Karlsruhe Institute of Technology

Is there an optimum scale for energy autarky?

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INSTITUTE OF INDUSTRIAL PRODUCTION, CHAIR OF ENERGY ECONOMICS

Agenda

- Background and motivation
- Model-based approach:
  - Definition of building cases
  - Generation of statistically average load profiles
  - Key assumptions
- Results
- Critical appraisal
- Summary and outlook

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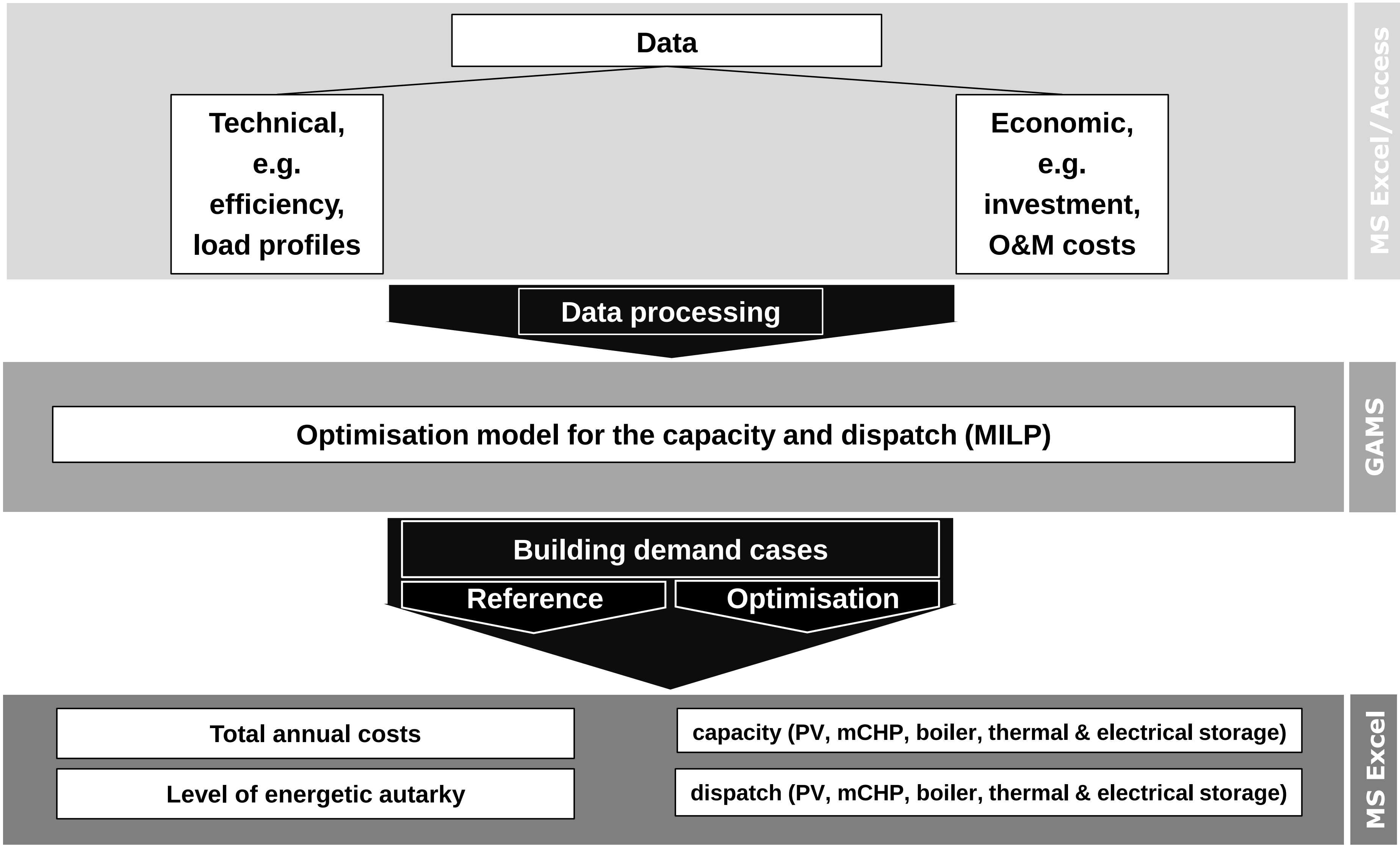
Background and objective

- Residential building sector with great potential of savings in energy consumption and greenhouse gas emissions, e.g. in Germany: 30 % of final energy consumption, 12 % of emissions of CO_2
- Photovoltaic (PV) and combined heat and power (CHP) are key technologies for the efficient provision of heat and electricity and are important pillars of energy and climate policy (Goal in Germany: Share of CHP in gross electricity generation in the amount of 25 % until 2020)
- Recent trends in PV investments, feed-in tariffs and electricity prices have led to interest in energy autarky on a household/building level
- There are also trends towards community energy projects which also (directly or indirectly) aim at energy autarky (Bioenergy villages, 100% RE regions etc.)

