

# On the viability of energy communities

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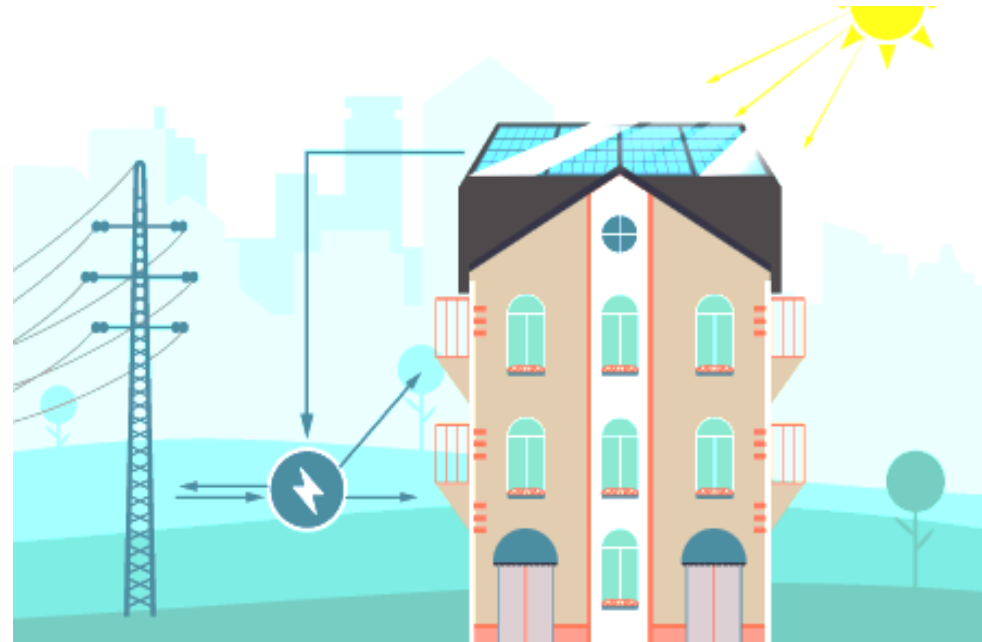
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# SUMMARY

**Part 1.**

**What are energy communities?**

**Part 2.**

**A simple model**

**Part 3.**

**No coordination costs**

**Part 4.**

**Introducing coordination costs**

# “Communauté énergétique ”: un concept en quête d’une définition

Paquet de mesures proposé en novembre 2016

## **Communauté énergétique locale** (Electricity Directive Art. 2(7) )

- (...) une organisation à but non lucratif (...) adoptant une démarche généralement axée sur les valeurs plutôt que sur le profit, active dans la production distribuée et la réalisation des activités d’un gestionnaire de réseau de distribution, d’un fournisseur ou d’un agrégateur au niveau local (...)

## **Communautés d’énergie renouvelable** (Renewable Energy Directive Art. 22(1) )

- une PME ou une organisation sans but lucratif, dont les actionnaires ou les membres coopèrent en vue de la production, de la distribution, du stockage ou de la fourniture d’énergie produite à partir de sources renouvelables(...)

## **Autoconsommation collective** (Renewable Energy Directive Art. 21)

- Les États membres veillent à ce que les autoconsommateurs d’énergie renouvelable habitant dans le même immeuble comprenant plusieurs appartements (...) , soient autorisés à pratiquer l’autoconsommation comme s’ils n’étaient qu’un seul autoconsommateur d’énergies renouvelables.

**Notre cas d’étude: Plusieurs ménages habitant dans un même immeuble décident d’utiliser un compteur unique, et d’investir conjointement dans des technologies renouvelables.**

# Why energy communities?

## Context

- European commission winter package: "Consumers are active and central players on the energy markets of the future"
  - Encouragement of : consumer empowerment, local generation, energy community initiatives
- Communities may bring about significant gains:
  - Overall: communities facilitate the decentralization of energy systems
    - Local management of load
  - Increased consumer participation
  - Better alignment of product with consumer preferences
  - Increased sense of community...

