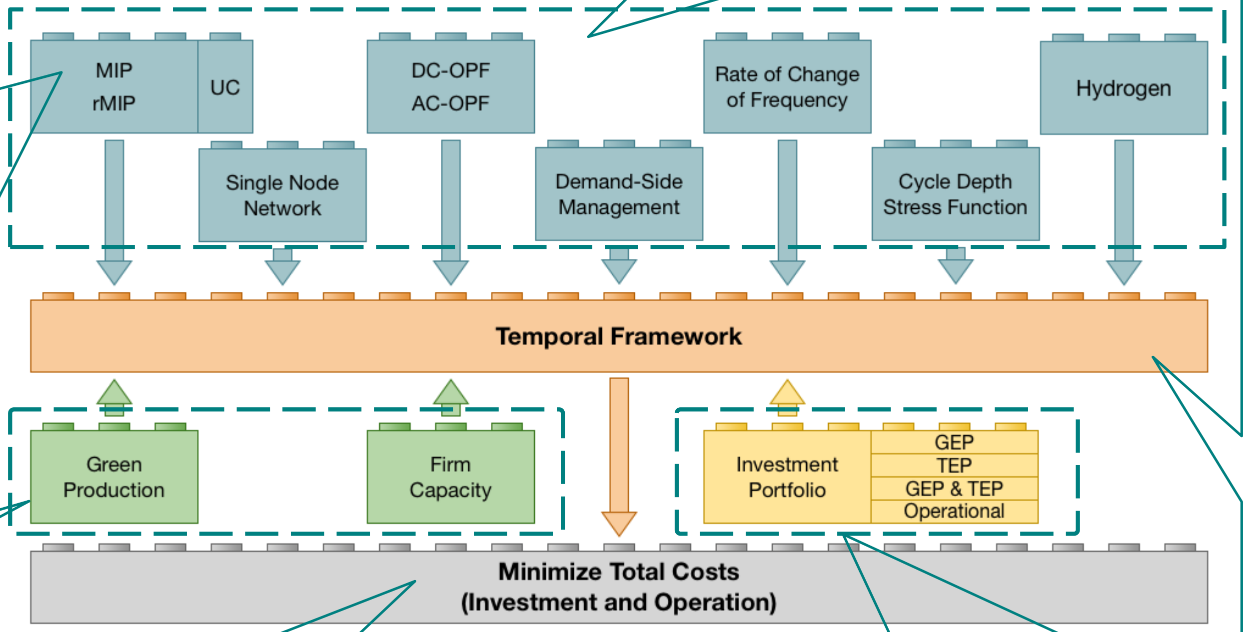
Open-source tool for Low-carbon Expansion and Generation Optimization (LEGO)

Source: Wogrin, S., Tejada-Arango, D., Delikaraoglou, S. and Botterud, A., 2020. Assessing the impact of inertia and reactive power constraints in generation expansion planning. Applied Energy, 280, p.115925.

GitHub https://github.com/wogrin/LEGO

Model options: yes/no?



Mixed-integer quadratically constrained program (MIQCP)
- deterministic
- single-year
- modular & flexible
- GAMS & Excel

Relaxed MIP (rMIP)
- relax UC
- economic results (prices & profits)

Policy constraints
- technical
- environmental
- political

Objective function

Generation units *g*:
- thermal *t* (CCGT, OCGT, …)
- renewable *r* (wind, solar)
- storage *s* (hydro, batteries)

Highly flexible temporal structure
- hours ***p***
- representative periods ***rp***
- hours within rp ***k***

mapping

```
hindex(p,rp,k)
relation among p, rp and k
/
h0001.rp07 .k0001
h0002.rp07 .k0002
h0003.rp07 .k0003
…     .…   .…
```

weights

```
pWeight_rp(rp)
representatives periods weight [h]
/
rp01    20
rp02   135
rp03    46
```

```
pWeight_k(k)
hourly weight for each rp [h]
/
k0001   1
k0002   1
k0003   1
```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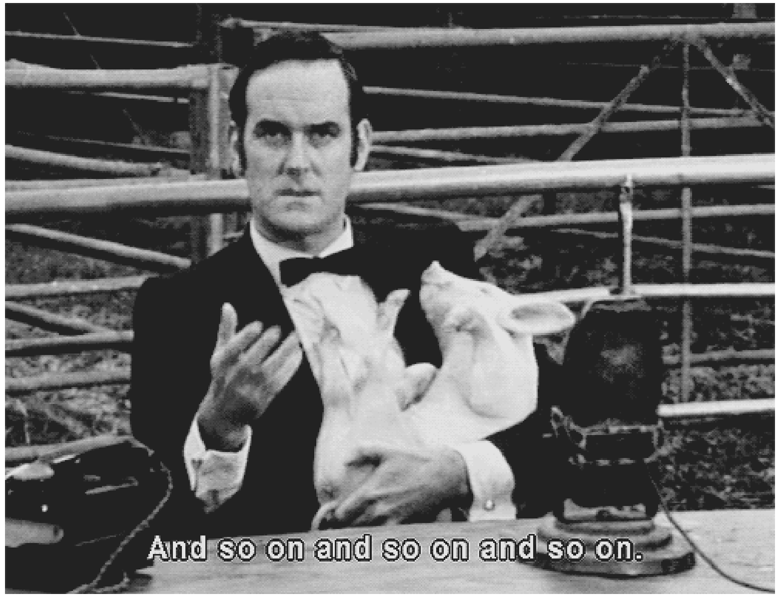
Mathematical Formulation …

