Formalizing the double edged sword of (partly) autonomous decentralized energy systems

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Workshop of the GOR Working Group „OR im Umweltschutz“

Overview

1. Centralized and decentralized energy systems
2. Energy autonomy: definitions and some examples
3. Some case studies:
   1. Municipality typology, which groups socio-energetically similar municipalities
   2. Geothermal analysis: potential for off-grid systems
4. What is the double-edged sword? Towards a framework
5. Summary and conclusions

1. Centralized energy systems

Characteristic(s)	Centralized
Structure	Linear: generation, transmission/distribution, demand
Number of power plants	Few large(r) plants
Ownership/actors	Few large(r) companies
Coordination and control	Generation, transmission and distribution
Predictability	High: supply follows demand
Storage requirements	Low, centralized
Flexibility requirements	Low, Mainly generation and transmission

CHP: Combined heat and power

- **Currently energy use is *dominated* by fossil fuels** (>90% CO2 is energy related): Finite resources, Climate change, Local and global environmental degradation
- Other important aspects: **energy security**, economic competitiveness
- Concept of the **Energy Hierarchy*** has evolved :
  1. Energy efficiency
  2. Renewable energy
  3. Centralised CHP and fossil fuels
  4. (Nuclear)

*House of Commons Environmental Audit Committee 1999, "Environmental Audit - Seventh Report: Energy Efficiency", The Stationery Office, London.

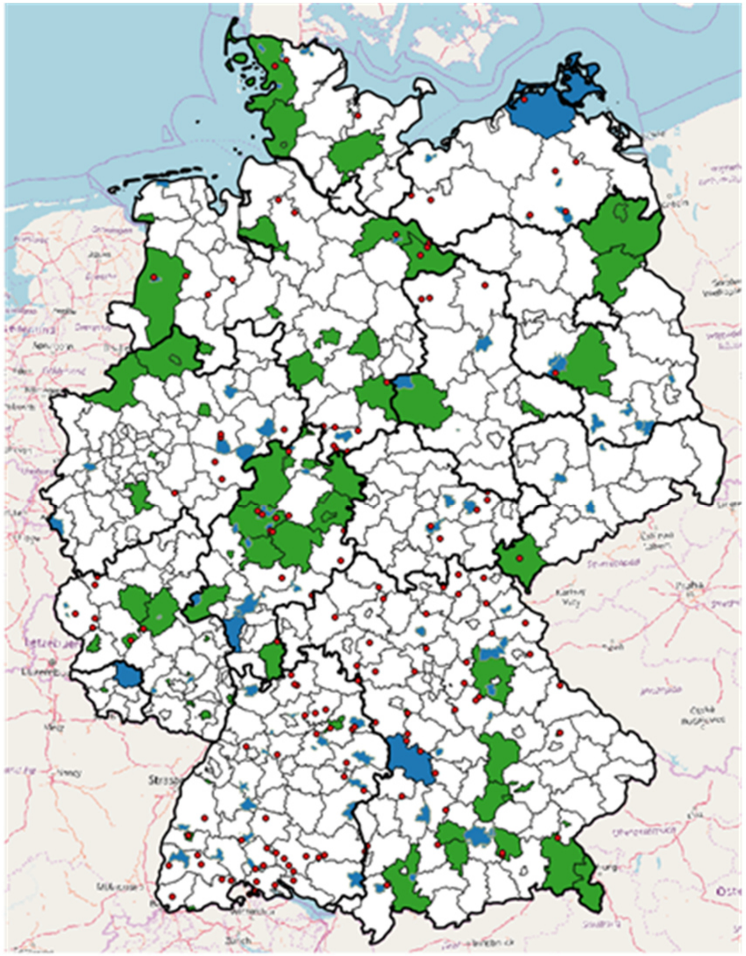
IET 2007, "The IET Energy Principles", The Institution of Engineering and Technology, London.

1. De(-centralized) energy systems

Characteristic(s)	Centralized	Decentralized
Structure	Linear: generation, transmission/distribution, demand	Integrated: • Vertically, between voltage levels • Horizontally, between energy carriers
Number of power plants	Few large(r) plants	Many small(er) plants
Ownership/actors	Few large(r) companies	Many small(er) owners, e.g. private individuals, farmers
Coordination and control	Generation, transmission and distribution	All areas of system
Predictability	High: supply follows demand	Low: supply and demand largely decoupled
Storage requirements	Low, centralized	High, centralized and decentralized
Flexibility requirements	Low, Mainly generation and transmission	Very high

McKenna, R. (2018): The double-edged sword of decentralized energy autonomy, Energy Policy, Volume 113, February 2018, Pages 747–750, https://doi.org/10.1016/j.enpol.2017.11.033.

2. Energy autonomy in Germany



100%-RES-Communities Energy Communities Bioenergy Villages

- Energy transition includes many decentralised plants: 98% of over 1 million (40 GW) of PV are in low voltage networks
- The majority of renewable plants are “community energy”, i.e. private individuals, farmers and cooperatives
- Hence many more contact points between individuals and the energy system
- Growing number of energy projects where municipalities strive for “energy autonomy”, partly due to grid parity (from around 2012):
  - Mostly on an annual basis (net or balanced autonomy)
  - Mostly electricity in focus (Engelken 2016)
- General research statement so far: Complete municipal energy autonomy (CMEA) is feasible, at enormous storage costs (Scheffer 2008; Peter 2013; Jenssen et al. 2014; Schmidt et al. 2012)

2. Definitions of energy autonomy

- We proposed three definitions:
  1. A tendency towards (higher) energy autonomy through decentralized plants
  2. Balanced energy autonomy, i.e. over the year
  3. Complete (off-grid) energy autonomy
- Some indicators:
  – Degree of self-sufficiency: Total onsite generation/total onsite demand
  – Degree of self-consumption: Onsite generation used onsite/total onsite generation
- Most studies and projects employ the second definition and focus on electricity
- Some inconsistencies and unanswered questions relating to:
  – Type of energy autonomy (see above)
  – System boundary
  – Energy carriers
  – Time horizon and resolution
  – Energy service demands
  – Applications and sectors considered
  – Embodied and „grey“ energy imports/exports
  – Considerd technologies
  – Etc.

McKenna, R., Herbes, C., Fichtner, W. (2015): Energieautarkie: Vorschlag einer Arbeitsdefinition als Grundlage für die Bewertung konkreter Projekte und Szenarien, Z Energiewirtsch, 39, 4, DOI 10.1007/s12398-015-0164-1.