# Some initiatives



## « Energy communities » in the paper

### Our definition :

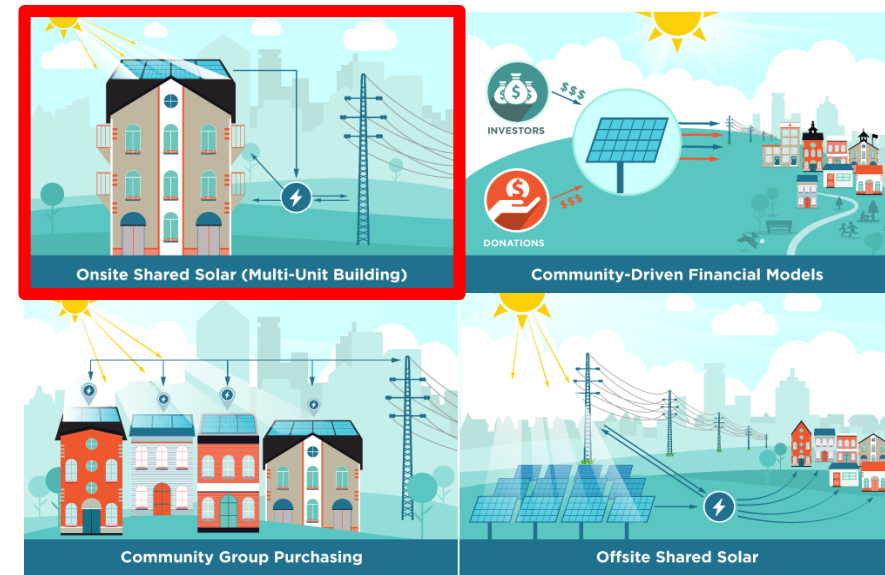
Several households in a given building decide to use a single meter, and potentially jointly install PV.

**Enables PV deployment where it is most needed**

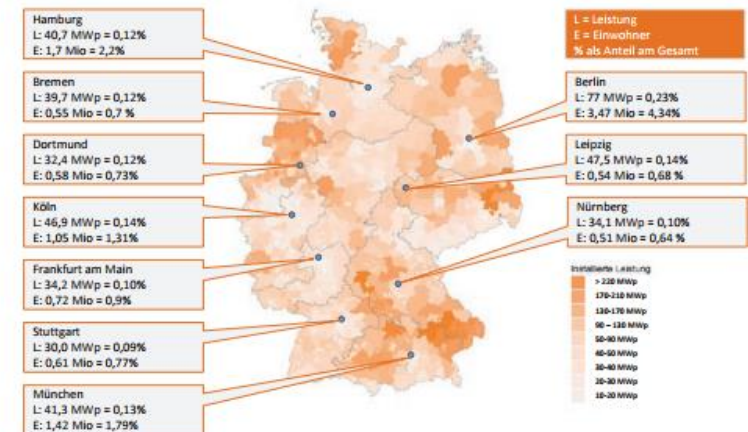
-Most PV is installed in low-populated areas

**Close in spirit to already rolled out « collective auto-consumption ».**

-Cf. Mieterstromgesetz (GY , 3.8 M households eligible)



PV Zubau 2009 bis 2015: Energiewende (noch) nicht in den Städten angekommen



10 Städte mit insgesamt 11,2 Mio Einwohner (14% der Gesamtbevölkerung) mit einer installierten Leistung von insgesamt 446 MW (1,4 % der Gesamtleistung)

## « Energy communities » in the paper

**We focus on:**

**Under which conditions will community participants be able to share gains in a stable way?**

- A subset of the community may find it profitable to exit the community and create one of their own
- Stability is key to success for long-term investment decisions

We disregard (for now) issues of grid cost recovery. The motivation of energy communities is purely financial.