Objective function

$$
\begin{aligned}
min \sum_{rp,k} W^{RP}_{rp} W^K_k \Big(& \sum_t (C^{SU}_t y_{rp,k,t} + C^{UP}_t u_{rp,k,t} + C^{VAR}_t p_{rp,k,t}) \\
& + \sum_r C^{OM}_r p_{rp,k,r} + \sum_s C^{OM}_s p_{rp,k,s} + \sum_i C^{ENS} pns_{rp,k,i} \Big) \\
+ \sum_{rp,k} W^{RP}_{rp} W^K_k \Big(& \sum_t (C^{VAR}_t C^{RES+} res^{+}_{rp,k,t} + C^{VAR}_t C^{RES-} res^{-}_{rp,k,t}) \\
& + \sum_s (C^{OM}_s C^{RES+} res^{+}_{rp,k,s} + C^{OM}_s C^{RES-} res^{-}_{rp,k,s}) \Big) \\
& + \sum_g C^{INV}_g x_g
\end{aligned}
$$



Power flow

Hydrogen production

$$0 \leq p^{H2}_{rp,k,h2g} \leq \overline{P}^E_{h2g} W^K_k HPE_{h2g} (x^{H2}_{h2g} + EU^{H2}_{h2g}) \quad \forall rp,k,h2g$$

$$cs^E_{rp,k,h2g} W^K_k HPE_{h2g} = p^{H2}_{rp,k,h2g} \quad \forall rp,k,h2g$$

$$\sum_{h2gh2i(h2g,h2i)} p^{H2}_{rp,k,h2g} + h2ns_{rp,k,h2i} = \sum_{h2sec} D^{H2}_{rp,k,h2i,h2sec} \quad \forall rp,k,h2i$$

$$0 \leq h2ns_{rp,k,h2i} \leq \sum_{h2sec} D^{H2}_{rp,k,h2i,h2sec} \quad \forall rp,k,hi$$

$$x^{H2}_{h2g} \in \mathbb{Z}^{+,0}, x^{H2}_{h2g} \leq \overline{X}^{H2}_{h2g} \quad \forall h2g$$

Unit commitment

$$\sum_t res^{+}_{rp,k,t} + \sum_s res^{+}_{rp,k,s} \geq RES^{+} \sum_i D^P_{rp,k,i} \quad \forall rp,k$$

$$\sum_t res^{-}_{rp,k,t} + \sum_s res^{-}_{rp,k,s} \geq RES^{-} \sum_i D^P_{rp,k,i} \quad \forall rp,k$$

$$p_{rp,k,t} = u_{rp,k,t} \underline{P}_t + \hat{p}_{rp,k,t} \quad \forall rp,k,t$$

$$\hat{p}_{rp,k,t} + res^{+}_{rp,k,t} \leq (\overline{P}_t - \underline{P}_t)(u_{rp,k,t} - y_{rp,k,t}) \quad \forall rp,k,t$$

$$\hat{p}_{rp,k,t} + res^{+}_{rp,k,t} \leq (\overline{P}_t - \underline{P}_t)(u_{rp,k,t} - z_{rp,k++1,t}) \quad \forall rp,k,t$$

$$\hat{p}_{rp,k,t} \geq res^{-}_{rp,k,t} \quad \forall rp,k,t$$

$$u_{rp,k,t} - u_{rp,k--1,t} = y_{rp,k,t} - z_{rp,k,t} \quad \forall rp,k,t$$

$$u_{rp,k,t} \leq x_t + EU_t \quad \forall rp,k,t$$

$$\hat{p}_{rp,k,t} - \hat{p}_{rp,k--1,t} + res^{+}_{rp,k,t} \leq u_{rp,k,t} RU_t \quad \forall rp,k,t$$

$$\hat{p}_{rp,k,t} - \hat{p}_{rp,k--1,t} - res^{-}_{rp,k,t} \geq -u_{rp,k--1,t} RD_t \quad \forall rp,k,t$$

