On the viability of energy communities

Dec 13, 2017

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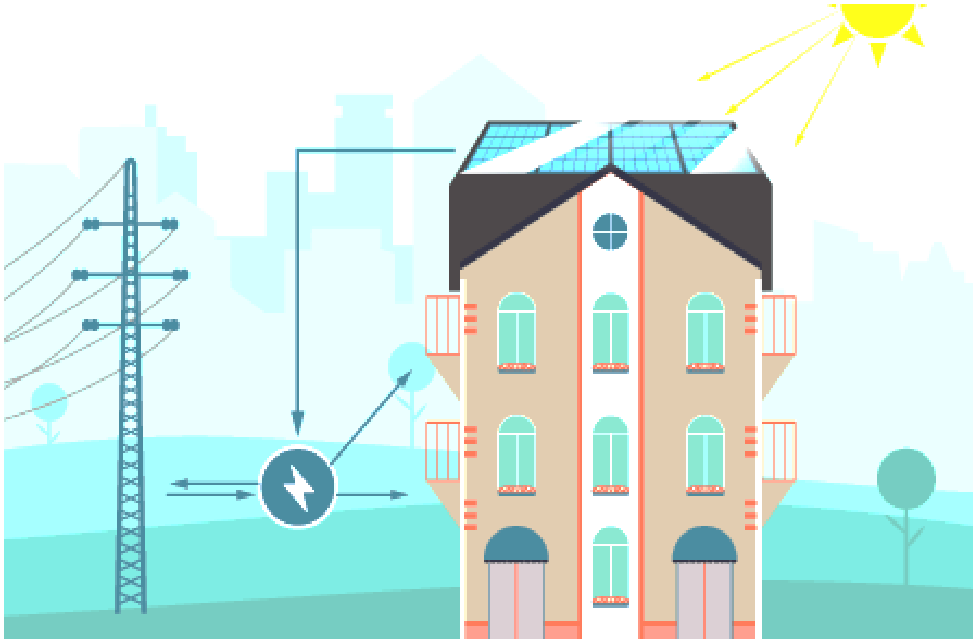


SUMMARY

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

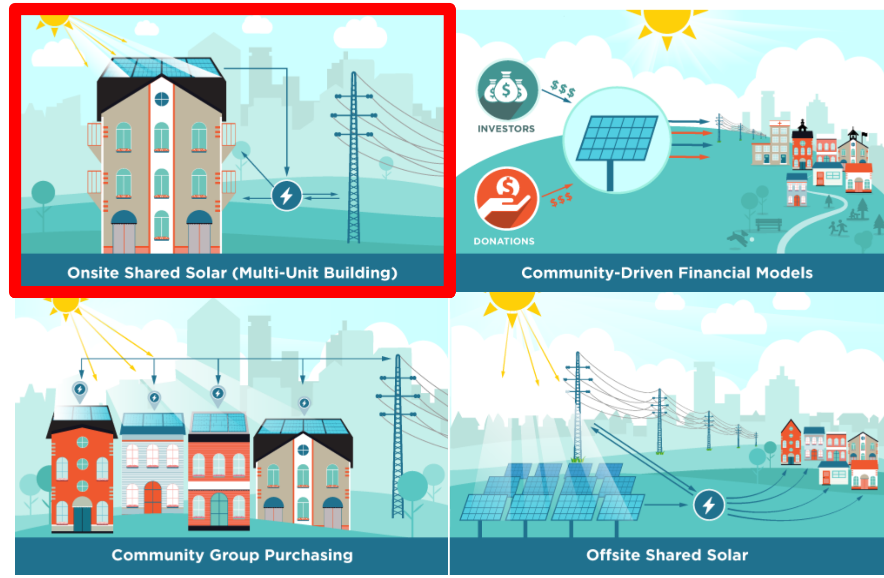
- Communities may bring about significant gains:
  - Overall: communities facilitate the decentralization of energy systems
    - Local management of load
  - Increased consumer participation
  - Better alignement of product with consumer preferences
  - Increased sense of community…