## Existing literature

- Cooperative game theory:
  - Seminal papers: Shapley (1953, 1971), Young (2014), Moulin and Shenker (2001), Moulin (2002)
  - In energy:
    - Allocation of network costs : Contreras et al (2009), Kattuman et al (2004)
    - CO2 emissions: Kellner (2013) , Pierru (2007)
    - LNG: Massol and Tchung-Ming (2010)
- Decentralized energy systems
  - Basak et al. (2012), Lopes (2016), Lidula and Rajapaske (2011), Lo prete et al. (2012), Costa et al. (2008)...
- Lo prete et al. (2016) and Lee et al. (2014) tackle both. But focus is on gain sharing between community and rest of the system
  - Here: gain sharing *within* the community



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**Part 2. A simple model**

**Part 3. No coordination costs**

**Part 4. Introducing coordination costs**

## Base model

- Energy communities defined in the spirit of the mieterstromgesetz
  - Owners/tenants in a collective building can self-consume locally produced electricity.
- A set of households (i.e. consumers)  $I = \{1, 2 \dots n\}$ ,  $n > 1$ , consider joining an energy community.
  - Consumption of household  $i$  over time is denoted  $f_i(t)$
  - Solar profile is:  $g(t)$
  - Share the costs of PV installation
    - capacity is  $\mu \frac{\sum_{i \in S} \sum_{t=1}^T f_i(t)}{\sum_{t=1}^T g(t)} \equiv \sum_{i \in S} k_i$
    - cost of PV installation  $c(\sum_{i \in S} k_i)$
  - Save on grid tariffs
    - household with profile  $f(t)$  pays:  $\alpha \max_t f(t) + \delta$
  - Electricity consumed locally if possible (retail price  $\beta$ )
  - Excess sold to system at market price  $\gamma$

## Base model

- The total value of the energy community is :

**(Aggregation benefits)**

$$\begin{aligned}
 v(S) = & \underbrace{\alpha \left[ \sum_{i \in S} \text{Max}_t (f_i(t)) - \text{Max}_t \left( \sum_{i \in S} (f_i(t)) \right) \right] + \delta(s-1)}_{\text{(Aggregation benefits)}} \\
 & + \beta \sum_{t=1}^T \left( \sum_{i \in S} f_i(t) - \left( \sum_{i \in S} (f_i(t) - k_i(\mu)g(t)) \right)^+ \right) \text{(Self-consumed PV)} \\
 & + \gamma \sum_{t=1}^T \left( \sum_{i \in S} (k_i(\mu)g(t) - f_i(t)) \right)^+ \text{(PV sold to system)} \\
 & - c \left( \sum_{i \in S} k_i(\mu) \right) \text{(PV costs)}
 \end{aligned}$$

- A similar expression holds for all coalitions  $S$  of  $I$

## Stability of the community and the notion of core

**Definition 2.** *The core of the game  $Ker(I)$  is the set of all allocations  $x(v) = (x_1(v), x_2(v), \dots, x_n(v)) \in \mathbb{R}^n$  such that:*

$$\forall S \subset I, \quad \sum_{i \in S} x_i(v) \geq v(S) \\ \sum_{i=1}^n x_i(v) = v(I)$$

- A community is said to be stable if it has a non-empty core.
- Assessing if the core of game is empty can be tricky.
  - Theory: stylized
  - Numerical application: more realistic

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## Convex case: results

**Theorem 1.** *When the investment cost is strictly concave and players are either symmetric or anti-symmetric, the coalition game is convex.*

- This implies the **core is non-empty, and Shapley is in the core**

— **Shapley:** (symmetric, linear, pareto-optimal: reflects marginal contribution of players to coalitions)

$$\forall i \in \{1, 2, \dots, n\}, x_i^s(v) = \sum_{i \in S \subset I} (v(S) - v(S/\{i\})) \frac{(n-s)!(s-1)!}{n!}$$

- Such communities are always stable (phew!)