$$0 \leq p_{rp,k,t} \leq \overline{P}_t (x_t + EU_t) \quad \forall rp,k,t$$

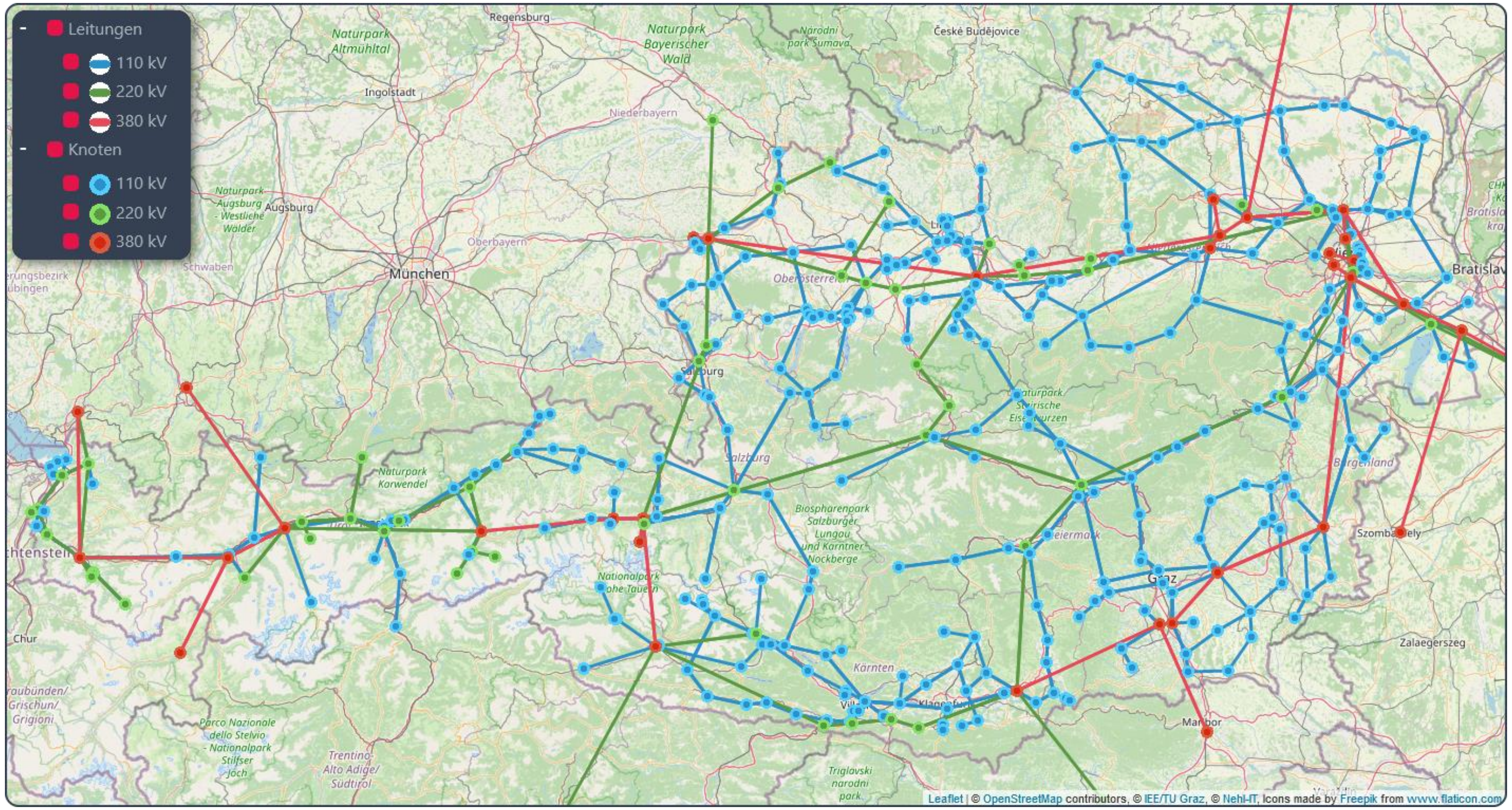
$$0 \leq \hat{p}_{rp,k,t}, res^{-}_{rp,k,t}, res^{+}_{rp,k,t} \leq (\overline{P}_t - \underline{P}_t)(x_t + EU_t) \quad \forall rp,k,t$$

$$u_{rp,k,t}, y_{rp,k,t}, z_{rp,k,t} \in \{0,1\} \quad \forall rp,k,t$$

Source: Wogrin, S., Tejada-Arango, D., Delikaraoglou, S. and Botterud, A., 2020. Assessing the impact of inertia and reactive power constraints in generation expansion planning. Applied Energy, 280, p.115925.

Case study: LEGO Austria

- Austria‘s electricity infrastructure:
  - 1,304 generators
  - 468 nodes
  - 1,097 power lines (110, 220, 380 kV)