→ **At what scale/aggregation level is (a degree of) energy autarky with this technology combination economically attractive?**

Methodological approach



Mathematical model description

- Objective function

$$\min f = \sum_{p=1}^{P} \left(c_{inv,p} + c_{fix,p} + \propto \cdot \sum_{t=1}^{T} \left(c_{var,p,t} - c_{rev,p,t} \right) \right)$$

$$c_{inv,p} = I_p \cdot CRF$$

$$CRF = \frac{(1+i)^{T^*} \cdot i}{(1+i)^{T^*} - 1}$$

$$c_{fix,p} = x_{cap}^{p} \cdot c_{fix}^{p} \quad \forall\, p \in P$$

$$c_{var,CHP,t} = \left(\left(x_{el,i}^{CHP}(t) + x_{el,e}^{CHP}(t) + x_{th}^{CHP}(t) \right) / \eta_{tot}^{CHP} \right) \cdot c_{gas} \cdot b_{gas} \cdot CRF + y(t) \cdot c_{ram} \quad \forall\, t \in T$$

$$c_{var,BOI,t} = \left(x_{th}^{BOI}(t) / \eta_{tot}^{BOI} \right) \cdot c_{gas} \cdot b_{gas} \cdot CRF \quad \forall\, t \in T$$

$$c_{var,EL,t} = x_{el}^{grid}(t) \cdot c_{el} \cdot b_{el} \cdot CRF \quad \forall\, t \in T$$

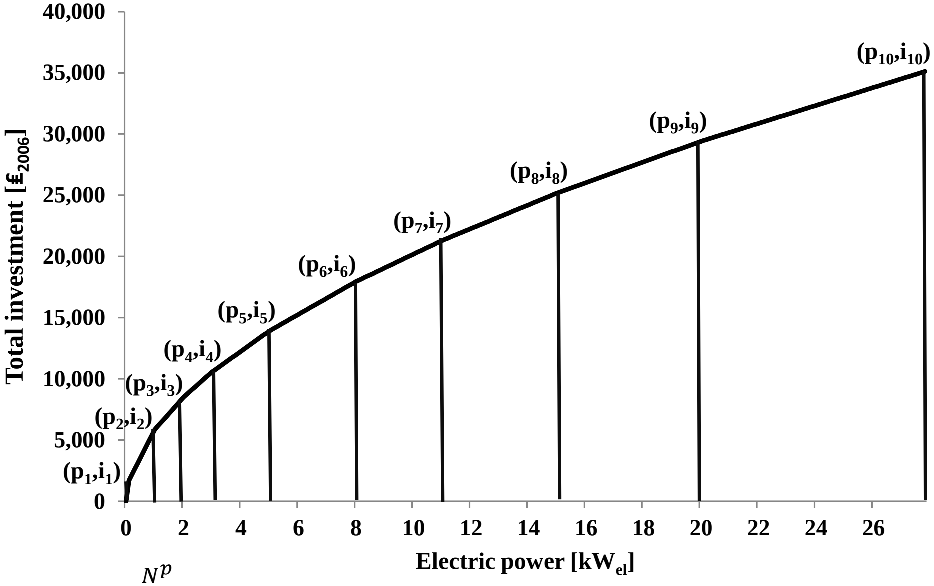
$$c_{rev,p,t} = x_{el,e}^{p}(t) \cdot c_{rev,p,e} + x_{el,i}^{p}(t) \cdot c_{rev,p,i} \quad \forall\, t \in T,\, p \in P$$

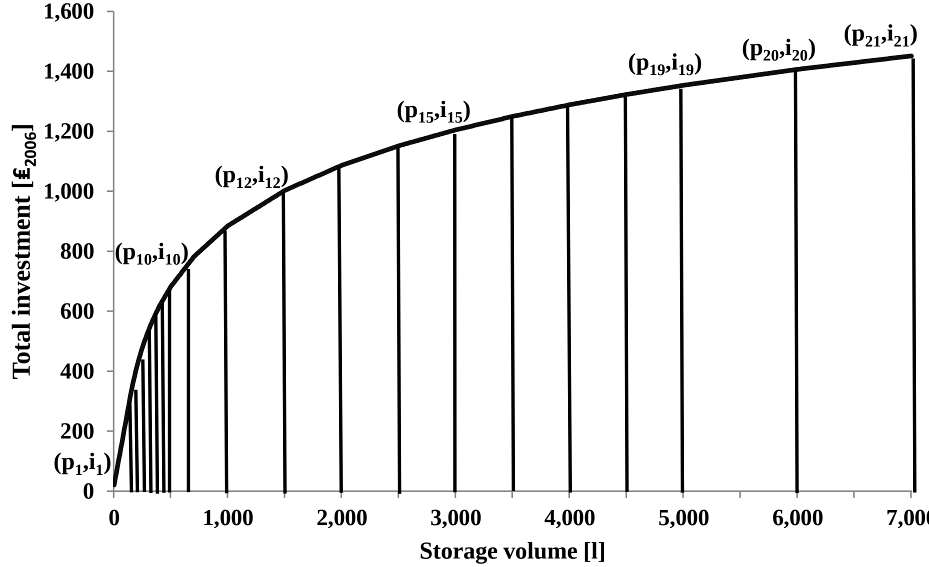
$$b_{ec} = 1 - \left(r_{ec}/(1+i) \right)^{T^*} / (1 + i - r_{ec}) \quad \forall\, ec \in EC$$

