Business models for power-to-gas: A real-options approach

Energy Finance Christmas Workshop 2018
Free University of Bozen, 13/12/2018

Florentina Paraschiv
NTNU Business School
Norwegian University of Science and Technology, Trondheim, Norway

<u>Michael Schürle</u>
Institute for Operations Research and Computational Finance (ior/cf-HSG)
University of St. Gallen, Switzerland

CC Energy Management
ior/cf-HSG
Universität St.Gallen

Agenda

This research is part of the activities of SCCER CREST, which is financially supported by the Swiss Commission for Technology and Innovation (CTI).

- "Renewable Methane for Transportation and Mobility"
  (joint SNF project in collaboration with HSR Rapperswil and other groups):
  Study business cases, recommendations to policy makers
- SNG = Synthetic Natural Gas (synthetic methane, CH_4)

- Economic feasibility for mobility
- Business cases: Configuration of SNG generation
- Investment analysis by real option approach
- Model components
- Optimization of P2G operations
- Preliminary results & discussion

Power-to-gas as energy storage

- Conversation of electricity to gas (hydrogen, methane)
- Synthetic methane can be stored in natural gas grid
- Links power and gas sector
- Long-term energy storage
  (e.g., excess power from renewable generation in summer)

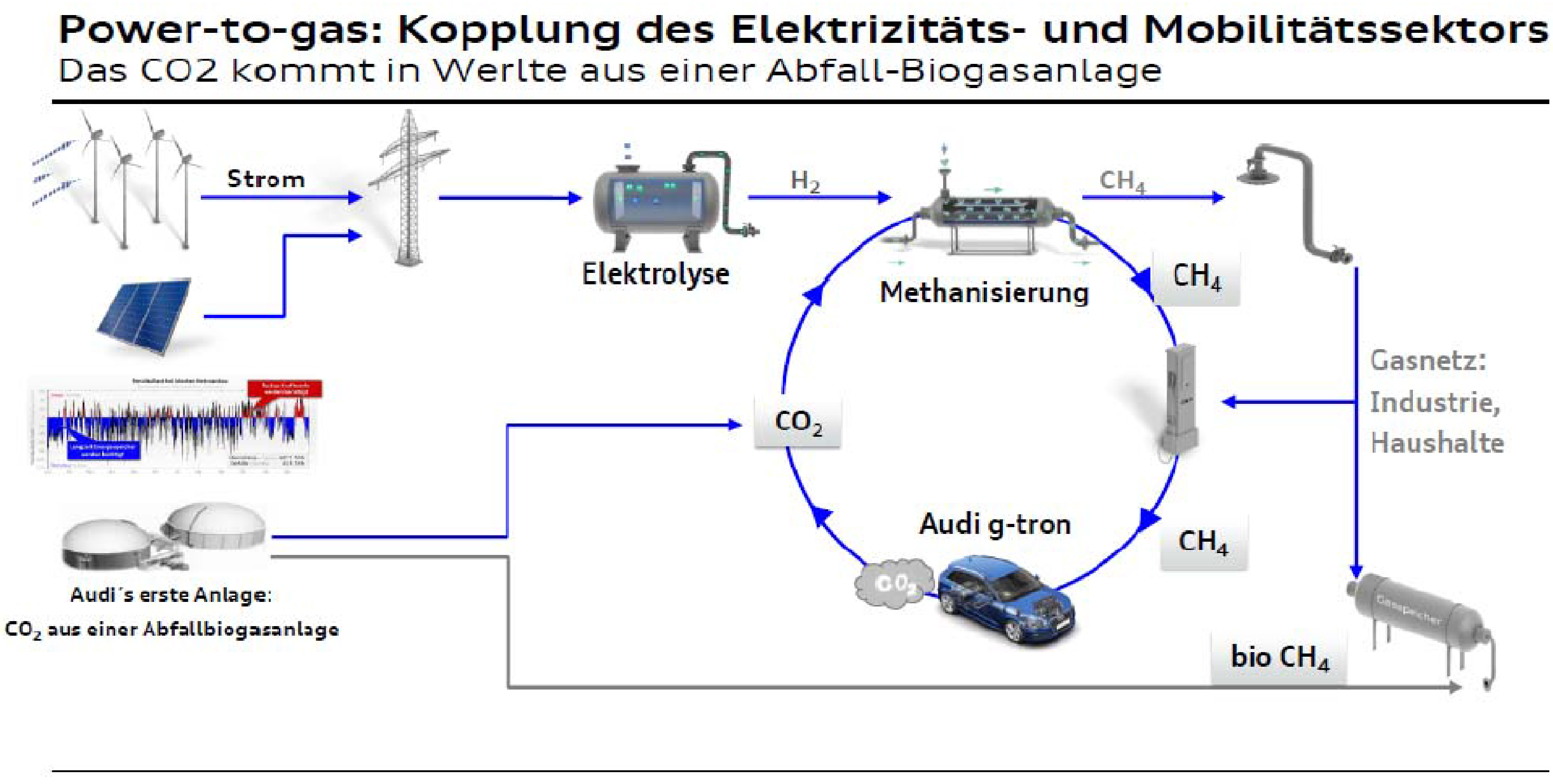
- Steps:
  - Electrolysis: $2H_2O$ (+ electricity) $\rightarrow 2H_2 + O_2$
  - Methanation: $CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$ (exothermic)
- CO_2 sources: Biogas plants, waste incinerators, sewage plants, industry (e.g., cement mills), air, …
- Overall efficiency $\approx$ 50%
- Economic feasibility?

Economic feasibility of P2G

- The profitability of P2G suffers from large installation costs and low efficiency
- Capacity utilization should be high and electricity cheap (no grid fees etc.)
- Conversion of synthetic gas back to electricity reduces efficiency to ≈30%
- Substitution of fossil gas leads to CO_2 reduction (if SNG is "renewable")
- Use gas for applications in mobility and heat sector

- From 2020 on, the automobile industry faces severe penalties if a limit for the CO_2-emissions of newly sold cars is exceeded (95 EUR per unit)
- New law in Switzerland:
  - Car manufactures/importers may offset CO_2 emissions of their fleet if they provide synthetic fuels for cars sold by them during the assumed lifetime
  - Input factors electricity and CO_2 must be "green"
  - In particular, the production of synthetic fuels <u>must not lead to an increase in demand for non-renewable electricity</u>

Power-to-gas for mobility



Economic feasibility of P2G

- The profitability of P2G suffers from large installation costs and low efficiency
- Capacity utilization should be high and electricity cheap (no grid fees etc.)
- Conversion of synthetic gas back to electricity reduces efficiency to ≈30%
- Substitution of fossil gas leads to CO2 reduction (if SNG is "renewable")
- Use gas for applications in mobility and heat sector