— However, basic sharing rules (pro-rata) unlikely to be suitable

## Numerical application

**In reality, consumers are neither symmetric nor anti-symmetric!**

- Simulation of several buildings/neighbourhoods composed of 6 households each.
- Abstract away from grid costs (focus on gain sharing)
- Sources:
  - Load from [loadprofilegenerator.de](http://loadprofilegenerator.de)
    - Various households in terms of occupation, children, age...
  - PV costs calibrated on latest observed panel prices
  - PV production curve from ELIA (year 2014)
  - PV gains set at German retail tariffs/ market prices

## Numerical application

- We investigate if the following allocations are stable:
  - Per-capita
  - Pro-rata of volume
  - Pro-rata of peak demand
  - Shapley
  - Minvar (allocation rule in the core that minimizes the inequality of gains)
- We also introduce a notion of stability ( $\approx$  size of the core)

$$\bar{c} = \max c$$

$$s.t. \quad (n-1).c + \sum_{i \in I} x_i = v(I)$$

$$(s-1).c + \sum_{i \in S} x_i \geq v(S) \quad (\forall S \subset I, S \neq I)$$



## Convex problem: homogenous building

Table 1: Building composed of retired people – BAU scenario

	Retired Man	Retired Woman	Retired Couple	Retired Couple	Retired Couple	Retired Couple	Total	In the core?
Annual demand (kWh)	1101	1016	2680	2088	1747	1747	10379	
Peak demand (kW)	5.4	5.1	8.2	7.3	7.0	7.0	40.0	
Individual value	21.5	20.1	50.7	40.5	32	32	196.8	n/a
per capita allocation	57.2	57.2	57.2	57.2	57.2	57.2	343.1	no
per volume allocation	36.4	33.6	88.6	69	57.8	57.8	343.1	no
per capacity allocation	50.3	32.1	68	74.3	59.2	59.2	343.1	no
Shapley	48.6	34.1	83.7	71.8	52.4	52.4	343.1	Yes
MinVar	58	38.4	68	68	55.4	55.4	343.1	Yes
Core is non-empty?	Yes			Installed PV (no coalition): 2.5 kW				
Total value	343.1			Installed PV (grand coalition): 3.6 kW				
Strength of stability	18.2							

Table shows the benefit of investing in PV either individually or jointly (in €/annum)

- Usual, simple allocation rules fail to provide stability
- Some benefit more than others from PV, and from getting in the grand coalition.
- More PV installation when players form a coalition

## Convex problem: heterogenous building

Table 3: Building composed of various consumers – BAU scenario

	Couple Working	Family Working One child	Man Work from home	Student	Storekeeper	Retired Couple	Total	In the core?
Annual demand (kWh)	2623	2613	1601	1563	4003	1747	9930	
Peak demand (kW)	10.1	6.7	2.1	5.4	1.4	7.0	36.3	
Individual value	40.9	23.2	15.2	26.6	196.7	32	334.6	n/a
per capita allocation	82.5	82.5	82.5	82.5	82.5	82.5	495.3	no
per volume allocation	91.8	91.5	56	54.7	140.1	61.1	495.3	no
per capacity allocation	108.4	112.4	55.9	83.3	41.2	94.1	495.3	no
Shapley	63.2	58	33.5	38.7	231.8	70.1	495.3	Yes
MinVar	70	70.7	39.8	41.1	197.4	76.2	495.3	Yes
Core is non-empty?	Yes			Installed PV (no coalition): 3.7 kW				
Total value	495.3			Installed PV (grand coalition): 4.7 kW				
Strength of stability	0.5							

- There is more value overall
- This does not mean more stability
- Heterogenous load profiles => heterogenous rewards

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## Coordination costs

**In reality, energy communities may induce coordination costs**

- Have to meet with neighbours, coordinate on technologies, agenda, sharing rule...
- Assume coordination cost is  $c'(s) = \frac{s(s-1)}{2} c_0$

**Theorem 2.** *When the coordination cost is taken into account and players are anti-symmetric, the following two propositions are equivalent:*

1. *The core of the game is not empty and the Shapley value is in the core*
- 2.