$\propto$	Time zoom factor	-
b_{ec}	Price-dynamic cash value factor for ec	-
c_{ec}	Specific electricity purchasing cost	[€/kWh]
c_{fix}^{p}	Capacity-specific fixed annual cost of p	[€/kW]
$c_{fix,p}$	Fixed annual cost of p	[€]
$c_{inv,p}$	Capital-related annual cost of p	[€]
c_{ram}	Ramp-up cost of the CHP unit	[€]
$c_{rev,e}$	Revenue for electricity exported	[€/kWh$_{el}$]
$c_{rev,i}$	Revenue for electricity generated	[€/kWh$_{el}$]
$c_{rev,p,t}$	Revenue from p in t	[€]
$c_{var,p,t}$	Variable operation cost of p in t	[€]
CRF	Capital recovery factor	-
ec	Energy carrier	{GAS; EL}
η_{tot}^{p}	Fuel utilisation ratio of p	[%]
f	Value of objective function	[€]
i	Interest rate	[% p.a.]
I_p	Investment of p	[€]
p	Technology	{CHP; BOI; STG; PV; BS}
r_{ec}	Price change factor for ec	-
T	Set of time intervals	-
T^*	Time horizon	-
$x_{th}^{BOI}(t)$	Heat output of the gas boiler in t	[kWh$_{th}$]
$x_{el,e}^{CHP}(t)$	Electricity output of the CHP unit for external use (electricity fed-back) in t	[kWh$_{el}$]
$x_{el,i}^{CHP}(t)$	Electricity output of the CHP unit for internal use (self-consumption) in t	[kWh$_{el}$]
$x_{th}^{CHP}(t)$	Heat output of the CHP unit in t	[kWh$_{th}$]
$x_{el}^{grid}(t)$	Electricity input from the grid in t	[kWh$_{el}$]
x_{cap}^{p}	Capacity of p	[kW$_{el}$], [l]
$y(t)$	Ramp-up of the CHP unit in t	{0;1}

Mathematical model description

- Economies of scale and piecewise linear approximation





$$x_{cap}^{p} = \sum_{k=0}^{N^p} p_k^p \cdot \lambda_k^p \qquad \forall\, p \in P$$

$$I_p = g\left(x_{cap}^{p}\right) = \sum_{k=0}^{N^p} i_k^p \cdot \lambda_k^p \quad \forall\, p \in P$$

$$\sum_{k=0}^{N^p} \lambda_k^p = 1 \quad \forall\, p \in P$$

$$\lambda_k^p, p_k^p, i_k^p \geq 0, \qquad \forall\, k = 0, \dots N^p;\ \forall\, p \in P$$