- Model summary
  - 900,000 variables
  - 800,000 equations

InfraTrans 2040

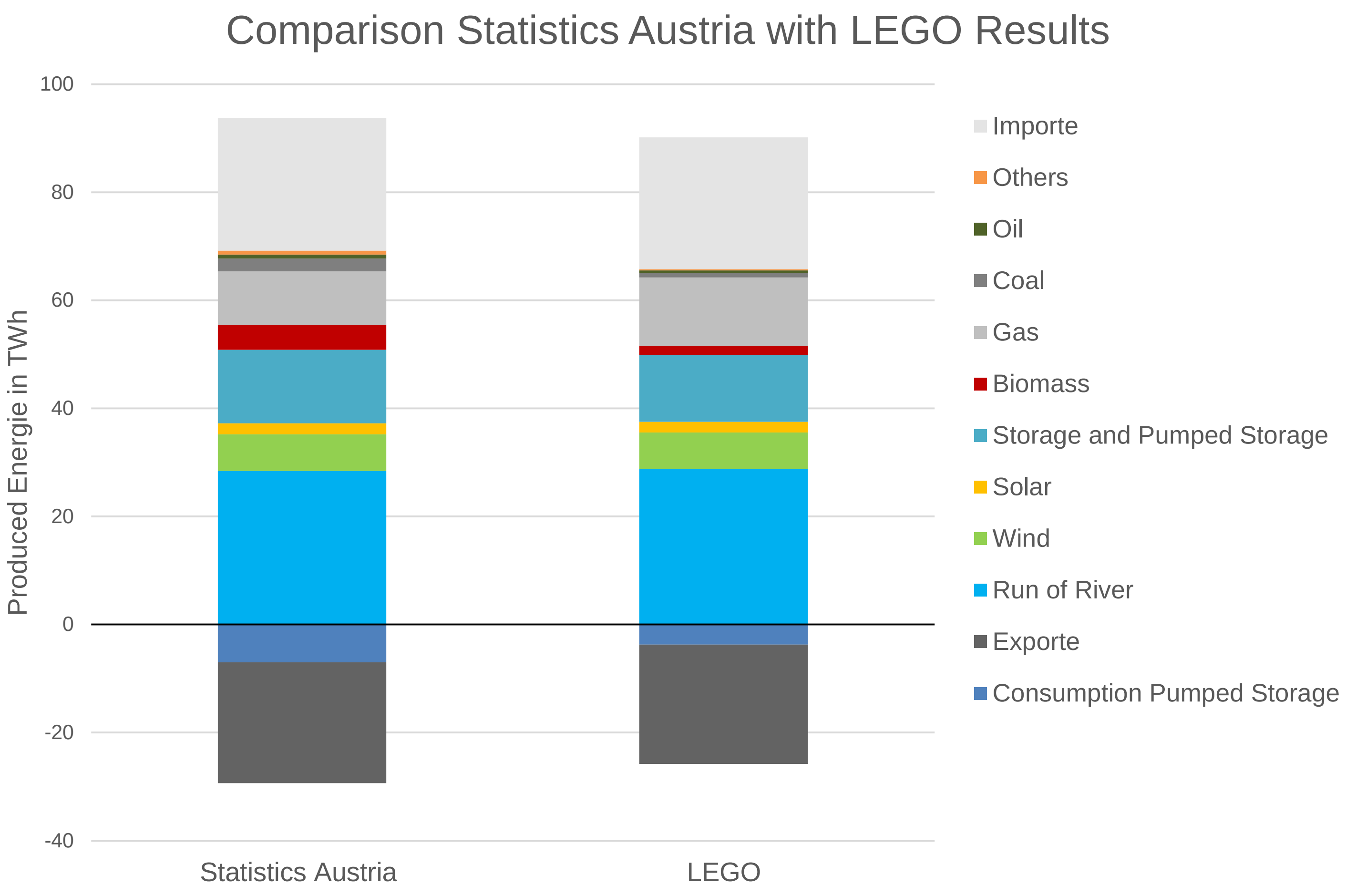
START2030

powered by klima+ energie fonds

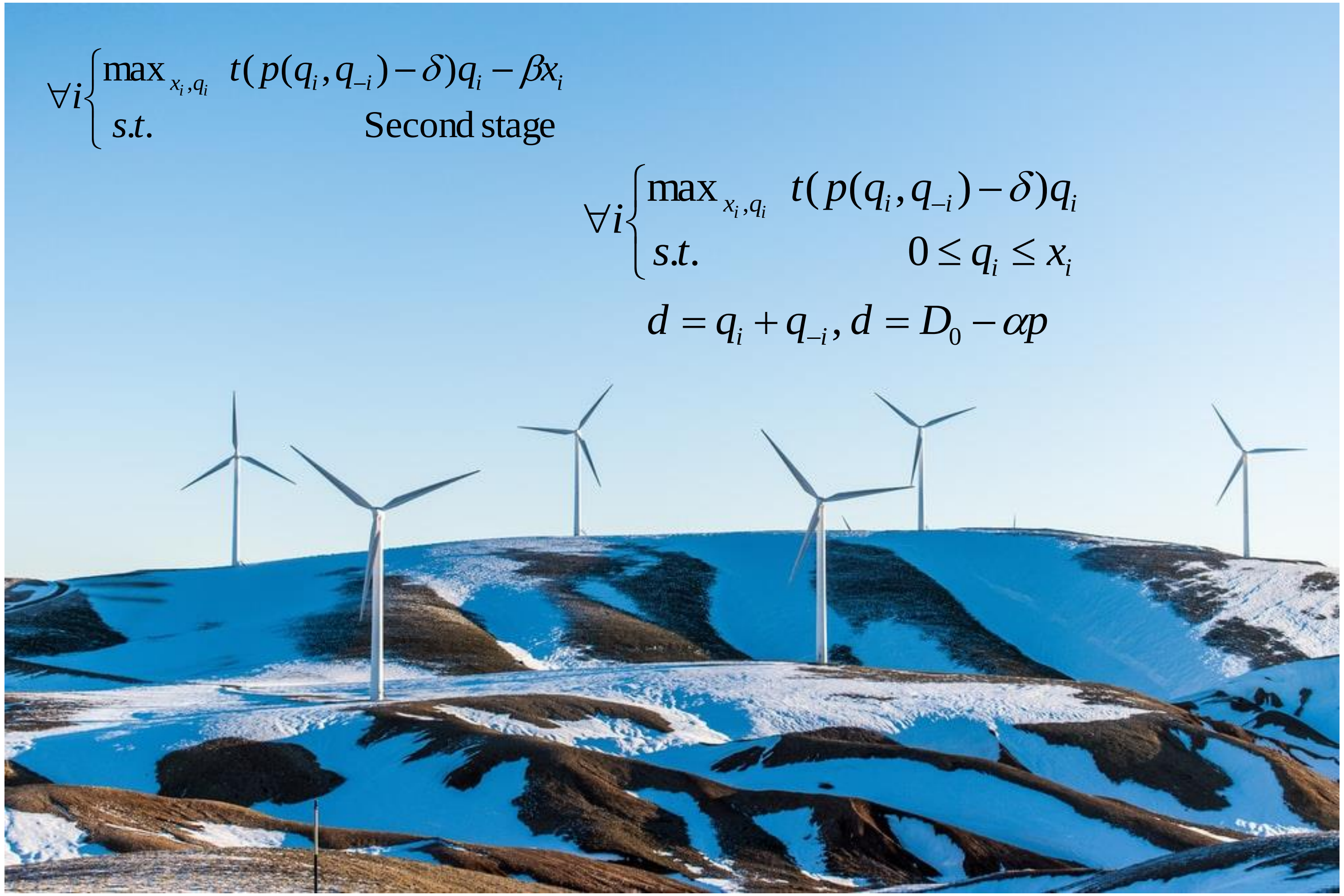
Case study: LEGO Austria

- Optimization to achieve goals of the **EAG by 2030** & **climate neutrality** by 2040.

- LEGO Austria has been validated by comparing produced electricity data for 2020 from Statistics Austria and LEGO Austria model results.



Strategic Generation Expansion Planning in Liberalized Electricity Markets



Source: https://unsplash.com/photos/kufsOr1-F-s

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Liberalization of electricity markets

The liberalization of electricity markets has complicated the organization of the electricity sector.

Centralized framework: social welfare maximization; versus **liberalized electricity markets**: private entities maximize profits.

Many decision-making problems in a liberalized power sector can be regarded as a game in search of equilibrium solutions.