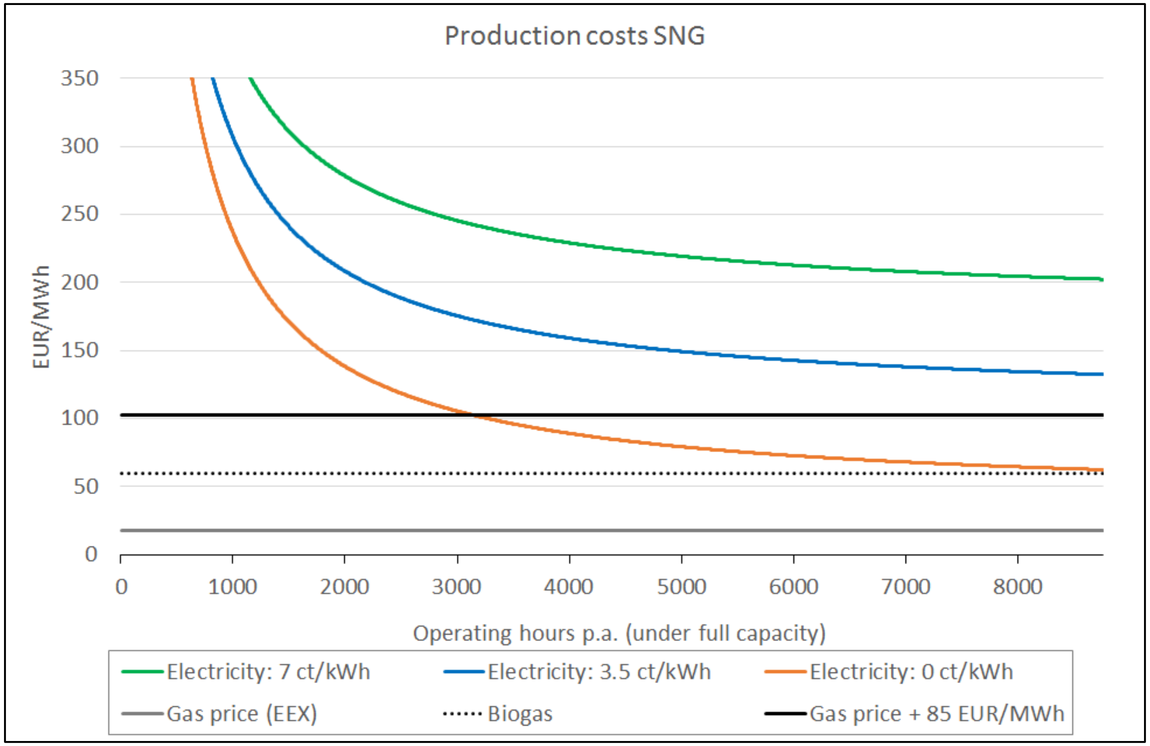
- From 2020 on, the automobile industry faces severe penalties if a limit for the CO2-emissions of newly sold cars is exceeded (95 EUR per unit)
- New law in Switzerland:
  - Car manufactures/importers may offset CO2 emissions of their fleet if they provide synthetic fuels for cars sold by them during the assumed lifetime
  - Input factors electricity and CO2 must be "green"
  - In particular, the production of synthetic fuels <u>must not lead to an increase in demand for non-renewable electricity</u>

Business case: Renewable SNG for mobility

- Under the new regulation, the savings in penalties could be used to subsidize the production of renewable SNG with a premium of 85 EUR/MWh
- Research question: Assuming that a car importer is willing to pay this to the operator of a SNG facility, would it be profitable to invest in it?
- Business case: Power is produced by waste incineration plant:
  - 50% of the generation capacity count as renewable
  - Constant own generation, no grid fees, provides CO2 for methanation
- Waste incineration plant has generation costs of 35 – 70 CHF/MWh, not competitive for sale on spot market, other must-run plants (e.g., run-of-river) have also costs around 30 CHF/MWh and higher
- Compare different configurations:
  - Sale of gas at market price + premium
  - In addition, provision of operating reserve (secondary control)
  - Sell electricity on market when prices are high instead of generating SNG

First comparison with production costs SNG

- Investment (Brunner et. al, 2015):
  - Elektrolyzer: 1000 EUR/kW_{el}
  - Methanation: 700 EUR/kW_{el}
- Lifetime: 30 years
- Interest rate: 4%
- Efficiency: 50%
- Electricity costs:
  a) 70 CHF/MWh (VSE study)
  b) 35 CHF/MWh ("optimistic")
  c) 0 CHF/MWh
- Operating costs (CHF): 2 ct/kWh_{el}
- Comparison with
  - gas price ≈ 18 EUR/MWh
  - biogas ≈ 60 EUR/MWh
  - gas price plus 85 EUR/MWh