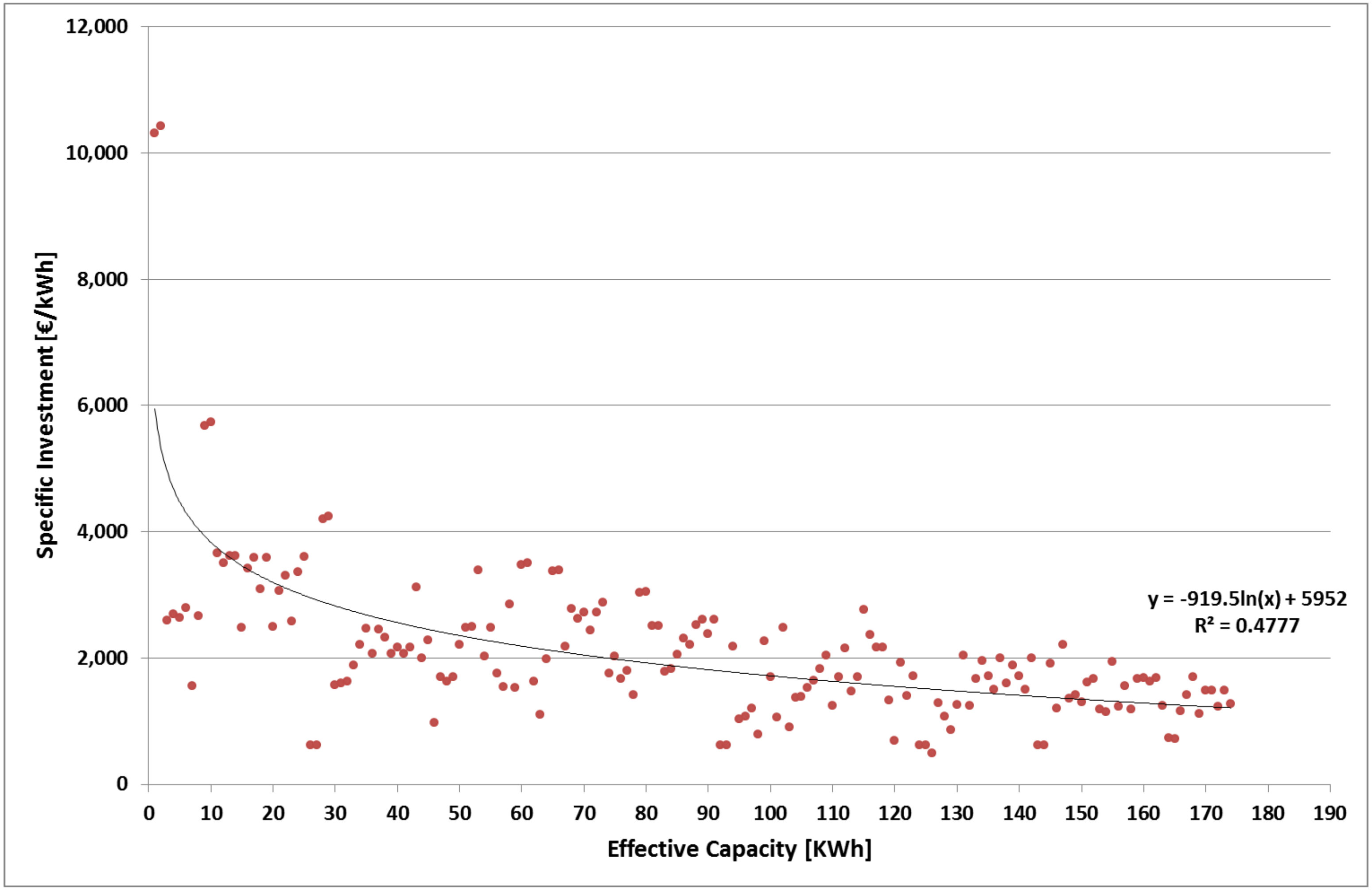
$$\left\{\lambda_k^p : k \in \{0, \dots N^p\}, \forall\, p \in P\right\}\ is\ SOS2$$

i_k^p	Auxiliary variable determining the investment of p	[€]
I_p	Investment of p	[€]
λ_k^p	Auxiliary variable of type SOS2 for p	-
N^p	Number of auxiliary points of investment for p	-
P	Set of technologies	{CHP; STG; PV; BS, BOI}
p_k^p	Auxiliary variable determining the capacity of p	[kW_{el}], [l]
SOS2	Special ordered set of type 2	-
x_{cap}^{p}	Capacity of p	[kW_{el}], [l]

Assumptions

- Framework: EEG 2014 and current market conditions in Germany

Investments based on current market data, e.g. for batteries >>



Load curve methodology

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Experimental design

Case		No. of households	No. of x-person households				
			1	2	3	4	5
2	SFH	1	-	1	-	-	-
4	SFH	1	-	-	-	1	-
6	MFH	13	7	4	1	1	0
8	100 SFH	100	19	40	18	17	6
10	H0	1000	Normalised to 10 x total annual electricity consumption of case 8				