Hierarchical decision making

The sequence in which decisions are taken, can convert simple equilibrium games into complicated hierarchical equilibrium problems.

An application of such hierarchical games in electricity markets: generation expansion planning. Results indicate that the game structure drastically influences outcomes.

Examples: Wogrin, Sonja, Salvador Pineda, and Diego A. Tejada-Arango. "Applications of bilevel optimization in energy and electricity markets." Bilevel Optimization. Springer, Cham, 2020. 139-168.
Gabriel, Steven A., et al. Complementarity modeling in energy markets. Vol. 180. Springer Science & Business Media, 2012.

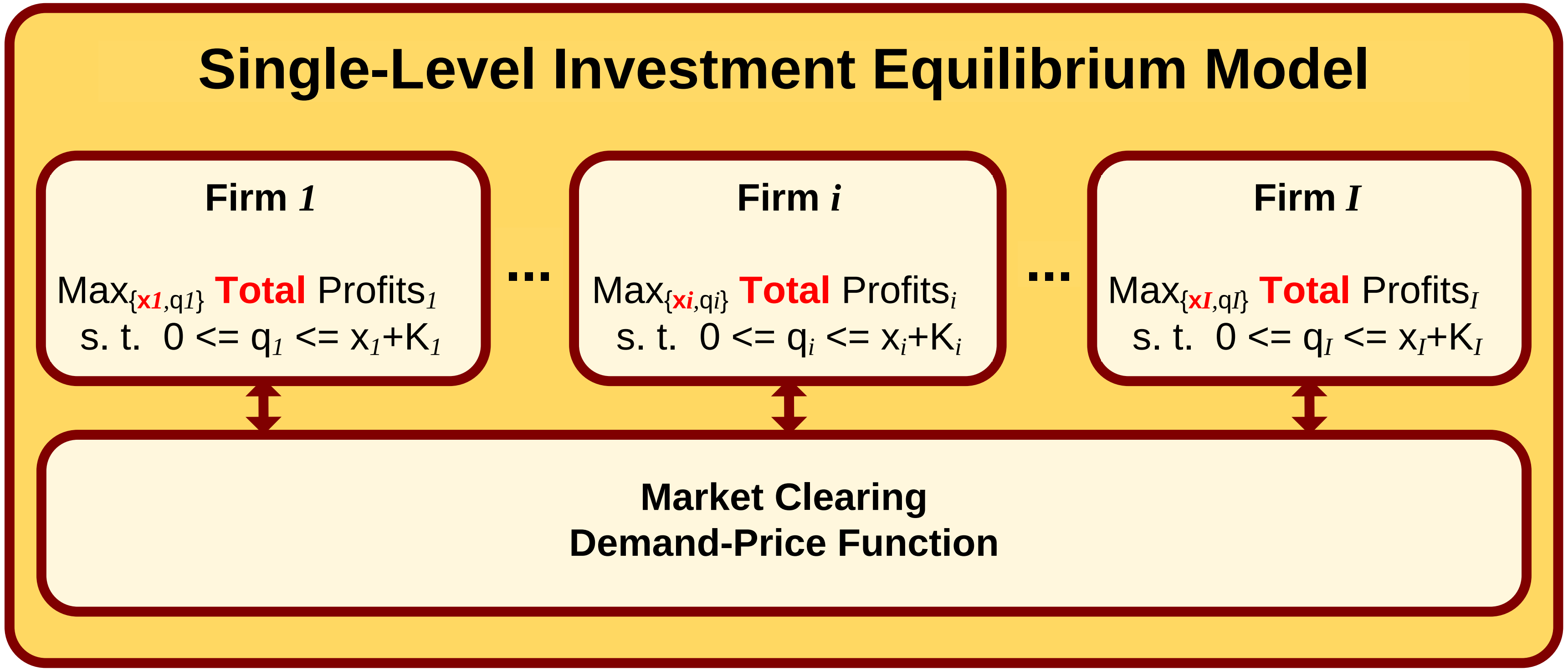
Generation Expansion Planning Problem Statement

We have two identical firms (e.g. generation companies - GENCOs) with perfectly substitutable products (e.g. electric energy), facing either a one-stage or a two-stage competitive situation.