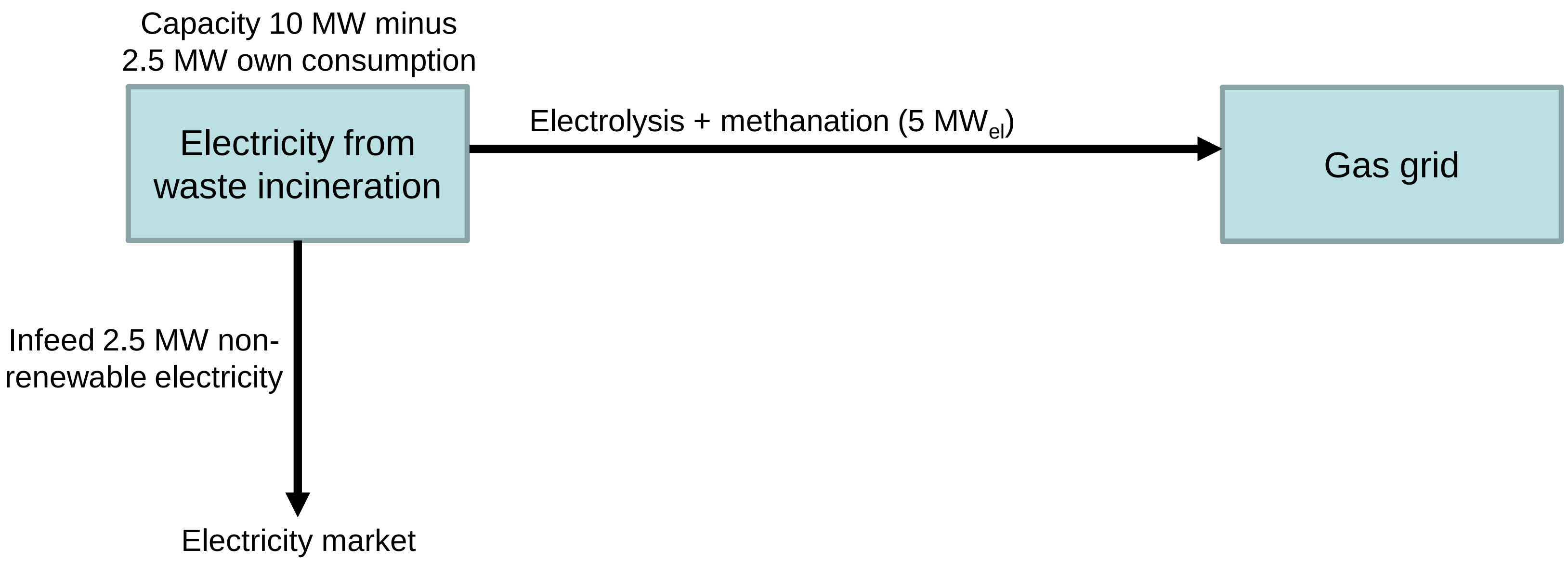


Business case: Renewable SNG for mobility

- Under the new regulation, the savings in penalties could be used to subsidize the production of green SNG with a premium of 85 EUR/MWh
- Research question: Assuming that a car importer is willing to pay this to the operator of a SNG facility, would it be profitable to invest in it?
- Business case: Power is produced by waste incineration plant:
  - 50% of the generation capacity count as renewable
  - Constant own generation, no grid fees, provides CO2 for methanation
- Waste incineration plant has generation costs of 35 – 70 CHF/MWh, not competitive for sale on spot market, other must-run plants (e.g., run-of-river) have also costs around 30 CHF/MWh and higher
- Compare different configurations:
  - Sale of gas at market price + premium
  - In addition, provision of operating reserve (secondary control)
  - Sell electricity on market when prices are high instead of generating SNG

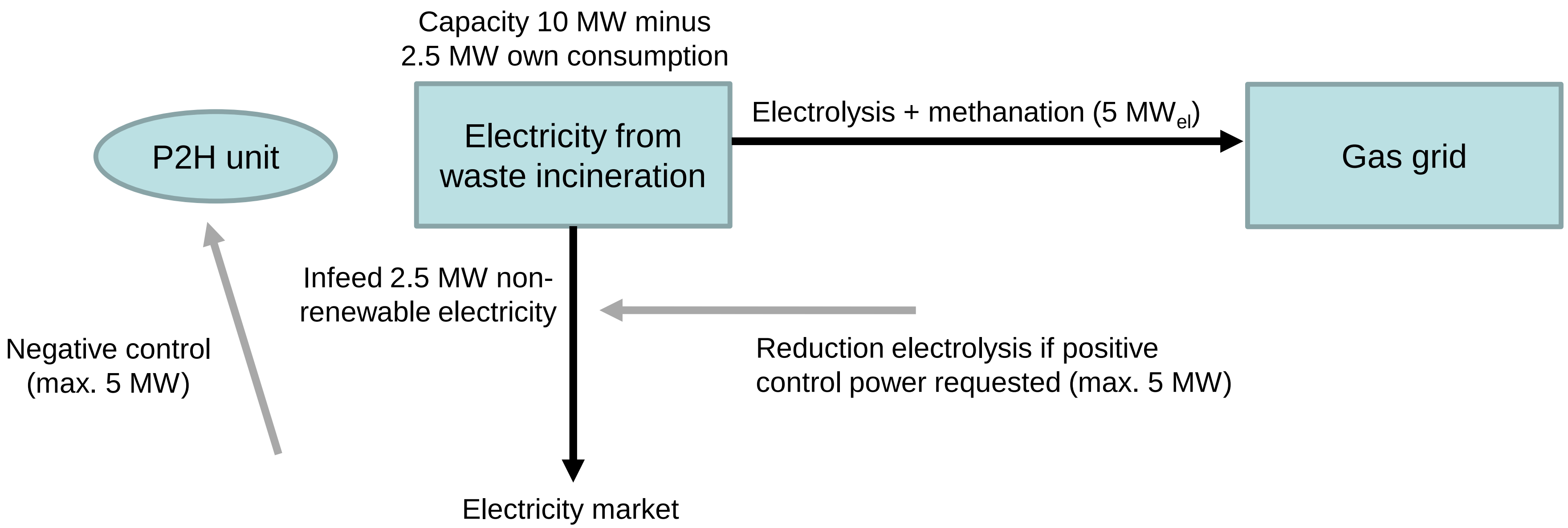
Case 1: SNG generation only

- Waste incineration plant provides constant electricity (50% renewable)
- Capacity 10 MW, 2.5 MW own consumption
- SNG generation from 5 MW renewable generation, rest is sold as base load at market price
- Electricity costs: 70 CHF/MWh (VSE study) vs. 35 CHF/MWh (optimistic)



Case 2: SNG generation plus secondary control

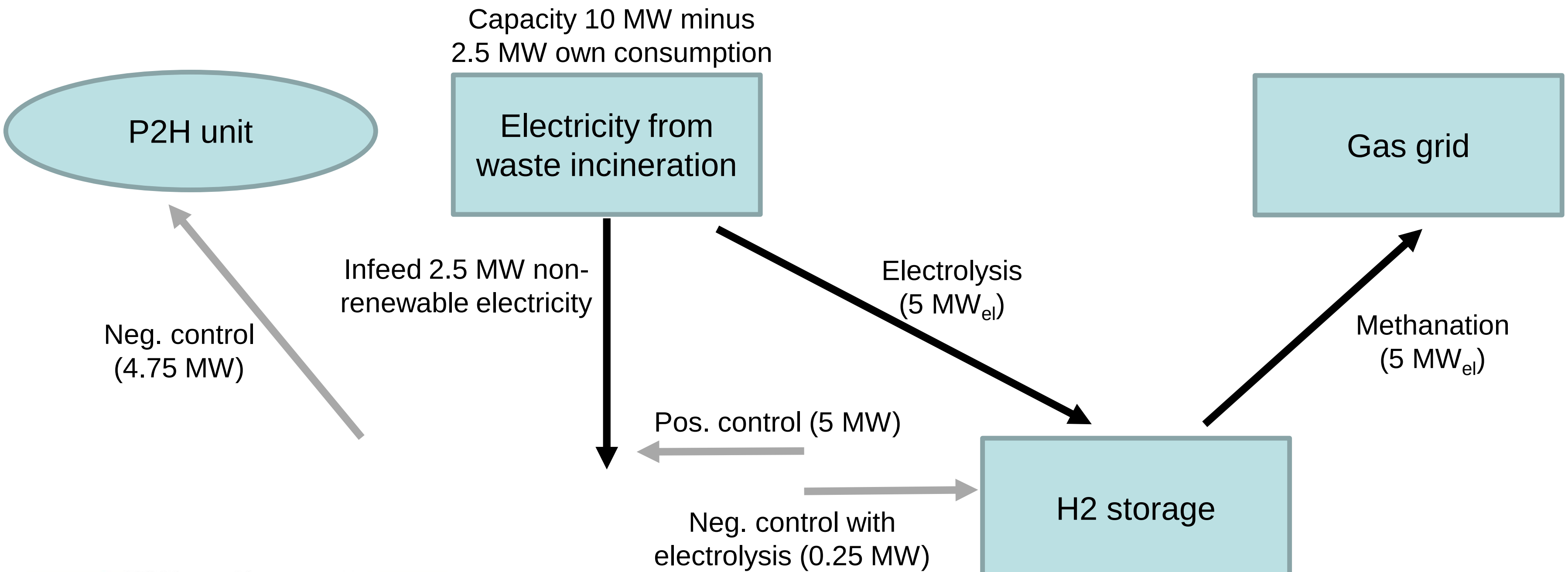
- Waste incineration plant provides electricity, 2.5 MW own consumption
- SNG generation from 5 MW renewable generation, rest is sold at market
- Provision of secondary control reserve (symmetrical): Electrolysis is reduced if positive control power is requested, negative control power provided by additional P2H unit (5 MW)