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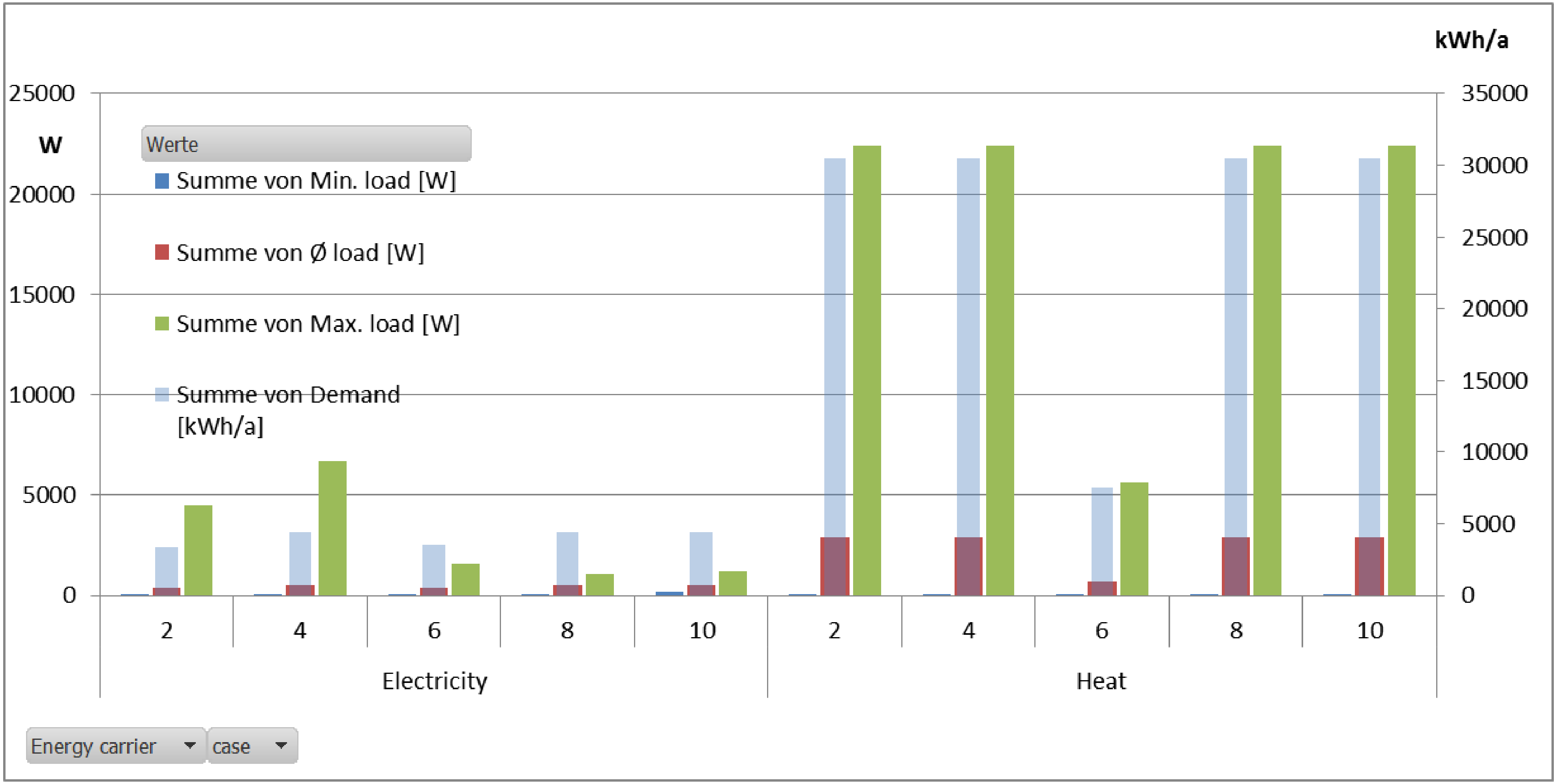
Characteristics of building demand cases



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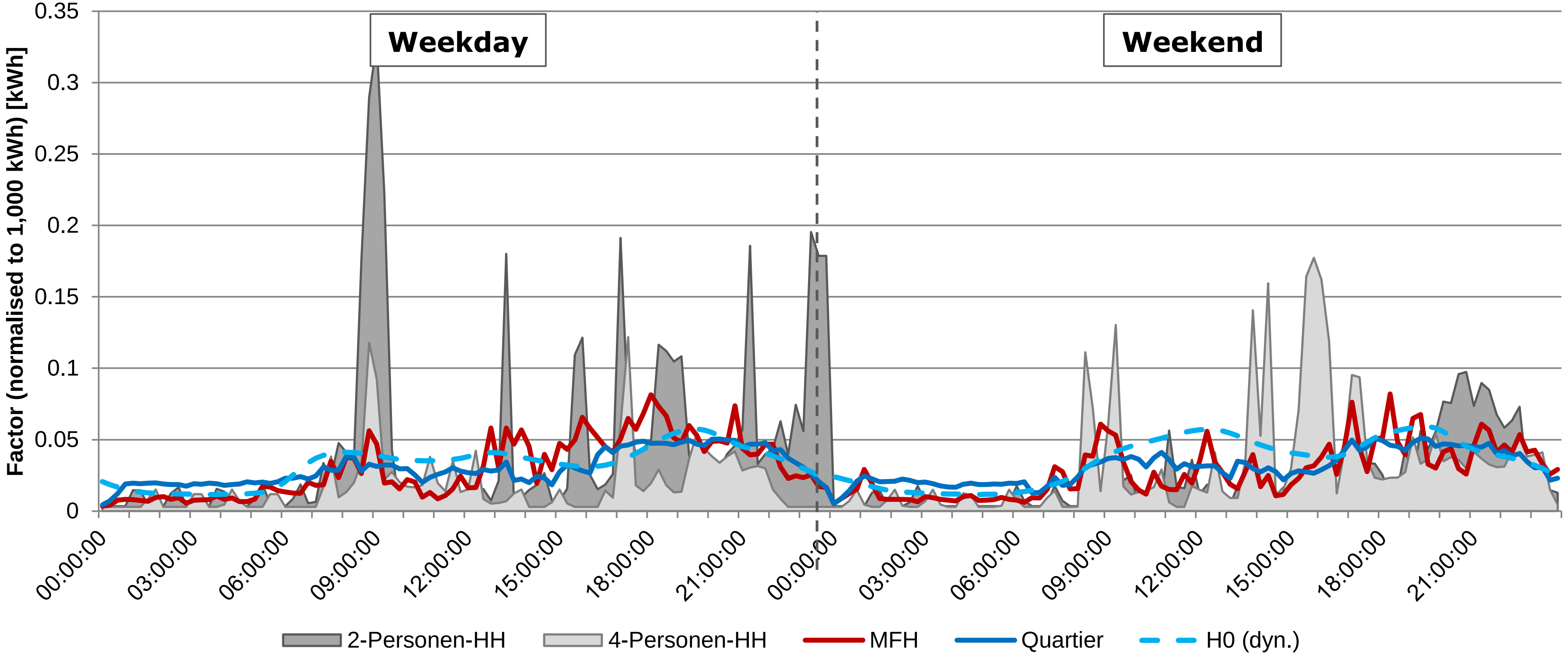
Exemplary load profiles for Febraury