DTU

2. Examples of studies analysing municipal energy autonomy

Municipality from	Number of inhabitants	Number of buildings	Average household size [people]	Share of settlements and traffic areas [%]	Population density [Inhabitants /km²]	Number of vehicles per 1,000 inhabitants	
Jenssen et al. (2014)	3,000	800	2.2	n/a	n/a	n/a	Fictitious model municipalities
Scheffer (2008)	10,000	n/a	n/a	n/a	n/a	630	
Peter (2013)	3,850	1,224	3.1	8	106	n/a	
Burgess et al. (2012)	25,550	n/a	2.4	8	310	n/a	Real municipalities
Schmidt et al. (2012)	20,619	n/a	n/a	< 11	68	n/a	
Woyke & Forero (2014)	1,100	n/a	n/a	n/a	n/a	n/a	
Average German municipality	7,380	1,670	2.4	13	183	830	

References: Scheffer 2008; Peter 2013; Jenssen et al. 2014; Schmidt et al. 2012; Woyke und Forero 2014; Burgess et al. 2012

Weinand et al. 2019

2. Relationship between energy autonomy and renewable energies (in Germany, France and Switzerland)

- Survey sample of around 1500 in Upper Rhine Region (URR), 2015
- Familiarity with term “energy autonomy”
  - Overall 42% familiar with the term
  - differed strongly by
    - sub-region: in France 63% compared to 35% and 28% in DE and CH
    - And education
    - And sex: 52% of males knew the term compared to 34% of females
  - Most respondents favoured approaches at neighbourhood, city and regional levels
- Strong correlation between ‘advocacy of renewable energies’ and ‘advocacy of energy autonomy’ in all sub regions and for URR, but not so for *engagement*

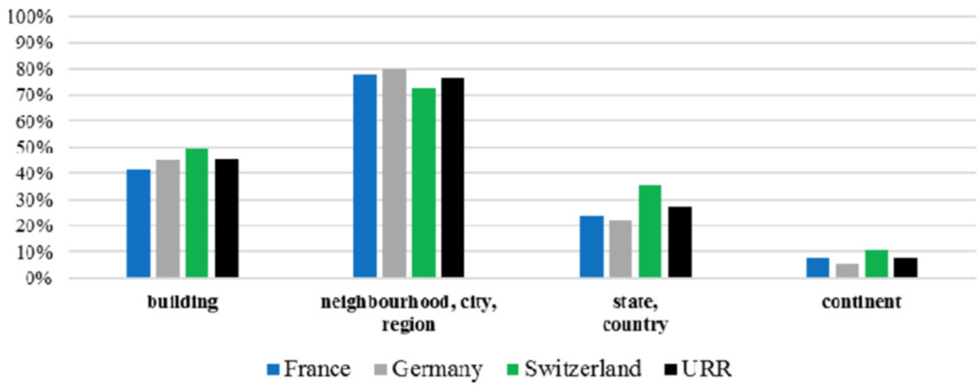


Fig. 6. Frequency distribution of the answers to the question “On what level do you find energy autonomy most appropriate?”. Note: Sample sizes: $n_{Germany} = 495$, $n_{Switzerland} = 493$, $n_{France} = 501$.

Schumacher, K., Krones, F., McKenna, R., Schultmann, F. (2019): Public Acceptance of Renewable Energies and Energy Autonomy in Different Energy Policy Contexts: A Comparative Study in the French, German and Swiss Upper Rhine Region, Energy Policy, 126, 315-332, https://doi.org/10.1016/j.enpol.2018.11.032.

3. Case studies analyzing municipal energy autonomy

- Given the objective to analyse complete municipal energy autonomy

- The research question arises about the suitability of local energy systems for this, in particular:
  1. Is energy autonomy economically and ecologically advantageous for (German) municipalities?
  2. Is energy autonomy more economical when multiple technologies are considered?
  3. How do many completely energy autonomous municipalities affect the overall (German) energy system?

- Two case studies:
  1. Developing a municipality typology for modelling decentralized energy systems
  2. Modelling completely energy-autonomous municipal energy systems with deep geothermal

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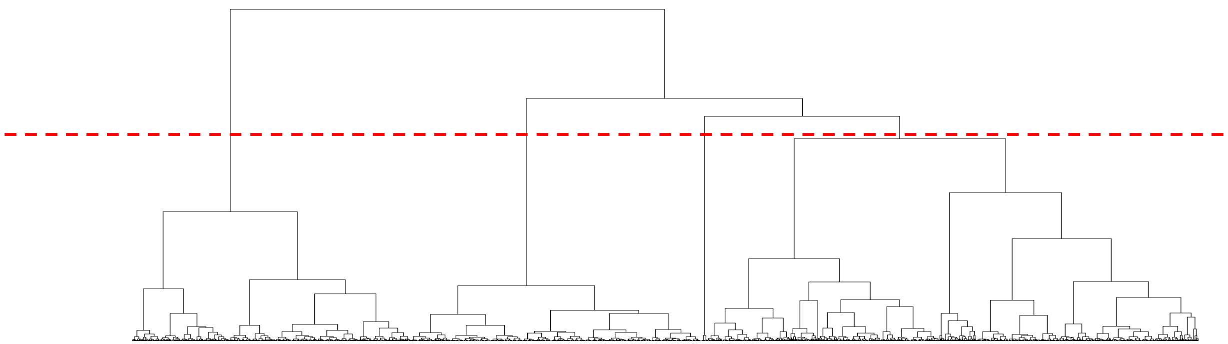
3.1 Methodology – Selection of municipalities:
Introduction of cluster analysis

- Heterogeneous objects are divided into homogeneous groups

Objects	11,131 German municipalities
Variables/Indicators	38 socio-energetic indicators
Cluster analysis method	Hierarchical-agglomerative, Ward algorithm
Criteria used to determine the number of clusters	26 different validation methods, elbow criterion and further analysis
Software used	R

- High quality clusters, better than other cluster algorithms, better availability
- Weakness: Outliers in a cluster
- „Bottom-up“-procedure:



Weinand, J. M, McKenna, R., Fichtner, W. (2019): Developing a municipality typology for modelling decentralised energy systems, Utilities Policy, 57, 75-96, https://doi.org/10.1016/j.jup.2019.02.003.

References: Bouguettaya et al. 2015; Jain and Dubes (1988, p. 140); Cutting et al. (1992); Larsen and Aone (1999)

3.1 Methodology:
Indicators on municipality (Gemeinde) level

Consumption sector Private Households (26)	Consumption sector Transport (4)	Consumption sector Industry and Commercial (1)	Potential for renewable energies (7)
Population development between 2010 and 2015 [%]	Number of motor vehicles per 1,000 inhabitants	Number of manufacturing enterprises per 1,000 households	Achievable hydrothermal temperature [°C]
Living space per person [m²]	Number of cars per 1,000 inhabitants		Necessary hydrothermal drilling depth [m]
Share of single-person households [%]	Population density [Inhabitants per km²]		Technical PV potential per inhabitant [kWh/y]
Average household size [Persons]	18-64-year-olds [%]		Technical PV potential per km² [MWh/y]
Household density [Households per km²]			Technical wind potential per inhabitant [MWh/y]
Share of owner-occupied apartments [%]			Technical wind potential per km² [MWh/y]
Income per household [k€]			Share of forest and agricultural land [%]
Share of over 65-year-olds [%]			
Unemployment rate [%]			
Share of settlement and traffic area [%]			
Share of heating types (3 indicators) [%]			
Share of building age class (9 indicators) [%]			
Share of building type (4 indicators) [%]			

➢ Factor analysis

Weinand, J. M, McKenna, R., Fichtner, W. (2019): Developing a municipality typology for modelling decentralised energy systems, Utilities Policy, 57, 75-96, https://doi.org/10.1016/j.jup.2019.02.003.