$$\alpha \text{Max}_t f(t) + \delta \geq (n-1)c'(n) - nc'(n-1) \quad (28)$$

- When coordination costs are taken into account, the aggregation benefit of the energy community has to be sufficient to compensate the increase of the marginal cost of the community due to coordination costs, to ensure stability

## Stabilizing energy communities in case of empty core: partitioning

- If the core is empty, we search for a partition that allows the community to be
  1. stable : each smaller coalition is stable
  2. optimal: the partition the value-maximizing partition

**Definition 9.**  *$P$  is an optimal partition of  $I$  if it is stable and provides the highest value among stable partitions:*

- *$P$  is stable*
- *$\forall P'$  stable partition of  $I$ ,  $VP(P') \leq VP(P)$*

## Coordination costs: results

Coordination cost is taken  $c_0 = 5 \text{ € / handshake}$

Table 5: Building composed of various households – BAU with coordination costs

	Couple Both working	Family Working One child	Man working at home	Student	Storekeeper	Retired Couple	Total	In the core?
Annual demand (kWh)	2623	2613	1601	1563	4003	1747	9930	
Peak demand (kW)	10.1	6.7	2.1	5.4	1.4	7.0	36.3	
Individual value	40.9	23.2	15.2	26.6	196.7	32	334.6	n/a
per capita allocation	68.8	68.8	68.8	68.8	68.8	68.8	412.8	no
per volume allocation	76.5	76.2	46.7	45.6	116.8	51	412.8	no
per capacity allocation	90.3	93.7	46.6	69.4	34.3	78.5	412.8	no
Shapley	49.5	44.3	19.7	25	218	56.4	412.8	no
MinVar	n/a	n/a	n/a	n/a	n/a	n/a	n/a	no
Core is non-empty?	no			Installed PV (no coalition): 3.7 kW				
Total value	412.8			Installed PV (grand coalition): 4.7 kW				
Strength of stability	-23.5							
Optimal partition	{Man working at home and student} and {Couple, family, storekeeper, retired couple}							
Value of the optimal partition	426.6	Installed PV:		4.5 kW				

- Core is empty!
- Can find stable sub-coalitions: PV installations still quite large.
- Need for a social planner?

## (Future work) Community formation: A snowball effect?

**Theorem 2.** *When the coordination cost is taken into account and players are anti-symmetric, the following two propositions are equivalent:*

1. *The core of the game is not empty and the Shapley value is in the core*
- 2.

$$\alpha \text{Max}_t f(t) + \delta \geq (n-1)c'(n) - nc'(n-1) = \frac{n(n-1)}{2}$$

- A closer look at theorem 2:
  - The greater  $\alpha$ , the more stable a community
  - Assume two building A and B with  $n_a < n_b$  households such that:

$$\frac{n_a(n_a-1)}{2} < \alpha \text{Max}_t f(t) + \delta < \approx \frac{n_b(n_b-1)}{2}$$

$\Rightarrow$  Community A forms (but not B)  $\Rightarrow \alpha \rightarrow \alpha' > \alpha$  (Cost recovery constraint)

$\Rightarrow$  Community B forms

- **The smaller community may push the bigger one to form too!**

## Potential extensions

- Accounting for incentives to reduce load ( $\sim$  coordination costs)
- Endogenize the PV investment decision when coupling it with an installation and operations of a battery
- Non-economic motivations of the energy community:
  - willingness to go green, become energetically independent, etc.
- Resilience to various tariff structures



## Conclusion

- Communities facilitate PV installations where land is scarce
- Inadequate gain sharing may jeopardize the stability of a community
  - most commonly used sharing rules (per capita, per capacity, per energy) fail to stabilize the community
  - Casts doubts on desirability of strong retail rate control
  - New technologies (personalized billing, individual real-time metering...) are enablers of energy communities
- When coordination costs are introduced, the community is stable only if aggregation benefits can compensate them
  - There may exist an optimal clustering in sub-communities so as to maximize total value
  - need for a social planner?

**Merci!**

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