Quantifying energy autarky

- Several indicators for load matching and grid interaction (right)
- Also several names for the same indicator
- We focus on the following two indictors:
  1. Degree of self-sufficiency:
     - Total onsite generation/total onsite demand
  2. Degree of self-consumption (I):
     - Onsite generation used onsite/total onsite generation
- Grid interaction (II) difficult to measure without a network model

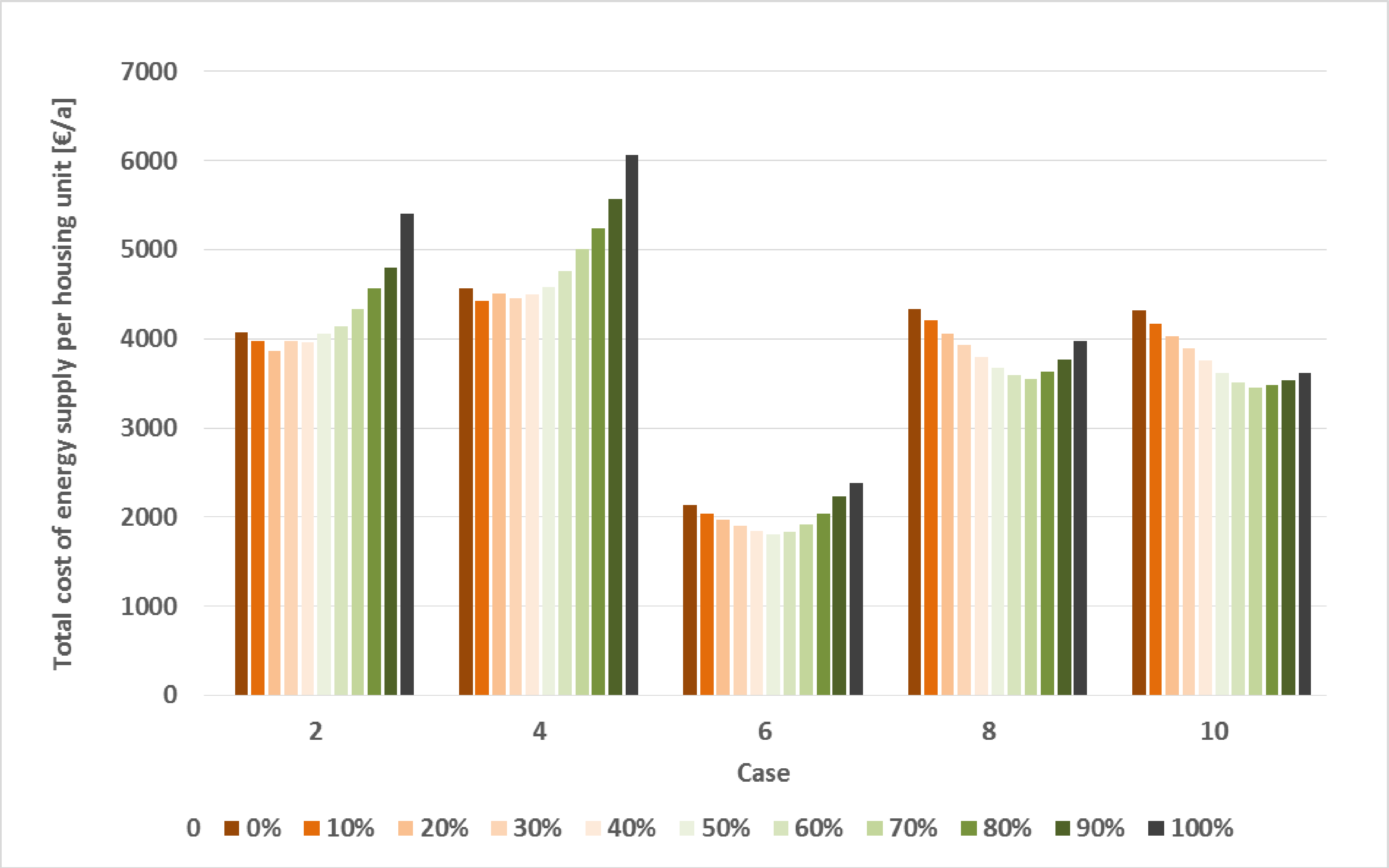
Table 1. Summary of LMGI indicators.