Some initiatives

« Energy communities » in the paper

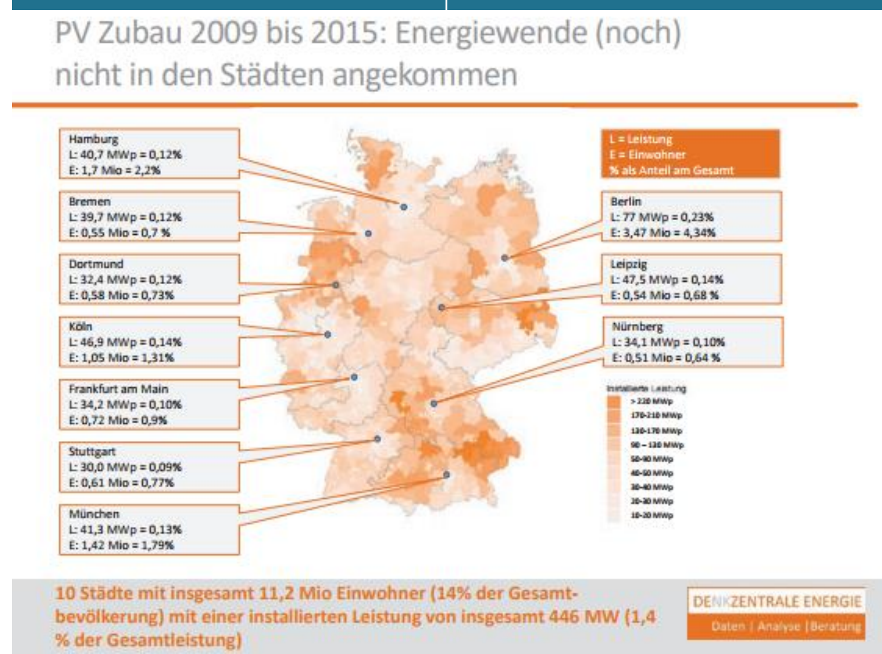
Our definition :

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)

« 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)
    - CO_2 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

SUMMARY

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) $I = \{1,2 \ldots n\}$, $n > 1$, 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 β)
  - Excess sold to system at market price γ

Base model

- The total value of the energy community is :

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

- 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 $x(v) = (x_1(v), x_2(v), ...x_n(v)) \in \mathbb{R}^n$ 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

SUMMARY

What are energy communities?

A simple model

No coordination costs

Introducing coordination costs

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)

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

- 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
    - 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 (≈ size of the core)

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

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
Total value	495.3
Strength of stability	0.5

Installed PV (no coalition): 3.7 kW
Installed PV (grand coalition): 4.7 kW

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

SUMMARY

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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. $$\alpha Max_t f(t) + \delta \geq (n-1)c'(n) - nc'(n-1) \tag{28}$$

- 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 € / 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. $$\alpha Max_t f(t) + \delta \geq (n-1)c'(n) - nc'(n-1) = \frac{n(n-1)}{2}$$

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

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

$\Rightarrow$ 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 (~ 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 (personnalized 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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Appendix

“Energy communities”: a concept in search of a definition

Winter package (proposed Nov 2016)

local energy community (Electricity Directive Art. 2(7))

- ‘local energy community' means: an association, a cooperative, a partnership, a non-profit organization or other legal entity which is effectively controlled by local shareholders or members, generally value rather than profit-driven, involved in distributed generation and in performing activities of a distribution system operator, supplier or aggregator at local level, including across borders.

Renewable Energy Communities (Renewable Energy Directive Art. 22(1))

- a renewable energy community shall be an SME or a not-for-profit organization, the shareholders or members of which cooperate in the generation, distribution, storage or supply of energy from renewable sources (…)

Collective auto-consumption (Renewable Energy Directive Art. 21)

- Member States shall ensure that renewable self-consumers living in the same multi-apartment block, or located in the same commercial, or shared services, site or closed distribution system, are allowed to jointly engage in self-consumption as if they were an individual renewable self-consumer.

We take a case that fits all of these definitions: Several households in a given building decide to use a single meter, and potentially jointly invest in PV.

Stability is not granted!
A simple example: treasure hunt

"An expedition of 3 treasure seekers discover a treasure in the mountains. Taking it home requires 2 people."

Players. There are N= 3 , treasure seekers.

Payoffs. Value of the treasure is 1.