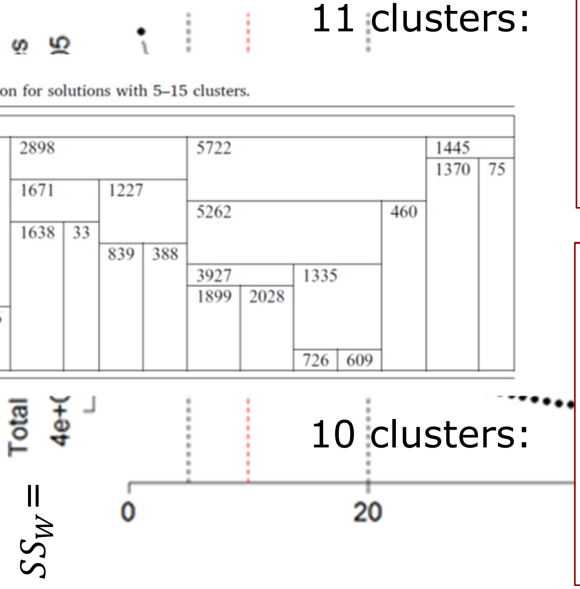
References: Bayri 2017, Wall 2016

3.1 Methodology – Selection of municipalities:
Determination of the number of clusters

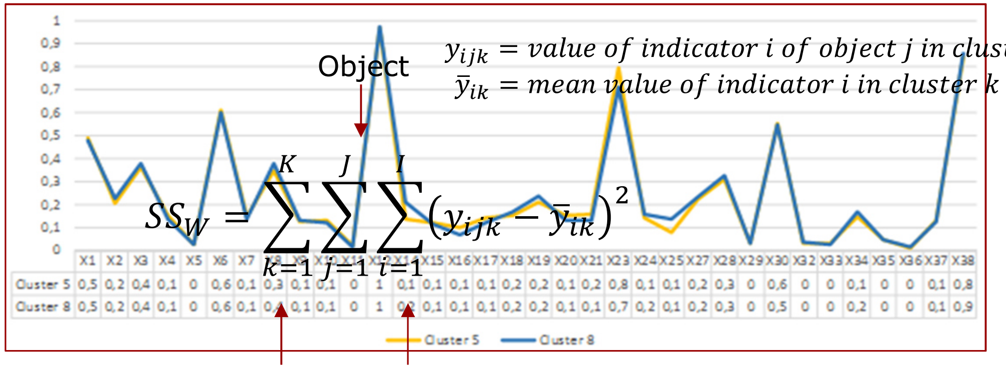
- 26 validation methods: heterogeneous results (suitable method: 10 clusters)
- Elbow criterion
- Further Analysis

Table 4
Development of cluster composition for solutions with 5–15 clusters.

Number	Cluster														
5	339		727		2898				5722					1445	
6														1370	75
7					1671		1227								
8									5262				460		
9					1638	33									
10							839	388							
11									3927		1335				
12									1899	2028					
13			181	546											
14	11	328													
15											726	609			



11 clusters:



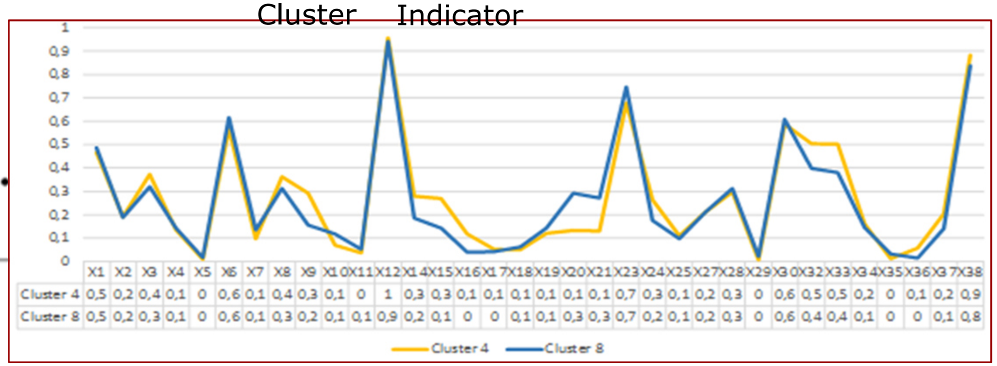
$$SS_W = \sum_{k=1}^{K}\sum_{j=1}^{J}\sum_{i=1}^{I}\left(y_{ijk} - \bar{y}_{ik}\right)^2$$

y_{ijk} = value of indicator i of object j in cluster k

$\bar{y}_{ik}$ = mean value of indicator i in cluster k

	X1	X2	X3	X4	X5	X6	X7	X8	X9	X10	X11	X12	X14	X15	X16	X17	X18	X19	X20	X21	X23	X24	X25	X27	X28	X29	X30	X32	X33	X34	X35	X36	X37	X38
Cluster 5	0,5	0,2	0,4	0,1	0	0,6	0,1	0,3	0,1	0,1	0	1	0,1	0,1	0,1	0,1	0,2	0,2	0,1	0,2	0,8	0,1	0,1	0,2	0,3	0	0,6	0	0	0,1	0	0	0,1	0,8
Cluster 8	0,5	0,2	0,4	0,1	0	0,6	0,1	0,4	0,1	0,1	0	1	0,2	0,1	0,1	0,1	0,2	0,2	0,1	0,1	0,7	0,2	0,1	0,2	0,3	0	0,5	0	0	0,2	0	0	0,1	0,9

10 clusters:



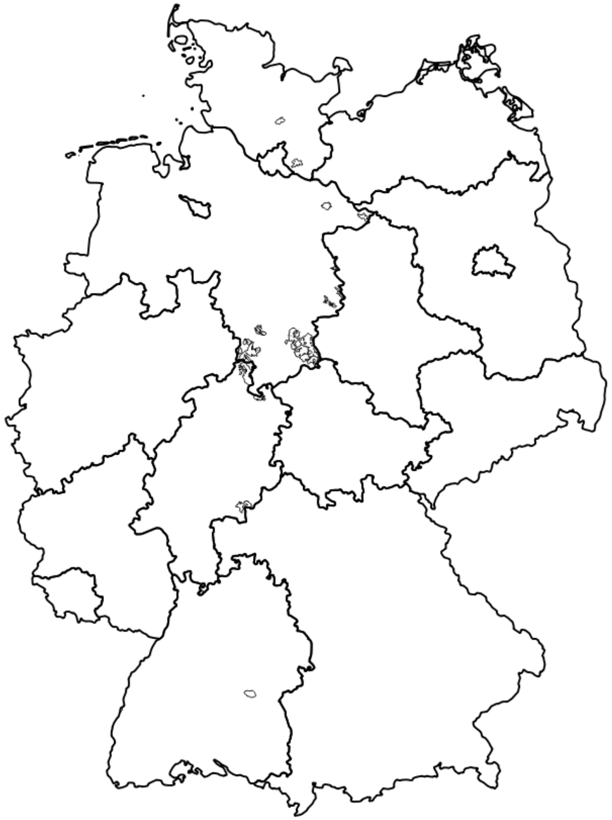
	X1	X2	X3	X4	X5	X6	X7	X8	X9	X10	X11	X12	X14	X15	X16	X17	X18	X19	X20	X21	X23	X24	X25	X27	X28	X29	X30	X32	X33	X34	X35	X36	X37	X38
Cluster 4	0,5	0,2	0,4	0,1	0	0,6	0,1	0,4	0,3	0,1	0	1	0,3	0,3	0,1	0,1	0,1	0,1	0,1	0,1	0,7	0,3	0,1	0,2	0,3	0	0,6	0,5	0,5	0,2	0	0,1	0,2	0,9
Cluster 8	0,5	0,2	0,3	0,1	0	0,6	0,1	0,3	0,2	0,1	0,1	0,9	0,2	0,1	0	0	0,1	0,1	0,3	0,3	0,7	0,2	0,1	0,2	0,3	0	0,6	0,4	0,4	0,1	0	0	0,1	0,8

➢ Number of clusters set to 10

Weinand, J. M, McKenna, R., Fichtner, W. (2019): Developing a municipality typology for modelling decentralised energy systems, Utilities Policy, 57, 75-96, https://doi.org/10.1016/j.jup.2019.02.003.

References: Islam et al. 2016; Arbelaitz et al. 2013; Vendramin et al. 2010; Milligan & Cooper 1985; Tibshirani et al. 2001; Albatineh & Niewiadomska-Bugaj 2011

3.1 Methodology – Selection of municipalities: Results of cluster analysis



Cluster	Objects	Properties
1	339	high share of district heating
2	727	all major German cities, low potential for renewables
3	1638	very high hydrothermal potential
4	839	former GDR, high building age and unemployment rate
5	5262	majority of municipalities (average cluster)
6	1370	former GDR, high building age and particularly low hydrothermal potential
7	460	very high potential for renewables
8	388	former GDR, low building age and minimum proportion of 65 year-olds
9	75	municipalities-free areas
10	33	outlier (high population growth)

➢ Transferability of the results of a case study to all municipalities in the cluster

Weinand, J. M, McKenna, R., Fichtner, W. (2019): Developing a municipality typology for modelling decentralised energy systems, Utilities Policy, 57, 75-96, https://doi.org/10.1016/j.jup.2019.02.003.

3. Case studies analyzing municipal energy autonomy

- Overall objective to analyze complete municipal energy autonomy

- The research question arises about the suitability of local energy systems for this, in particular:
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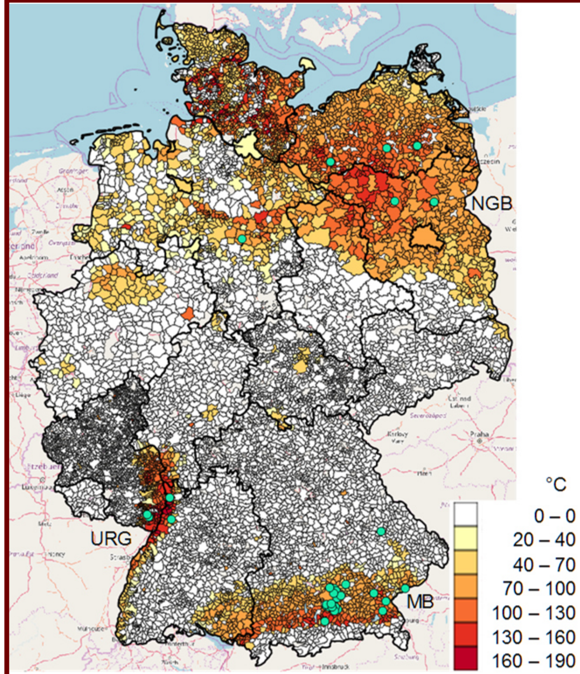
- Two case studies:
  1. Developing a municipality typology for modelling decentralised energy systems
  2. **Modelling completely energy-autonomous municipal energy systems with deep geothermal**

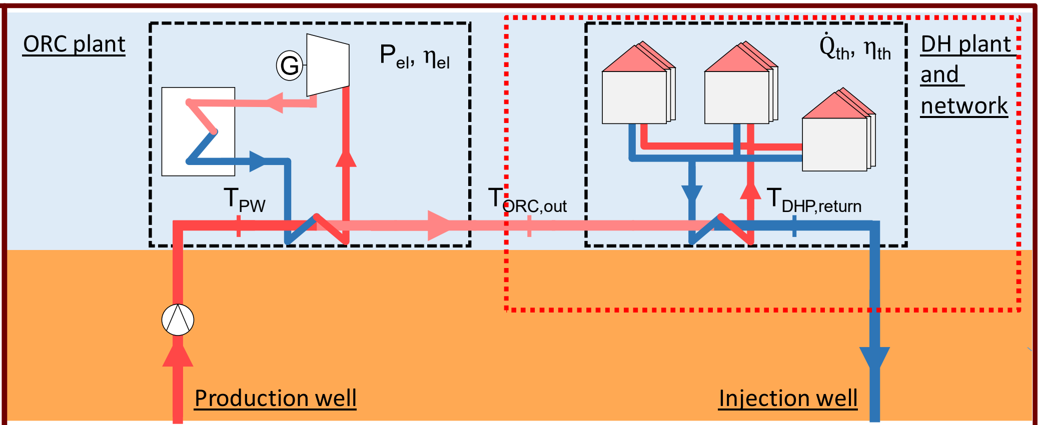
3.2 Modelling a geothermal system: plant (GTP)



Agemar et al. (2014)

● Existing geothermal plants

- Transfer of hydrothermal temperatures
- Different temperature gradients
- Linearisation of cost functions (drilling, ~5 M€/km)



$$\dot{V}_B \cdot \rho_w \cdot c_{p,w} \cdot \left(\boldsymbol{T_{PW}(t)} - \boldsymbol{T_{ORC,out}(t)}\right) = \boldsymbol{P_{el}(t)}/\eta_{el} \qquad \forall t$$