CC Energy Management
ior/cf-HSG
Universität St.Gallen

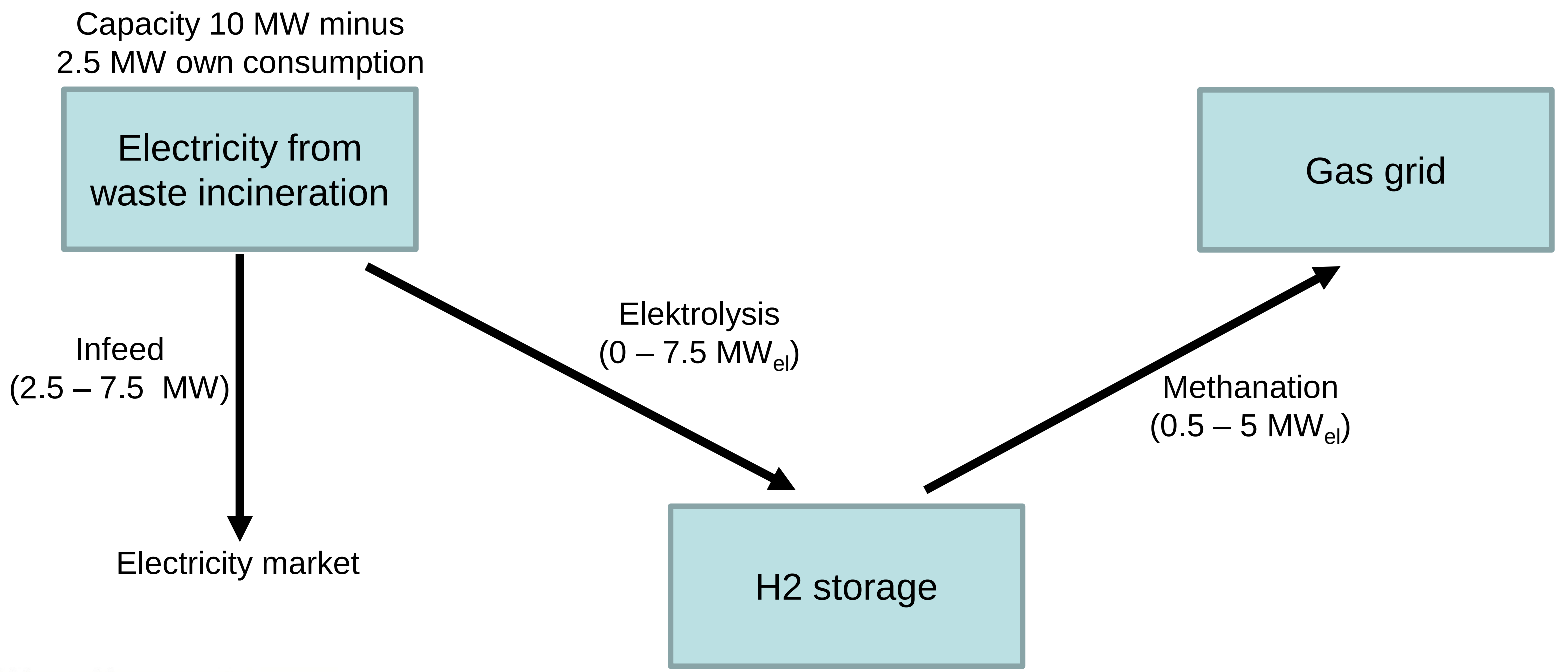
Case 3: SNG + secondary control + H2 storage

- Waste incineration plant provides electricity, 2.5 MW own consumption
- SNG generation from 5 MW renewable generation, rest is sold at market
- Provision of secondary control reserve (symmetrical): Electrolysis is reduced if positive control power is requested, negative control power provided by consumption electrolyzer (5.25 MW) additional P2H unit (4.75 MW)