		Indicator category	
		Load matching	Grid interaction
Data requirements	On-site load and generation	**I** Load match index[1] Solar fraction[2] Cover factor[4] Self-consumption factor[7] Loss-of-load probability (LOLP)[4]	**II** Grid interaction index[1] Capacity factor[4] Peak power indicators[4] Dimensioning rate[4] Grid citizenship tool[8]
Data requirements	Additional data	**III** Mismatch compensation factor[5] Market matching[3]	**IV** Profile addition indicators[3] Coincidence factor[6]

[1]Voss et al. (2010), [2]Widén et al. (2009), [3]Widén and Wäckelgård (2010), [4]Verbruggen et al. (2011), [5]Lund et al. (2011), [6]Willis and Scott (2000), [7]Castillo-Cagigal et al. (2010), [8]Colson and Nehrir (2009).

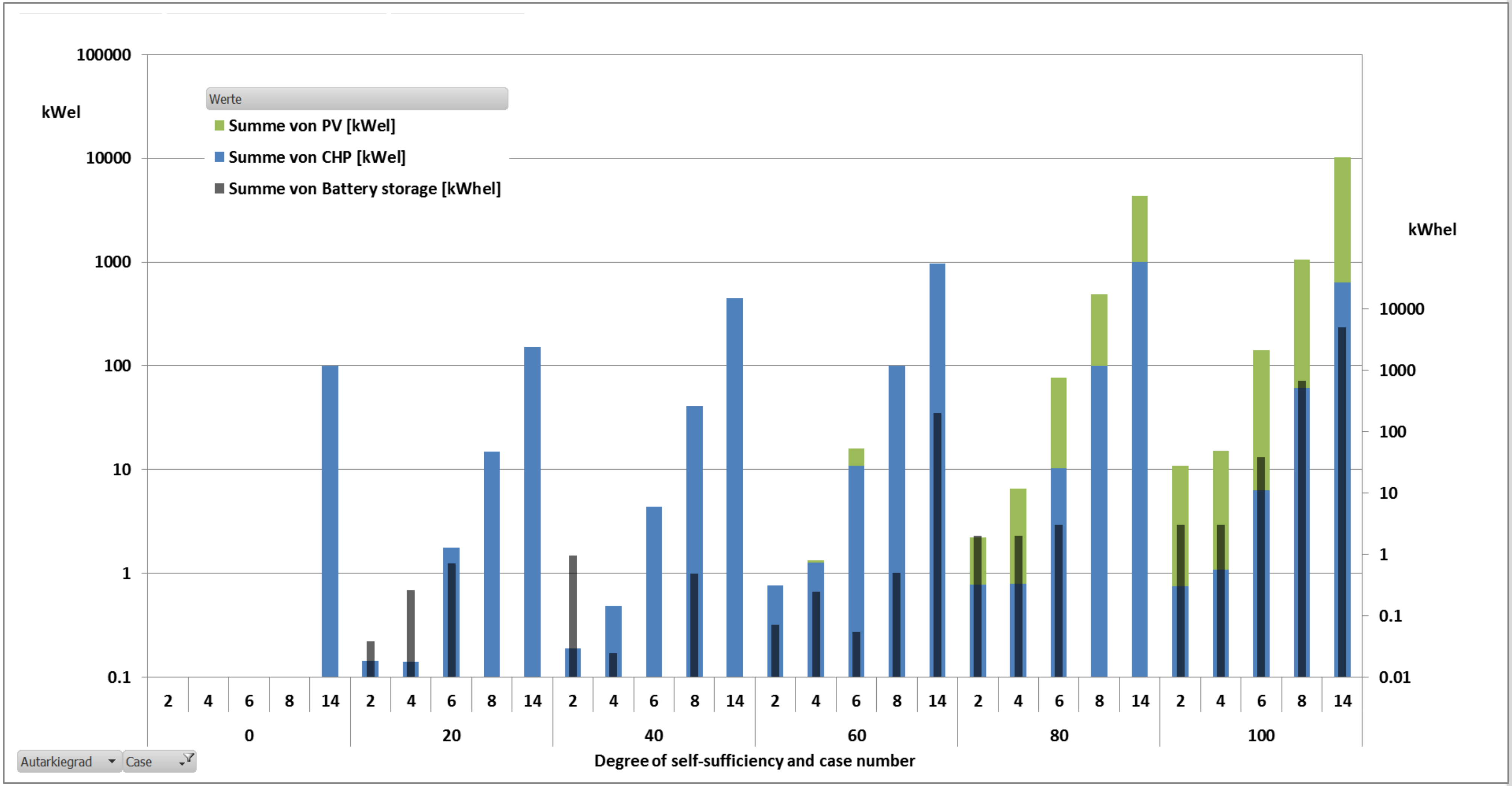
Salom et al. 2011

Results: annual discounted costs and degree of self sufficiency

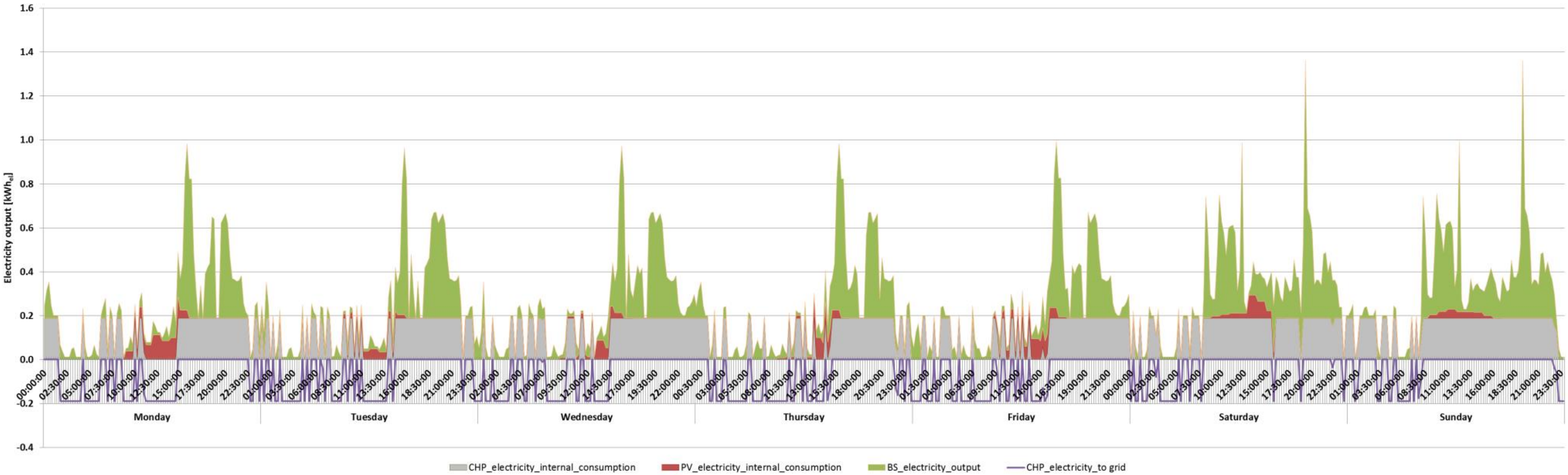


Degree of self sufficiency = (total on site generation)/(total demand)

Results: installed electrical capacities



Results: typical dispatch profile in summer
(case 2, 100% self-sufficiency)



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Some sensitivities from earlier model runs: a „2020 scenario“

Base

Case	CHP [kWel]	Thermal storage [l]	PV [kWel]	Battery storage [kWhel]	Boiler [kWth]
2	0.3	507.4	0.0	0.0	16.9
4	3.3	2620.2	0.0	0.0	29.3
7	37.9	40000.0	0.0	0.0	703.1
8	15.0	64253.8	100000.0	300.0	919.8
9	75.0	202893.1	100000.0	200.0	2889.1
10	501.0	500000.0	100000.0	21696.3	24652.3

2020

Case	CHP [kWel]	Thermal storage [l]	PV [kWel]	Battery storage [kWhel]	Boiler [kWth]
2	0.4	400.0	0.0	0.0	16.3
4	3.7	3000.0	0.0	0.0	24.0
7	44.3	45263.6	0.0	0.0	670.3
8	51.0	70964.3	100000.0	3010.0	822.3
9	51.0	195009.0	100000.0	2959.2	2964.8
10	613.8	500000.0	100000.0	23360.7	24426.7

Assuming: 37 €ct/kWh electricity price, no FITs, PV and Battery 75% of investment