One-stage situation (open loop model)	Two-stage situation (closed loop model)	
Investment and operation decisions are made simultaneously.	First, firms choose capacities that maximize their profit anticipating the second stage, where…	…quantities and prices are determined by a conjectured price response market equilibrium.

Single-Level (SL) Investment Equilibrium

- All GENCOs simultaneously maximize their **total** profits (market revenues minus **investment costs** minus production costs) subject to lower and upper bounds on production and a demand balance.



Single-Level (SL) Investment Formulation

Concept:

$$\forall i \begin{cases} \max_{x_i, q_i} & t(p(q_i, q_{\text{-}i}) - \delta)q_i - \beta x_i \\ s.t. & q_i \leq x_i \end{cases}$$

$$d = q_i + q_{\text{-}i}, \quad d = D_0 - \alpha p(q_i, q_{\text{-}i})$$

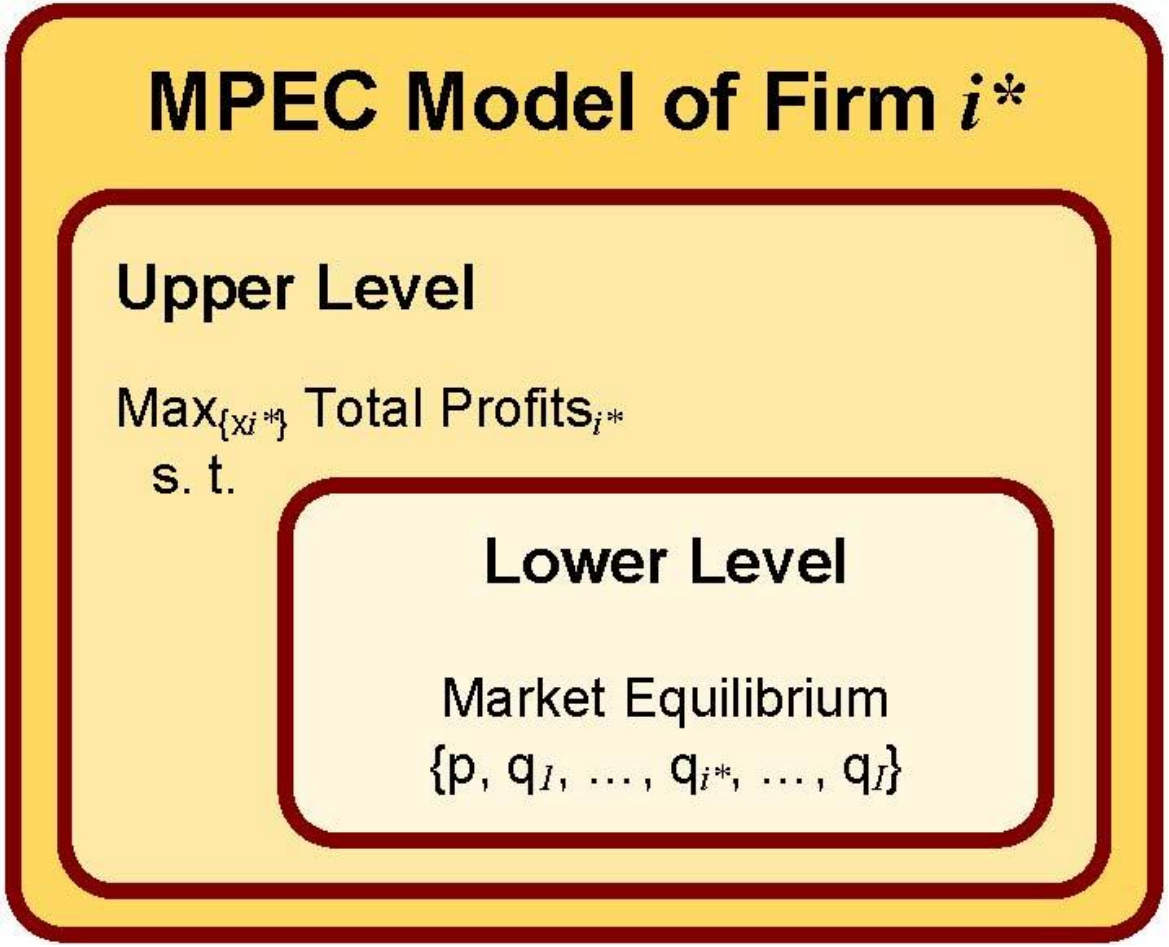
KKT-conditions:

$$\forall i \begin{cases} \frac{\partial \mathcal{L}_i}{\partial q_i} = tp(q_i, q_{\text{-}i}) - t\theta q_i - t\delta - \lambda_i = 0 \\ \frac{\partial \mathcal{L}_i}{\partial x_i} = \beta - \lambda_i = 0 \\ q_i \leq x_i \\ \lambda_i \geq 0 \\ \lambda_i (x_i - q_i) = 0 \end{cases}$$