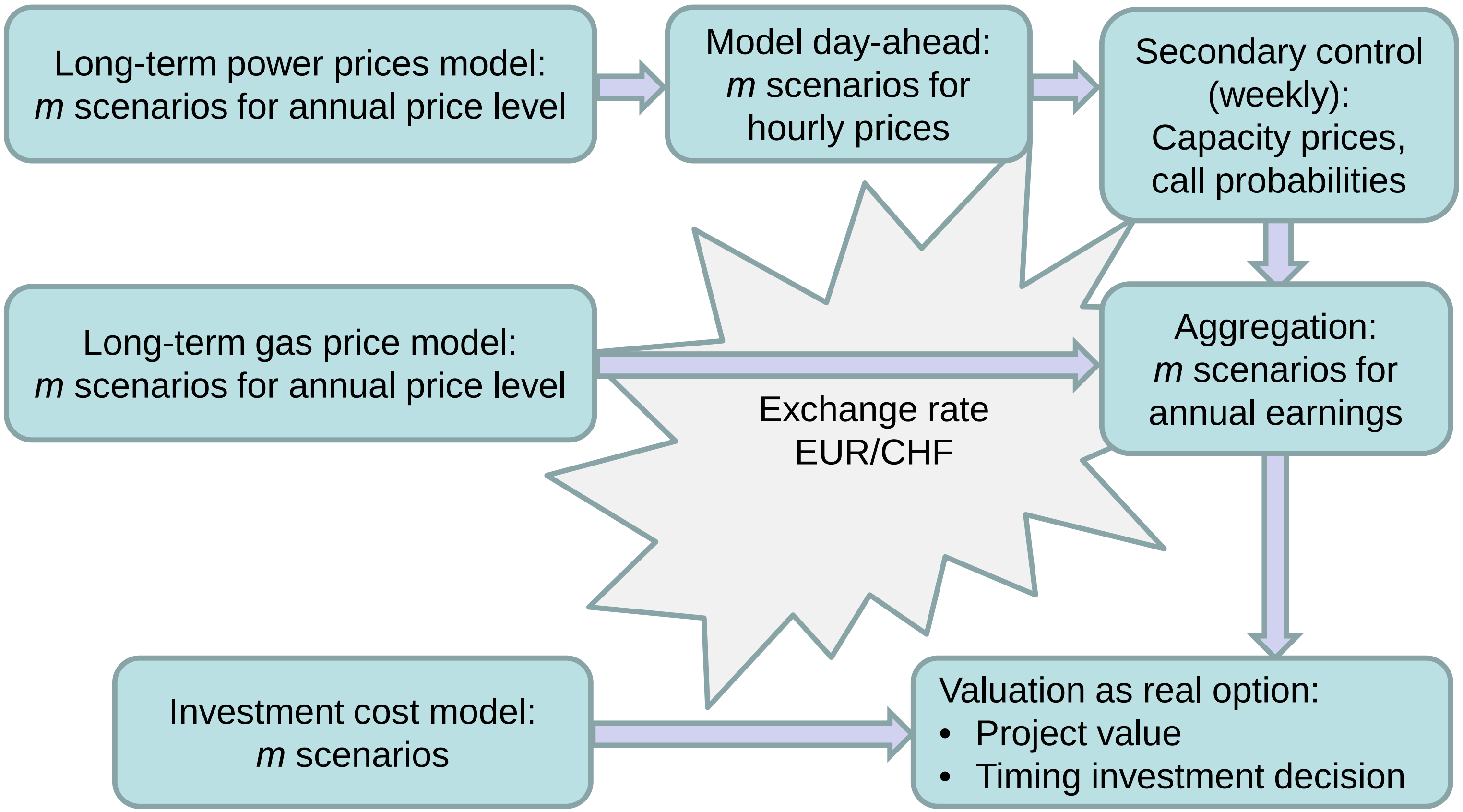


Case 4: SNG + electricity sale at high prices

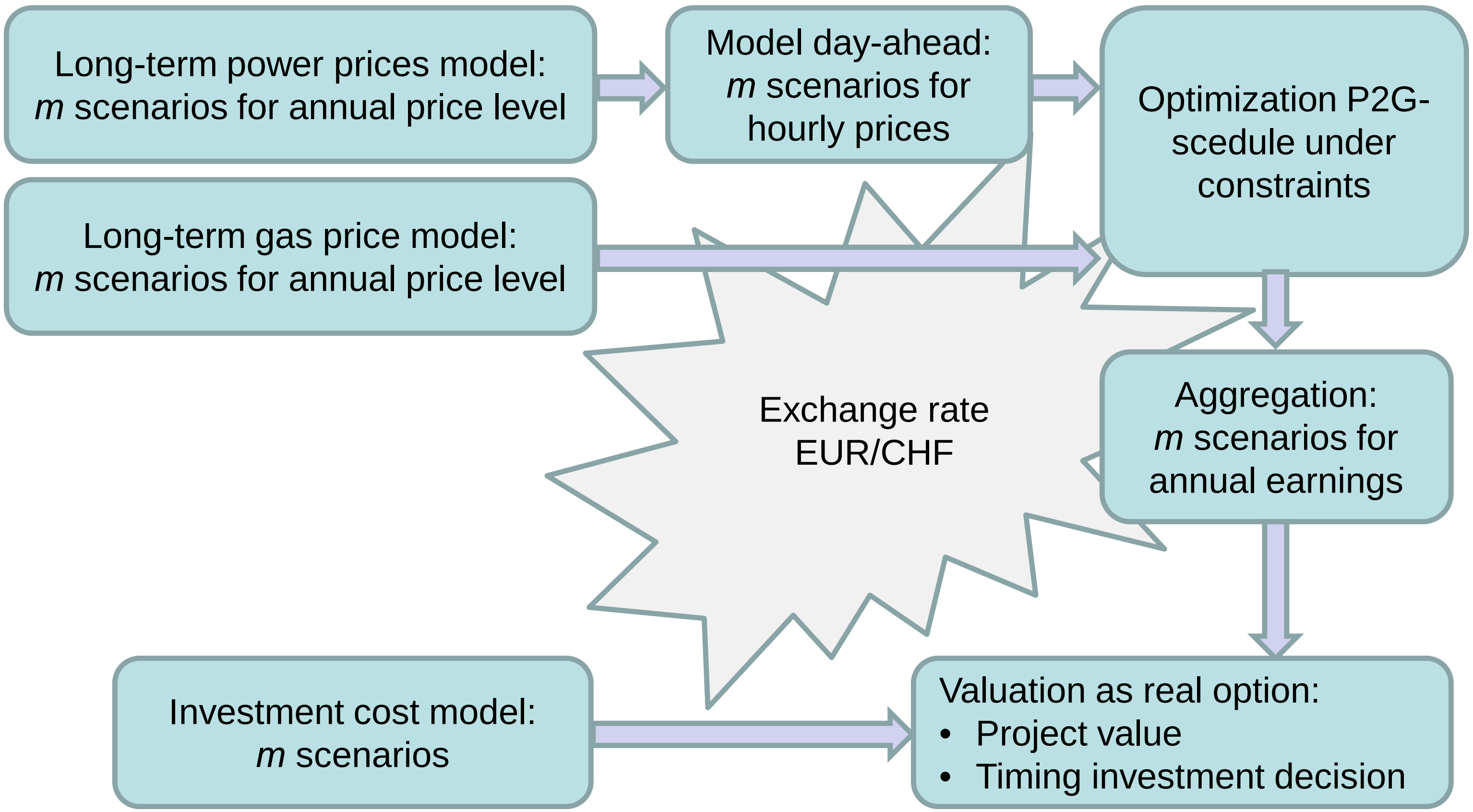
- Waste incineration plant provides electricity, 2.5 MW own consumption
- SNG generation from 5 MW renewable generation when market prices low
- When prices are high, electricity is sold on the market (Swissix, in EUR/MWh)
- H2 storage ensures that methanation can run with at least 10% capacity



Model components (with secondary control)