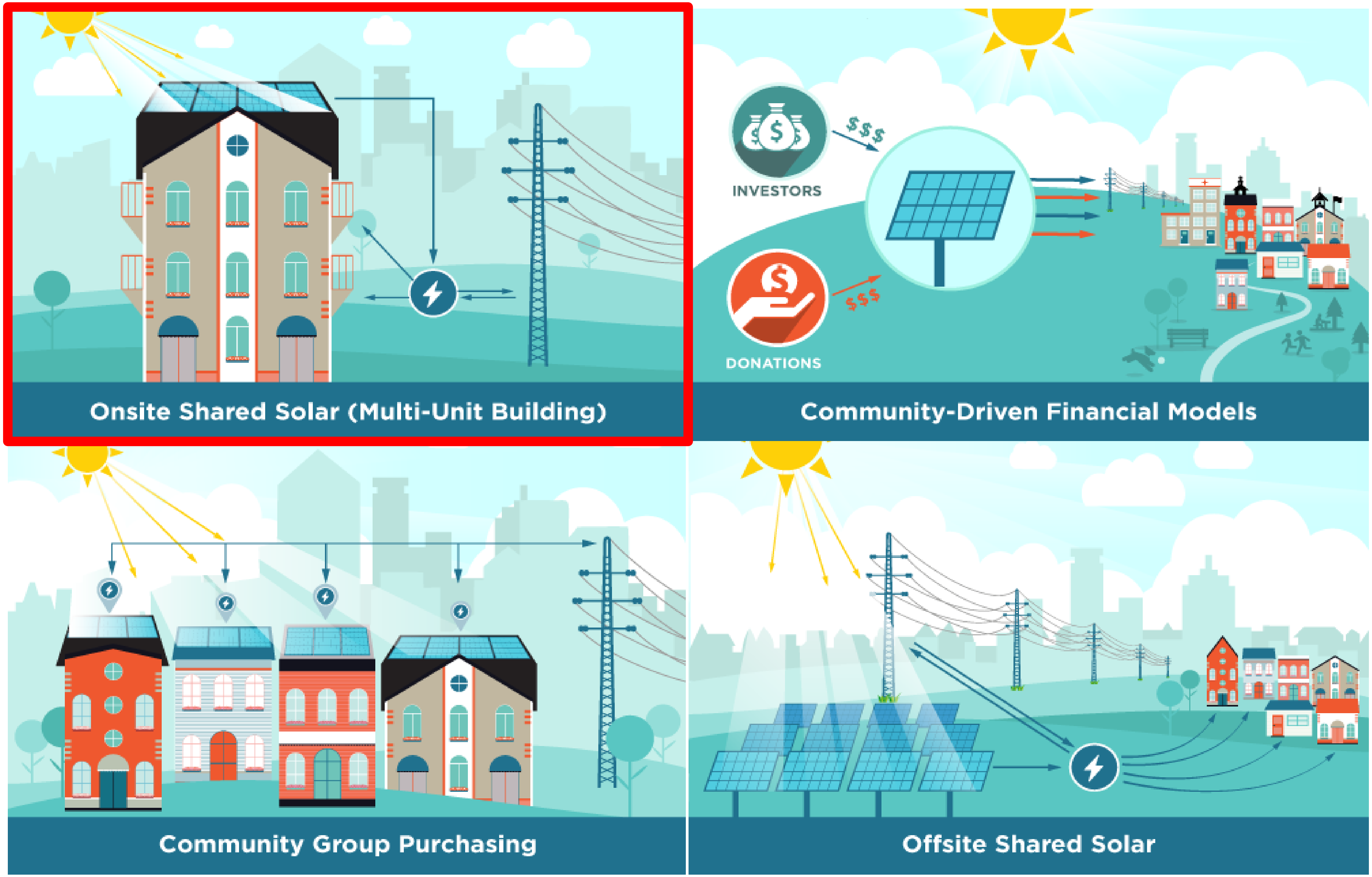
Assume each treasure seeker receives a positive amount of money.

- 2 treasure seekers may choose to exclude the 3rd one and get increased surplus.

Assume 1 treasure seeker gets 0.

- He may team-up with the second least well paid and exclude the best paid treasure-seeker.

⇒ **The game has an empty core!**


Onsite Shared Solar (Multi-Unit Building)
INVESTORS
$$$
DONATIONS
$$$
Community-Driven Financial Models
Community Group Purchasing
Offsite Shared Solar

Appendix

Table 2: Building composed of retired people – TEC 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	42.7	33.2	97.3	78.6	68	68	387.8	n/a
per capita allocation	94.9	94.9	94.9	94.9	94.9	94.9	569.6	no
per volume allocation	83.4	53.2	113	123.3	98.4	98.4	569.6	no
per capacity allocation	83.4	53.2	113	123.3	98.4	98.4	569.6	no
Shapley	78.4	52	136.9	118	92.1	92.1	569.6	no
MinVar	87.9	56.7	118.7	118.7	93.8	93.8	569.6	Yes

Core is non-empty?	Yes	Installed PV (no coalition): 5.5 kW
Total value	569.6	Installed PV (grand coalition): 5.7 kW
Strength of stability	23.6	

Appendix

Table 4: Building composed of various consumers – TEC 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	74.2	65.6	35.1	45	302.8	68	590.7	n/a
per capita allocation	131.2	131.2	131.2	131.2	131.2	131.2	787.4	no
per volume allocation	145.9	145.4	89.1	87	222.8	97.2	787.4	no
per capacity allocation	172.3	178.7	88.8	132.4	65.5	149.7	787.4	no
Shapley	106	112.2	61.3	60	338.3	109.6	787.4	Yes
MinVar	113.3	121.4	69.4	61.5	302.9	118.8	787.4	Yes

Core is non-empty?	Yes	Installed PV (no coalition): 7.0 kW
Total value	787.4	Installed PV (grand coalition): 7.2 kW
Strength of stability	16.5	

Appendix

Table 6: Building composed of various households – TEC 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	74.2	65.6	35.1	45	302.8	68	590.7	n/a
per capita allocation	117.5	117.5	117.5	117.5	117.5	117.5	704.9	no
per volume allocation	130.7	130.2	79.7	77.9	199.4	87	704.9	no
per capacity allocation	154.2	160	79.5	118.6	58.6	134	704.9	no
Shapley	92.3	98.4	47.5	46.2	324.5	95.9	704.9	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): 7.0 kW
Total value	704.9		Installed PV (grand coalition): 7.2 kW
Strength of stability	-26.4		
Optimal partition	{Student} and {Couple, family, Man working at home, storekeeper, retired couple}		
Value of the optimal partition	715.8	Installed PV: 7.2 kW	