$$d = q_i + q_{\text{-}i}, \quad d = D_0 - \alpha p(q_i, q_{\text{-}i})$$

Bilevel (BL) Investment Optimization

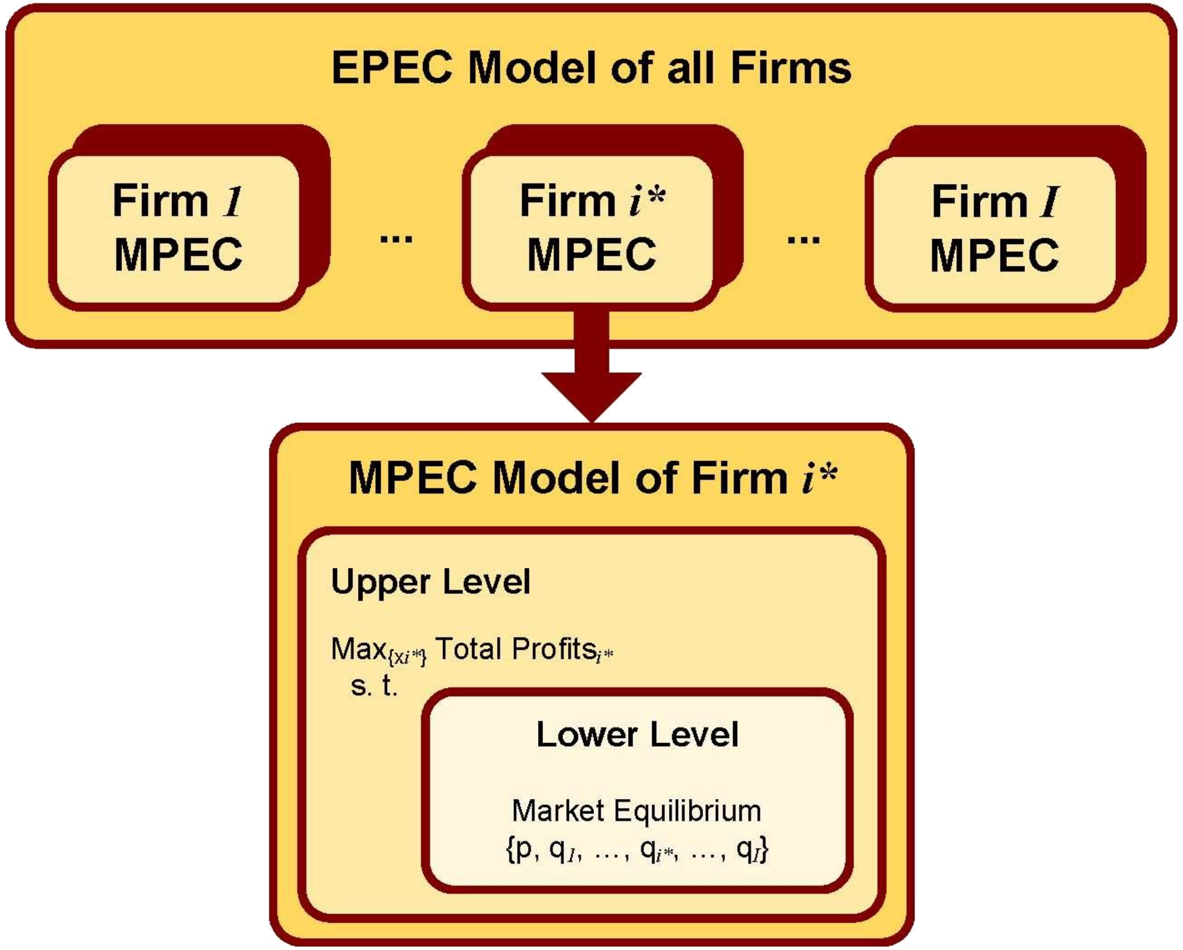
- This model assists **one GENCO** in taking capacity decisions while considering the competitors' investments as fixed.
- This model is a Mathematical Problem with Equilibrium Constraints (**MPEC**).
- In the upper level investment decisions of firm i* are taken.



Bilevel (BL) Investment Equilibrium

- This model assists **ALL** GENCOs in taking capacity decisions.

- This problem is an Equilibrium Problem with Equilibrium Constraints (**EPEC**): all GENCOs simultaneously face an MPEC.



Bilevel (BL) Investment Formulation

First Stage (Investment):

$$\forall i \begin{cases} \max_{x_i} & t(p(q_i, q_{-i}) - \delta)q_i - \beta x_i \\ s.t. & \text{Second Stage} \end{cases}$$

Second Stage (Production):

$$\forall i \begin{cases} \max_{q_i} & t(p(q_i, q_{-i}) - \delta)q_i \\ s.t. & q_i \leq x_i \end{cases}$$

$$d = q_i + q_{-i}, \quad d = D_0 - \alpha p(q_i, q_{-i}),$$

Comparison Single- and Bilevel Equilibria

Source: Wogrin, Sonja, et al. "Open versus closed loop capacity equilibria in electricity markets under perfect and oligopolistic competition." Mathematical Programming 140.2 (2013): 295-322.

We compare (Wogrin et al, 2013) two generation expansion models:

- A **single-level** model where investment and production decisions are considered to be taken **simultaneously**.
- A **bilevel** model where first investment decisions are taken and then **sequentially** production decisions are decided in the market.
- The intensity of competition among producers in the energy market is represented using **conjectural variations**.
- For simplicity, in each of the models we consider two identical generation companies, a one-year time horizon and investment in one technology.