Model components (with electricity trading)



Model components

- Annual decision on investment, solution analogous to Longstaff/Schwartz
- Yearly power & gas price levels are modeled as geometric Brownian motions (estimated from synthetic 1Y future prices, correlation $\approx$ 0.6)
- Exchange rate follows also GBM (uncorrelated with energy prices)
- Model for day-ahead market prices:
  - Deterministic component (seasonal effects): Temperature, calendar data, residual load Germany (impact of infeed from renewables on seasonality)
  - Stochastic component: Dimensionality reduction of 24 hourly prices by principal component analysis, factors are modeled by Ornstein-Uhlenbeck processes (open: use NIG increments)
- Capacity price in CHF/MW: Assumption that operator bids/receives average price of auction and is always chosen; (log) price explained by seasonal variation (storage levels) and weekly quartiles Swissix prices (in CHF/MWh)
- Energy price in EUR/MWh linked to Swissix (Swiss particularity)
- Probability of request follows beta distribution

Model for investment costs

- Highly critical for resulting option values and timing decision (probability of investment)
- Wide range of assumptions in literature
- Current prices: Investment costs as before ("conservative") and half of current values ("optimistic")
- Schoots et al. (2008): Investment costs for electrolyzers C_t at time t depend on installed capacity P_t:

$$C_t = C_0 \left(P_t / P_0\right)^{-\alpha}$$

  where α is the "learning index", which is related to the learning rate by

$$lr = 1 - 2^{-\alpha}$$

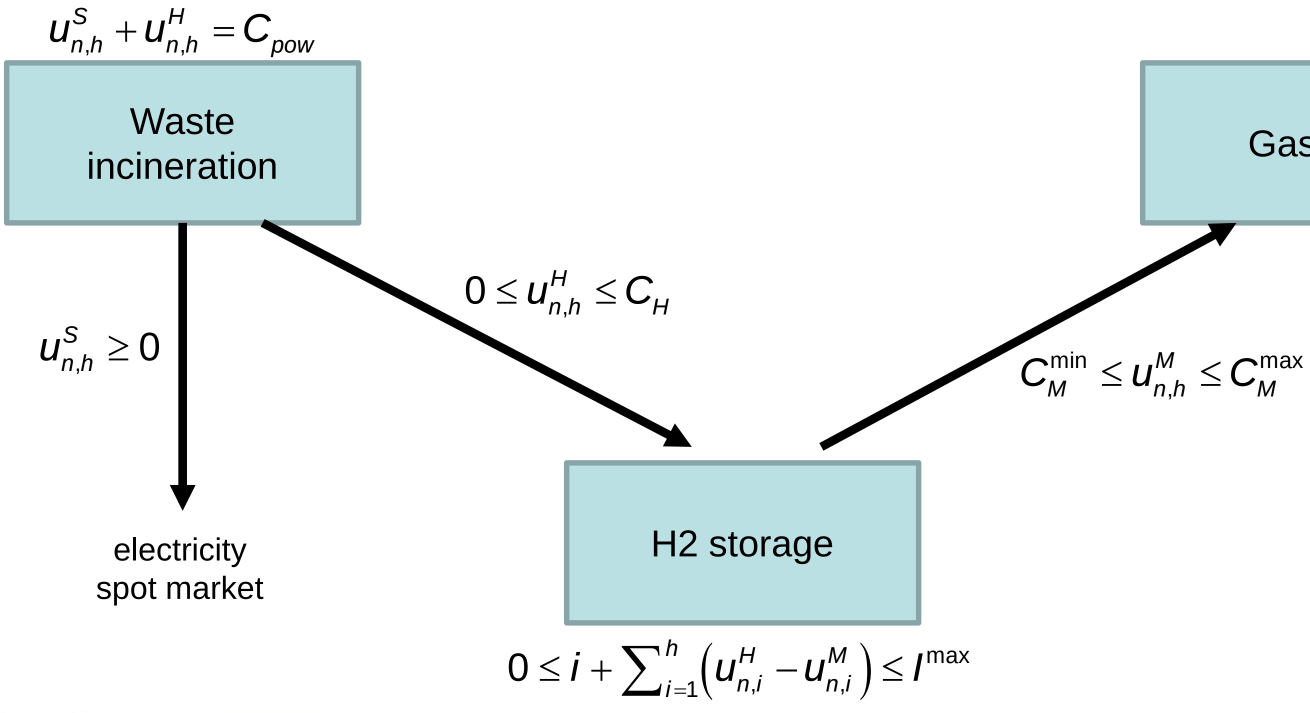
- The literature reports values $lr \approx 0.2$, which implies $\alpha \approx 0.32$
- Expert opinion: Capacity likely to triple within 10 years so that

$$C_t / C_0 \approx 3^{-0.32} = 0.7$$

- Assumption: Investment costs of other components stay constant

Optimization of P2G operations

- Decide in each (daily) step n on the amounts of hydrogen $u^H_{n,h}$ and methane $u^M_{n,h}$ generated in hour h, remaining electricity $u^S_{n,h}$ is sold on the spot market
- Constraints must be observed in all hours $h = 1, \ldots, 24$
- C_{pow}, C_H and C_M are capacities of power generation, electrolyzer and methanation unit



CC Energy Management
ior/cf-HSG
Universität St.Gallen

Optimization of P2G plant operations: RLMC

- Regress-later Monte Carlo, RLMC (cf. Balata/Palczewski, 2017)
- Let (X_n, I_n) be the values of state variables (prices) and inventory (storage) at step n
- In *regress-now* MC methods, the conditional expectation of the value function at time $n + 1$ is approximated by regression w.r.t. (X_n, I_n)
- In *regress-later* MC, first a conditional expectation w.r.t. (X_{n+1}, I_{n+1}) is approximated by a linear combination of basis functions in a regression step (using randomly sampled training points)
- Then analytical formulas are applied to condition the linear combinations of functions of future values on current values (X_n, I_n)
- Backward iteration through generated scenarios:
  - "Value iteration": $O(n)$ vs.
  - "Performance iteration": $O(n^2)$
- After optimization of the current policy, a forward iteration is performed an another set of scenarios to re-estimate the resulting profits

General problem statement (continuous time)

Consider a multidimensional process (X, I) with exogenous random component X_t and endogenous control component $I_t(u)$, where u is a control (see Balata/Palczewski, 2017, for full specification).