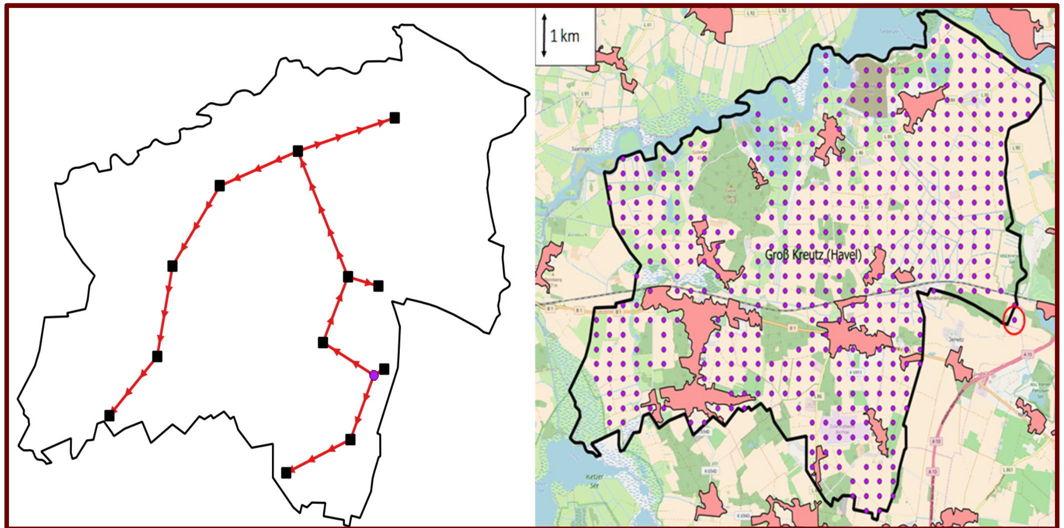
$$\dot{V}_B \cdot \rho_w \cdot c_{p,w} \cdot \left(\boldsymbol{T_{ORC,out}(t)} - \boldsymbol{T_{DHP,back}(t)}\right) = \boldsymbol{\dot{Q}_{th}(t)}/\eta_{th} \qquad \forall t$$

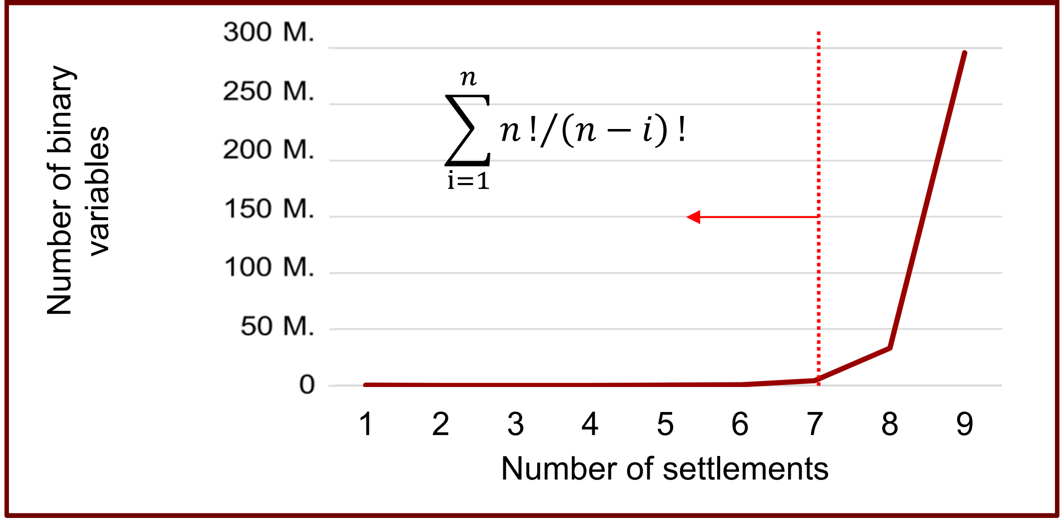
$\dot{V}_B$	Brine volume flow	$\boldsymbol{T_{DHP,back}}$	Temperature after DH
ρ_w	Water density	$\boldsymbol{P_{el}}$	Power generation
$c_{p,w}$	Water heat capacity	η_{el}	ORC efficiency
$\boldsymbol{T_{PW}}$	Temperature before ORC	$\boldsymbol{\dot{Q}_{th}}$	Heat generation
$\boldsymbol{T_{ORC,out}}$	Temperature after ORC	η_{th}	DH efficiency

Simultaneous optimisation of the District Heating Network topology and the Organic Rankine Cycle

Weinand et al. 2019

3.2 Input determination and optimisation of DH network





- Determination of distances between area centroids
- Determination of heat demand using census data
- Determination of building densities in settlements
  - Calculation of heat distribution costs
- Specification of possible GTP locations
  - by excluding areas like water, forest etc.

- DH Optimisation:
  - Costs for pipelines and substations
  - 4 M. binary variables in the case of 7 settlements
    - Duration: Up to 7 days
    - Not feasible above 7 settlements
      - Heuristic

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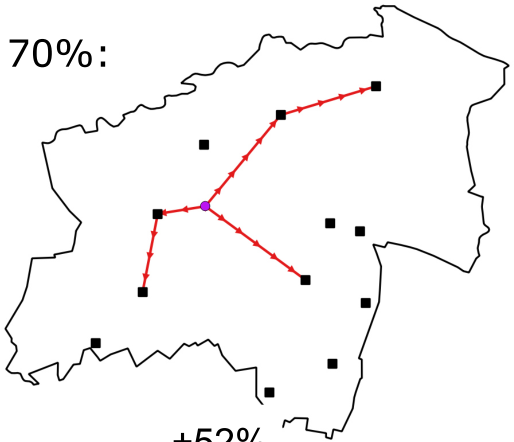
3.2 Integration in RE³ASON and Results