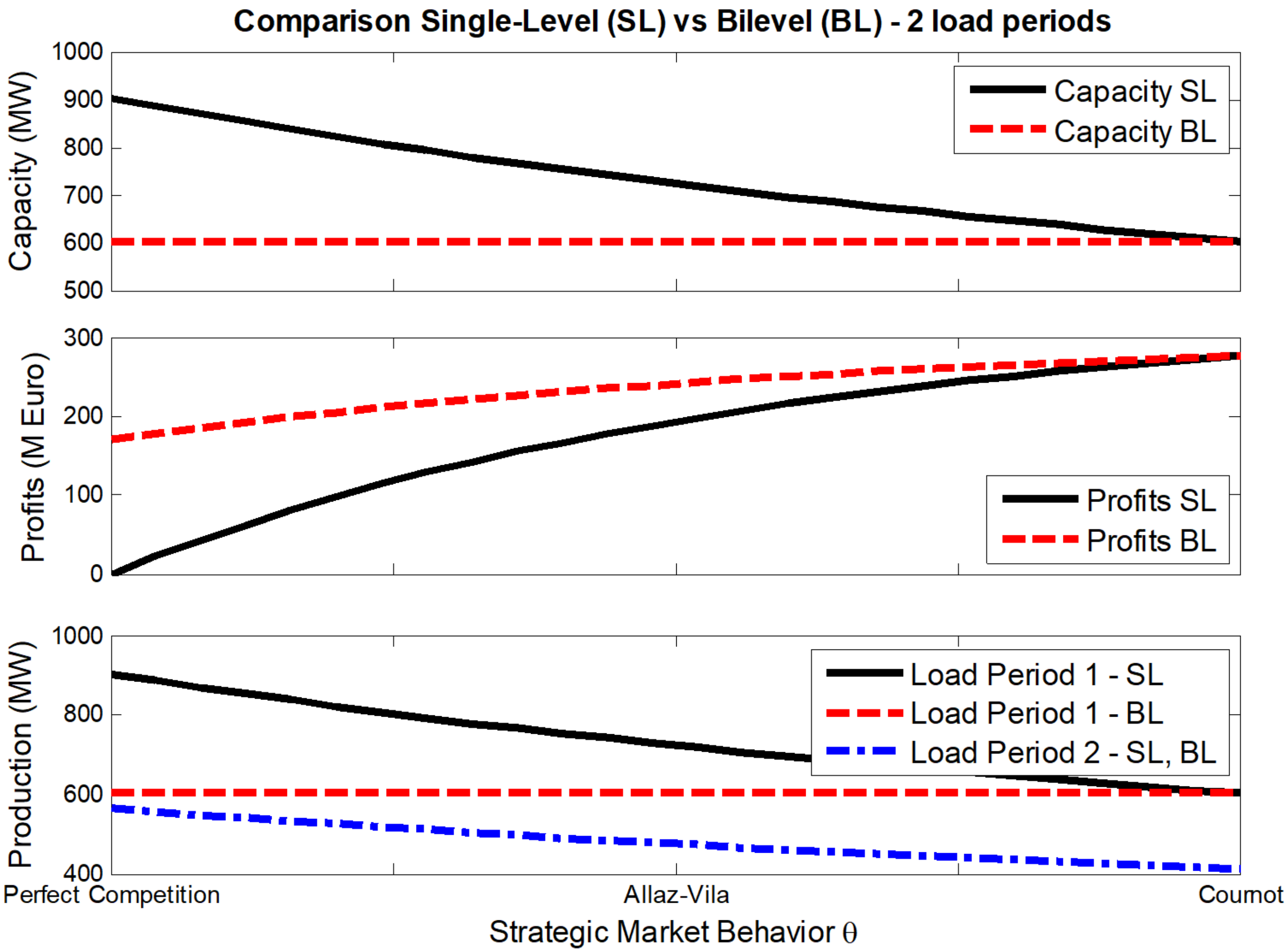
Comparison Single- and Bilevel Equilibria

Theorem

Let there be two identical firms with perfectly substitutable products and one load period and let the affine price $p(d)$ and the parameters be as previously defined. When comparing the open and closed loop competitive equilibria for two firms, we find the following:
The open loop Cournot solution, is a solution to the closed loop conjectured price response equilibrium for any choice of the conjectured price response parameter θ from perfect competition to Cournot competition.

- The result extends to multiple load periods and – under certain circumstances – to asymmetric firms.
- This is an extension of (Kreps and Scheinkman, 1983).

Numerical Example: 2 Load Periods



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Summary of Results and Policy Implications

1. The **bilevel** model always yields **Cournot capacities** independent of strategic spot market behavior.

2. This makes them **more realistic** than single-level models whose capacity decisions vary with market behavior.

3. Therefore bilevel models are very useful to study realistic generation expansion decisions and to evaluate the effect of alternative **market designs** for mitigating **market power**.

4. Under certain circumstances (Cournot market behavior) both **single-level and bilevel results can coincide**.

5. In bilevel models, **more competition can lead to less consumer surplus and less overall market efficiency**, depending on the model parameters.

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Final Takeaways

- **Climate neutrality** poses a complex challenge

- **Mathematical modeling** and **optimization** can help via techno-economic analyses

Source: dba

- **We need young people in/for science!**

Thank you. Questions?

Univ. Prof. Dipl.-Ing. Dr. M.Sc. **Sonja Wogrin**

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