Assumed dynamics:

$$dX_t = \mu(t, X_t)dt + \sigma(t, X_t)dW_t$$
$$dI_t = \hat{\varphi}(t, u_t, I_t)dt$$

Pathwise performance measure given process (X, I, u):

$$\hat{J}(t, X, I, u) = \int_t^T \hat{f}(s, X_s, I_s, U_s)ds + \hat{g}(X_T, I_T) \qquad \text{("expectation")}$$

Maximize expected value of above measure over control process u_t:

$$V(t, x, i) = \sup_u \mathbb{E}\left[\hat{J}(t, X, I, u) | X_t = x, I_t = i\right]$$

General discrete time model

Dynamics in discrete time (Euler discretization):

$$\begin{aligned} X_{n+1} &= X_n + \mu(n, X_n)\Delta + \sigma(n, X_n)\Delta W_n \\ I_{n+1} &= I_n + \hat{\varphi}(n, u_n, I_n)\Delta \end{aligned}$$

(X_n) is Markov process and I is controlled process with dynamics $I_{n+1} = \varphi(n, u_n, I_n)$.

Process of controls $(u_n)_{n=0,\dots,N-1}$ is adapted to filtration generated by (X_n) and satisfies $u_n \in [\underline{u}, \overline{u}]$ and $I_n \in [0, I_{\max}]$ for all n.

Performance measure:

$$J(n, X, i, u) = \sum_{s=n}^{N-1} f(s, X_s, I_s, u_s) + g(X_N, I_N)$$

Value function: $V(n, x, i) = \sup_u \mathbb{E}[J(n, X, I, u) | X_n = x, I_n = i]$

Bellman equation for value function:

$$\begin{cases} V(n, X, i) = \sup\limits_{\substack{u \in [\underline{u}, \overline{u}], \\ i + \varphi(n,u,i) \in [0, I_{\max}]}} \{ f(n, x, i, u) + \mathbb{E}[V(n+1, X_{n+1}, \varphi(n, u, i)) | X_n = x] \} \\ V(N, x, i) = g(x, i) \end{cases}$$

RLMC Algorithm

Generate training points $\{Z_n^m\}_{n=1,m=1}^{N,M}$ according to dynamics induced by X (M number of scenarios)

Choose training points for control $\{Y_n^m\}_{n=1,m=1}^{N,M}$

Initialize value function $V(N, Z_N^m, Y_N^m) = g(Z_N^m, Y_N^m)$ for all m

for $n = N - 1$ to 0 **do**

$$\alpha_{n+1} = \underset{\alpha \in \mathbb{R}^K}{\operatorname{argmin}} \left\{ \sum_{m=1}^{M} [V(n+1, Z_{n+1}, Z_{n+1}^m, Y_{n+1}^m) - \sum_{k=1}^{K} \alpha_k \phi_k (Z_{n+1}^m, Y_{n+1}^m)]^2 \right\}$$

for all m **do**

$$V(n, Z_n^m, Y_n^m) = \sup_{\substack{u \in [\underline{u}, \overline{u}], \\ i + \varphi(n,u,i)\Delta \in [0, I_{\max}]}} \left\{ f(n, Z_n^m, Y_n^m, u) + \sum_{k=1}^{K} \alpha_{n+1}^k \hat{\phi}_k^n (Z_n^m, \varphi(n, u, Y_n^m)) \right\}$$

Evaluate policy (for different scenarios M'):

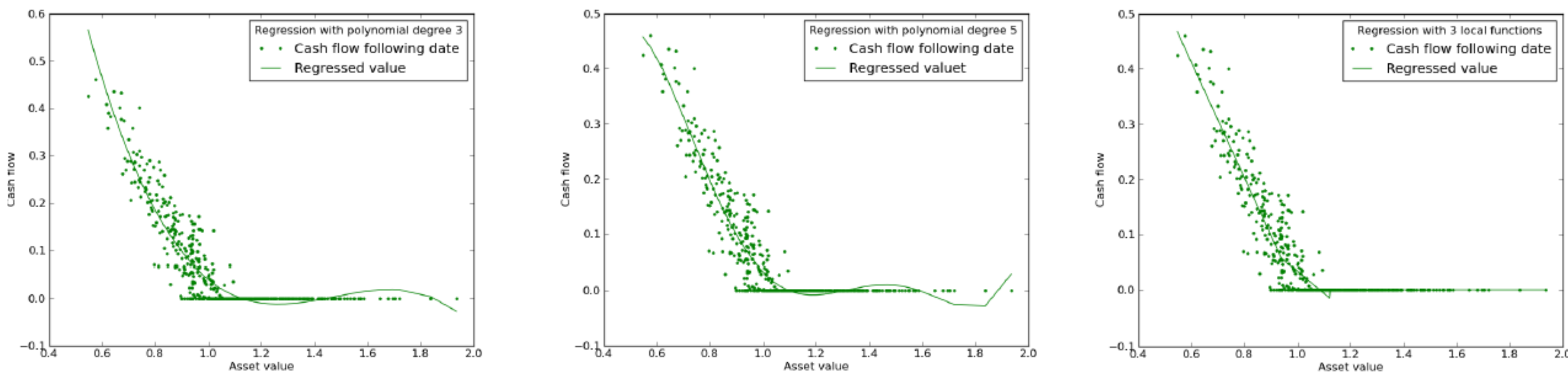
$$v(x, i) = \frac{1}{M'} \sum_{m=1}^{M'} \left(\sum_{n=0}^{N-1} f(n, Z_n^m, Y_n^m, \nu_n^m) + g(Z_N^m, Y_N^m) \right)$$

where the inventory process evolves as $Y_{n+1}^m = \phi(Z_n^M, Y_n^m, \mu_n^m)$ with $Z_0^m = x, Y_0^m = i$ and

$$\nu_n^m = \underset{\substack{u \in [\underline{u}, \overline{u}], \\ i + \varphi(n,u,Y_n^m) \in [0, I_{\max}]}}{\operatorname{argmax}} \left\{ f(n, Z_n^m, Y_n^m, u) + \sum_{k=1}^{K} \alpha_k^n \phi_k (Z_n^m, Y_n^m) \right\}$$