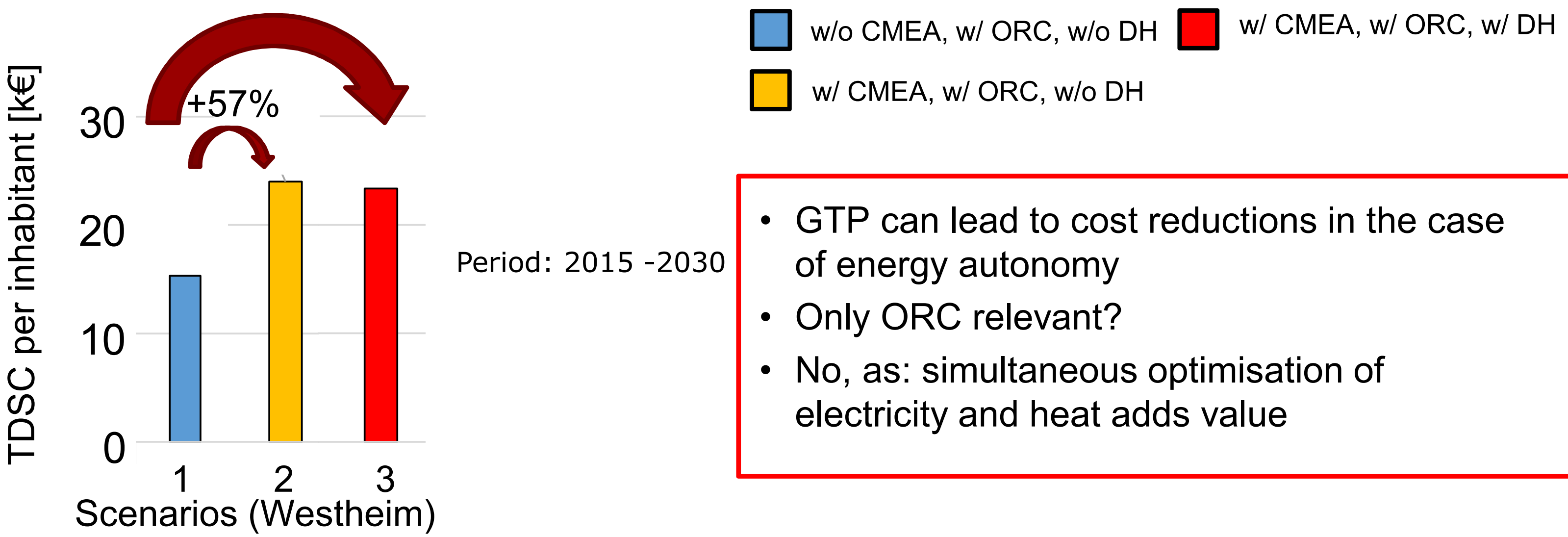


$$\sum_{i=1}^{10} b_{DH,S,i} \leq 1$$

$$\dot{Q}_G(t) \leq \sum_{i=1}^{9} \left(b_{DH,S,i} \cdot 10\% \cdot i \cdot D_{heat}(t) \right) + \left(b_{DH,S,10} \cdot M \right)$$

$b_{DH,S,i}$	which % of heat demand should be covered by DH
$\dot{Q}_G$	District heat supply of GTP
D_{heat}	Heat demand
M	Big M

CMEA = Complete municipal energy autonomy



Period: 2015 -2030

- GTP can lead to cost reductions in the case of energy autonomy
- Only ORC relevant?
- No, as: simultaneous optimisation of electricity and heat adds value

Weinand et al. 2019

*Renewable Energies and Energy Efficiency Analysis and System Optimization, CMEA: Complete Municipal Energy Autonomy

3.2 Method validation

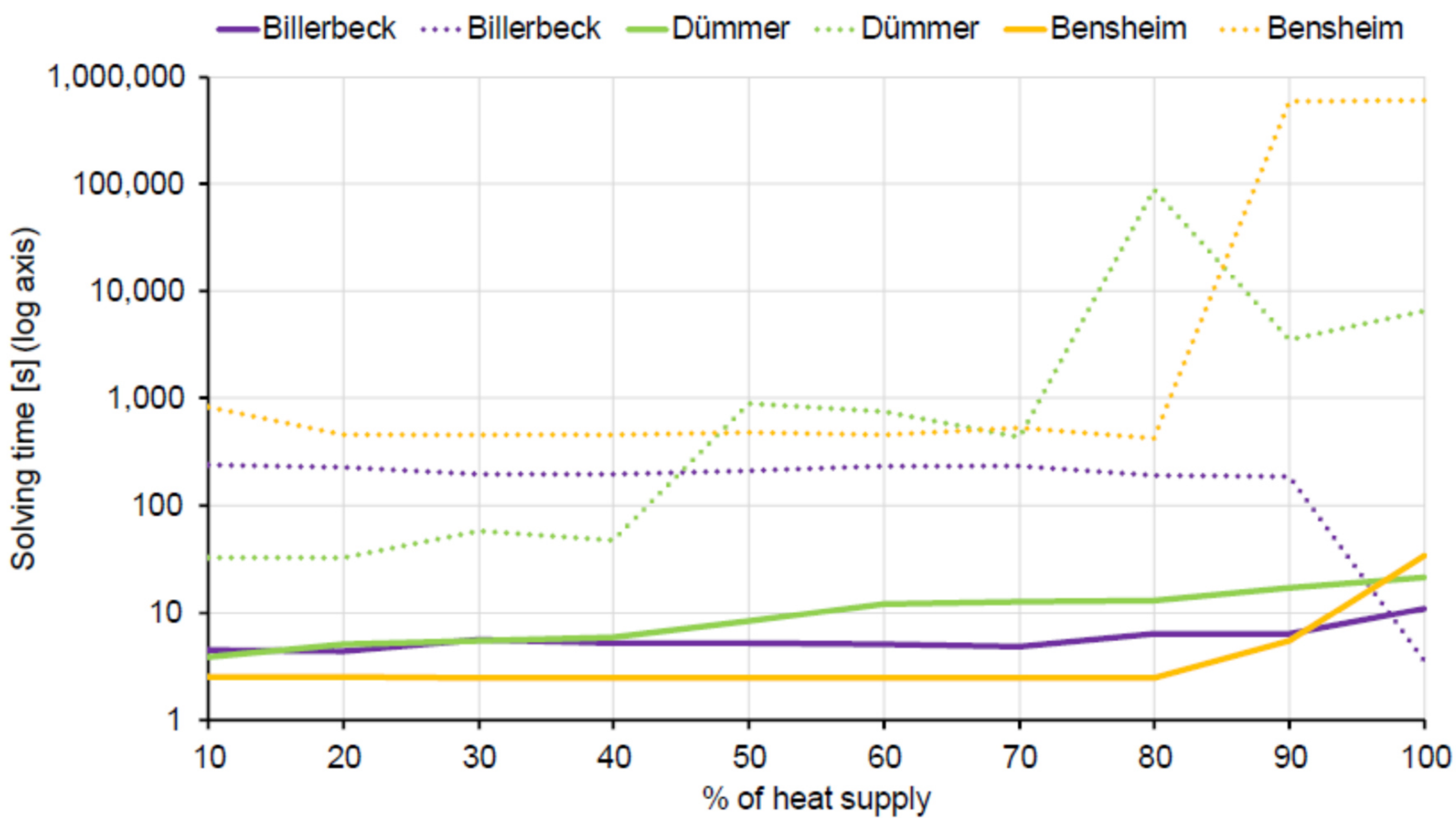


Figure 8: Solving time of the optimisation (dashed lines) and the heuristic (continuous lines) for the municipalities Billerbeck, Dümmer and Bensheim.