Critical appraisal of employed approach

- Uncertainties:
  - of input parameters, especially specific investment curves for PV and batteries
  - Perfect foresight, ex-post consideration
  - Conditions of reference year (thermal and electrical demand [pattern, level] etc.) constant for the whole planning horizon of 20 years
- Behavioural aspects of occupants: only presence considered
- Existence of real plants vs. theoretically optimal capacity (continuous capacity)
- Only residential sector investigated – commercial sector better suited for PV
- Temporal mismatch/grid interaction not yet investigated
- Environmental aspects of batteries

Summary and outlook

Summary

- Optimisation model of capacity and dispatch of decentralised CHP **extended to include PV and battery systems**
- Smoothing of load curves through aggregation seems to make **higher levels of energy autarky more economical at higher aggregations – though optimum scale not yet clear**
- **PV is only economically attractive above 80% self-sufficiency,** and battery storage only in larger objects (in current framework)
- A “2020 scenario” with 75% of investment for PV/batteries, an electricity price of 37 €ct/kWh and no feet-in tariffs makes centralised CHP supply and batteries more attractive

Outlook for further work

- More realistic MFH and application to **further building types and sectors**
- Consideration of interaction with the electricity distribution network
- Further validation with **empirical load curves** for heat and electricity (e.g. from field trials)
- Improve depiction of **building inhabitants’ behaviour**
- Consideration of **other criteria than cost:** technical feasibility, environmental aspects etc.

Thank you very much for your attention

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