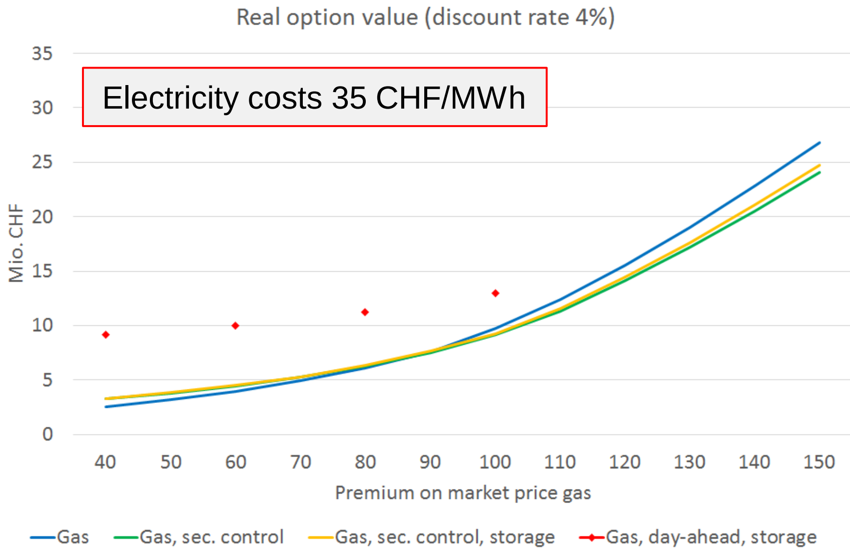
RLMC: Choice of basis functions

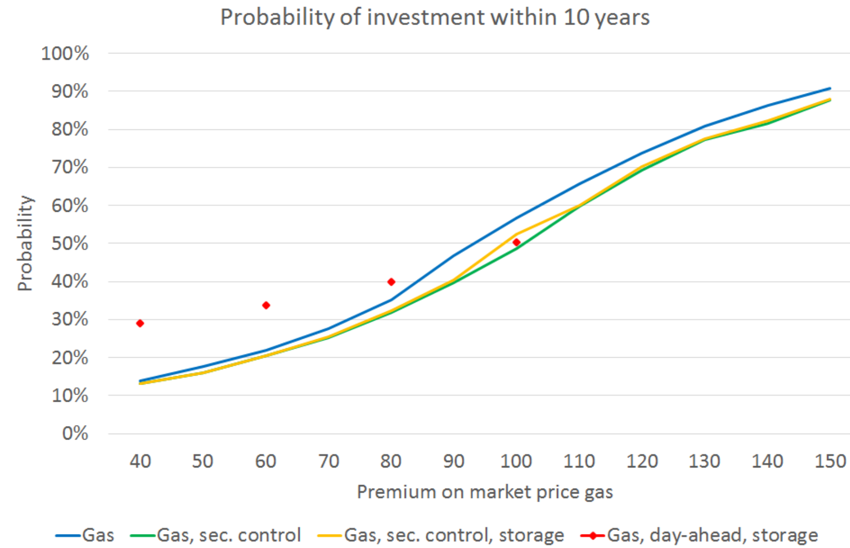
- $\phi_k(X_n, I_n),\ k = 1, \ldots, K$ are basis functions
- $\hat{\phi}_k^n(x,i) = \mathbb{E}[\phi_k(X_{n+1}, i) | X_n = x]$ is the conditional expectation of ϕ_k
- A common approach for base functions are polynomials, but the optimal degree is often not obvious
- An increase may even lead to deterioration of results, see example for put:

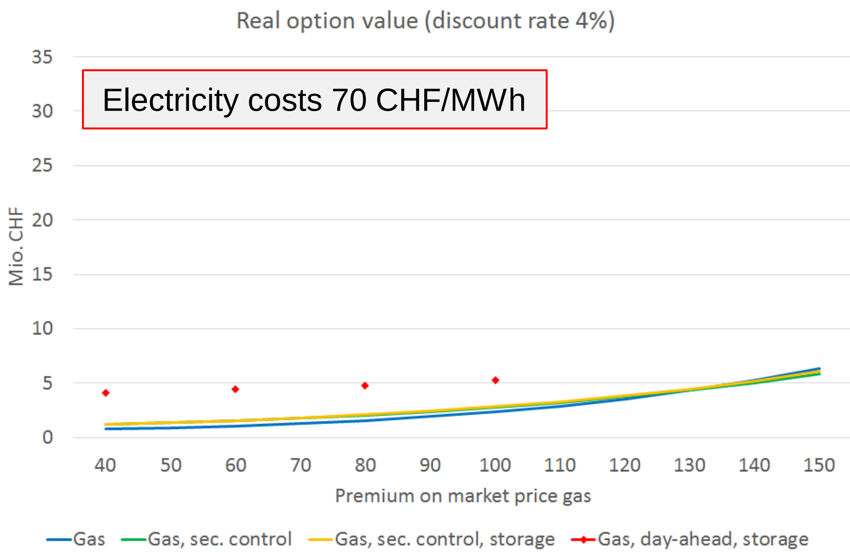


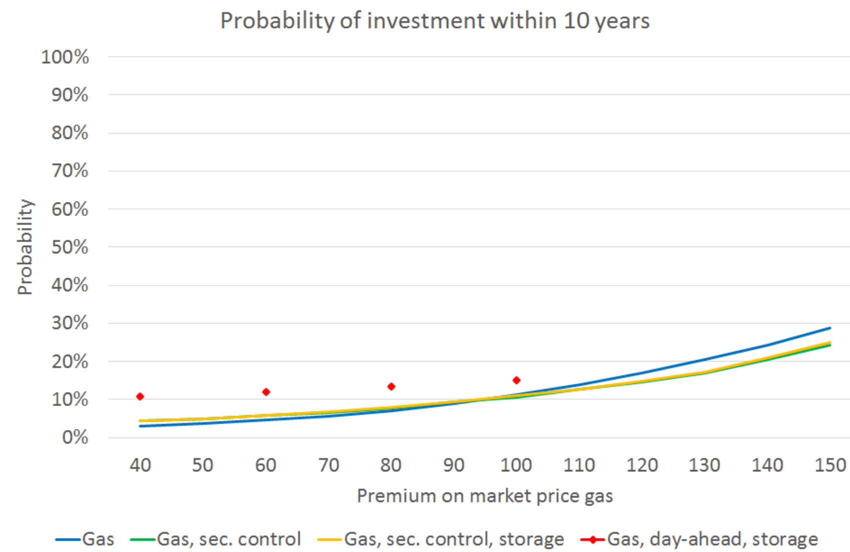
- Alternative (Bouchard/Warin 2012): Divide state space into hypercubes and choose affine functions within them, allows to capture complex shapes
- Here: Linear functions in spot prices, gas price, exchange rate, inventory

Conservative case (current investment costs)









Optimistic case (half of current investment costs)

Discussion

- Assessment of profitability:
  - Investment costs too high and/or
  - penalty for violation of CO_2 limits too low and
  - mainly power generation costs critical
- Flexibility of P2G generation allows combination with electricity trading
- Further steps:
  - Improvement of spot price model
  - Assess impact of basis functions/partitions
  - Alternative power generation sources (wind, ...)
  - Combination of power trading and ancillary services in optimization
- Concept may also be applied to other
  - energy storages (pumped-storage hydropower, batteries),
  - volatile renewable generation and
  - markets (intraday)

  possibly with better economic feasibility