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3. Some case studies:
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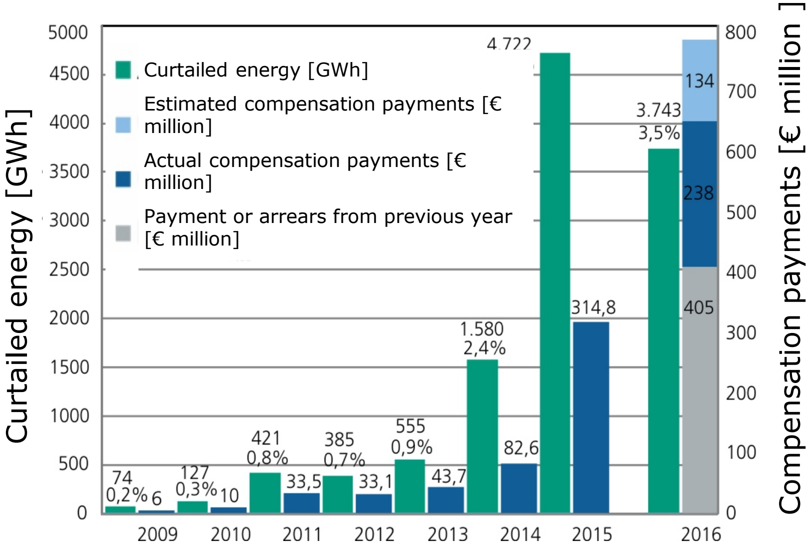
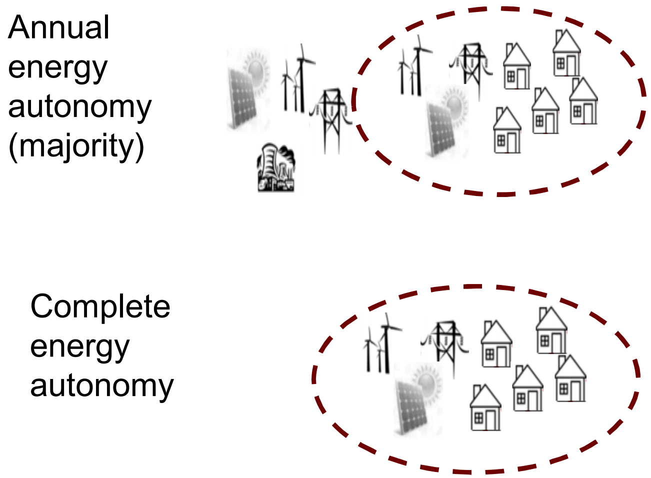
5. Summary and conclusions

4. Aspirations for energy autonomy

- Community energy accounts for over half of capacity in Germany
- Many aim at so-called energy autonomy and use the grid to import and export
- Significant portions of renewable electricity are curtailed (below), balanced energy autonomy can worsen this situation
- But the grid is currently financed by a charge per unit of electricity consumed
- The best case would be a new regulation, i.e. reapportionment system, or failing that complete energy autonomy

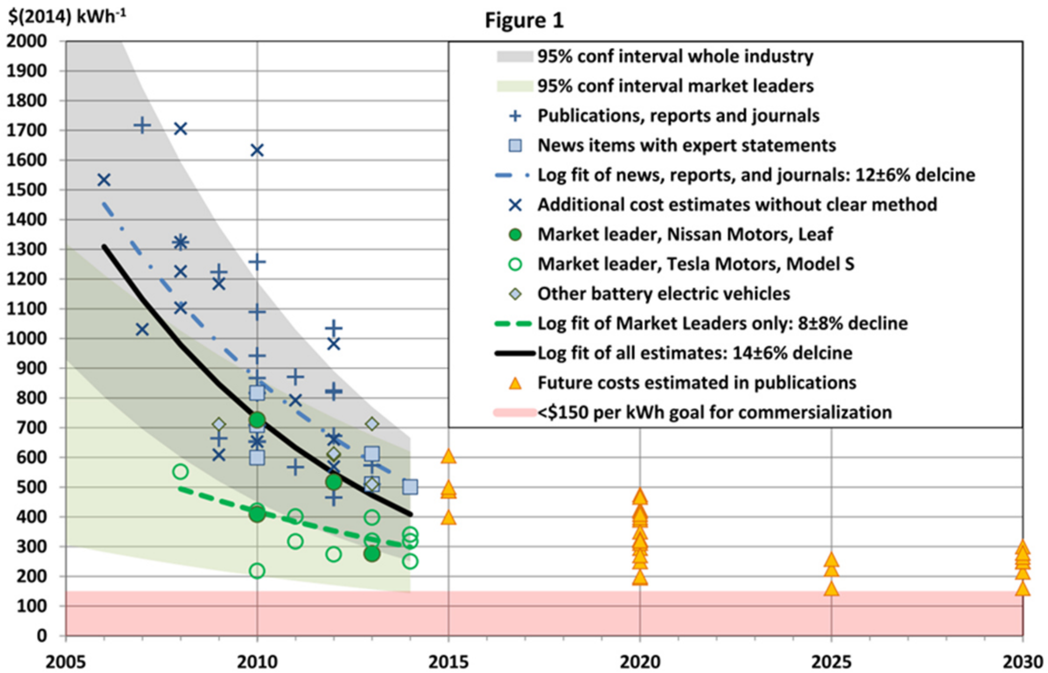




*Fraunhofer IEE 2017, data from BNetzA 2017

4. Increased motivations for complete energy autonomy

- Rapidly falling battery costs (below)



- Achievement of grid parity, e.g. for solar PV in Germany around 2014
- Current (r)evolution underway in energy political framework for regional energy markets and peer-to-peer trading

➢ For some (types of) municipalities, complete energy autonomy could be economical

Nykvist, B., Nilsson, M. (2015): Rapidly falling costs of battery packs for electric vehicles, Nature Climate Change Letters, 5, 329-332, DOI: 10.1038/NCLIMATE2564

4. Framework for analysing the trade-offs of the double-edged sword

- Arguments for aggregating: 1. smoothing/portfolio effects

Figure 3: Correlation of two wind parks depending on the distance of the wind parks and time of forecast. [7]

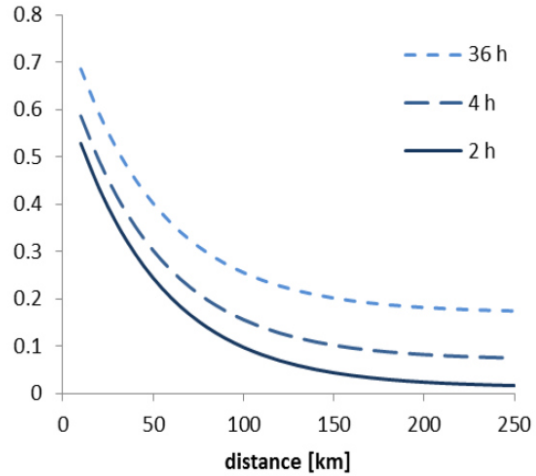
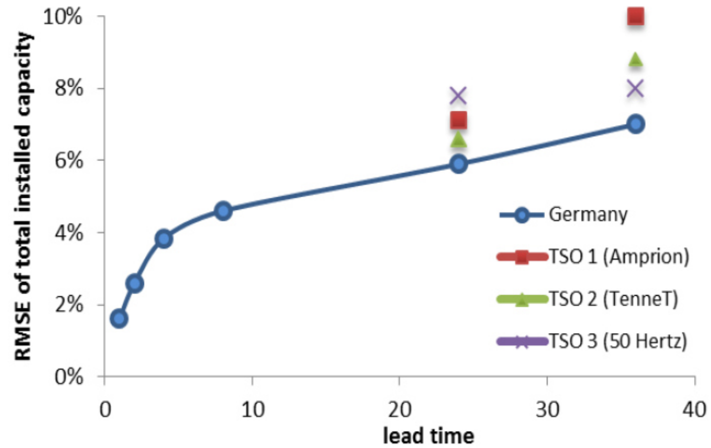


Figure 2: Increasing wind uncertainty depending on the forecast horizon for Germany and three transmission zones[6].



- Arguments for aggregating: 2. economies of scale

Source: Borggrefe, F. & Neuhoff, K. 2011, Balancing and Intraday Market Design: Options for Wind Integration, DIW Discussion Paper 1162, Berlin.

4. Framework for analysing the trade-offs of the double-edged sword

- Arguments for disaggregating: 1. reduced transmission/distribution losses in networks
  - The literature contains some empirical cost functions for distribution networks (e.g. below)
  - But note that this is based on a green field approach as the network exists already and most of the costs are sunk

- Arguments for disaggregating: 2. integration of energy systems: heat suppy is mainly object-based or transported only short distances

- Arguments for disaggregating: 3. existing network can focus on integrated centralised supply from e.g. large wind parks

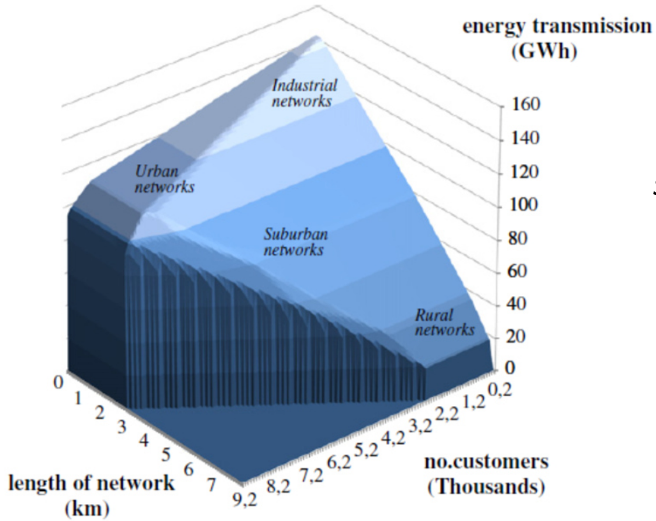
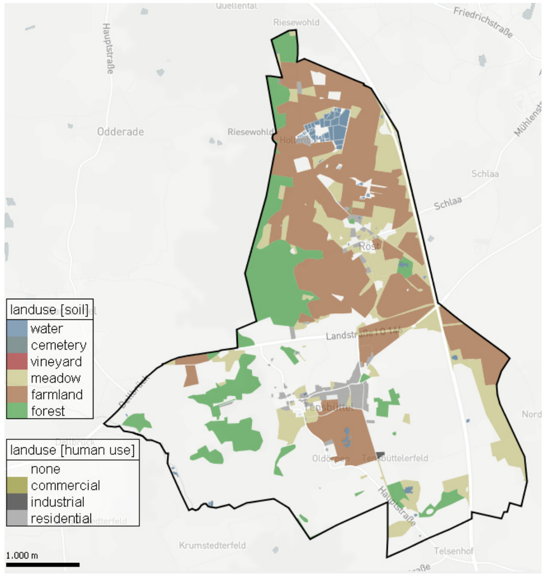


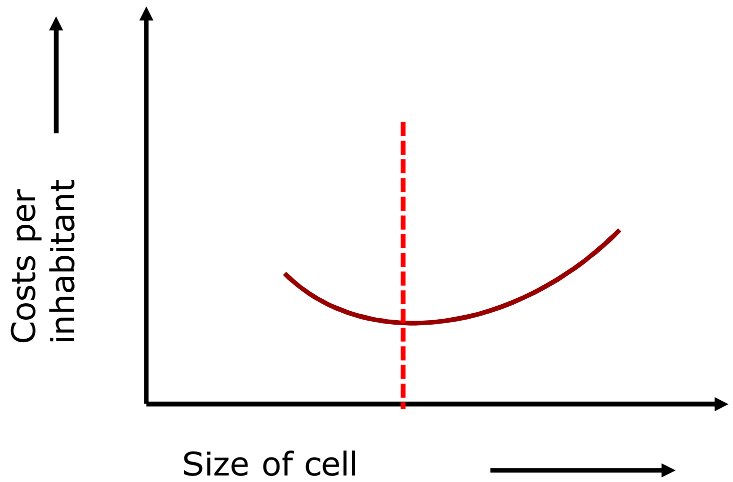
Fig. 1. Three-dimensional illustration of the output set of the estimated StoNED frontier at the total cost of 1 million €.

Kuosmanen, T. (2012): Stochastic semi-nonparametric frontier estimation of electricity distribution networks: Application of the StoNED method in the Finnish regulatory model, Energy Economics, 34, 2189-2199.

4. Framework for analysing the trade-offs of the double-edged sword

- Hence it is likely that there is an optimum economic scale for complete energy autonomy
- Future work should analyse this research question in order to find the optimum economic scale of these energy cells





5. Summary and conclusions

- Transition to decentralized energy systems requires more flexibility, storage, energy system integration > increased complexity.
- Energy autonomy
  - is strived for in many projects, mostly on an annual basis for electricity
  - an assessment framework should consider many diverse facets
- Two (German) case studies of municipal energy autonomy:
  - Municipal typology based on socio-energetic criteria
  - Complete energy autonomy with geothermal cogeneration plants
- The double-edged sword requires new regulation or…
- …adds to other motivations for complete energy autonomy, i.e. off grid
- Future research should focus on the optimum scale for such off-grid systems