Final report

1. Project details

Project title	The Energy Collective
File no.	12530
Name of the funding scheme	ForskEL/EUDP
Project managing company / institution	DTU Elektro
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Project partners	RMIT, WeOU, DFE, University College Dublin, University of California in Berkeley, Radius, Aalborg University, DTU Wind
Submission date	26 March 2021

2. Summary

English: The Energy Collective has the main objective to explore new approaches to future electricity markets, with a special emphasis on community-based and peer-to-peer approaches. This was strongly motivated by recent development related to energy communities, new technologies e.g. blockchain, etc. Eventually, the Energy Collective project gave a large focus on how to design and deploy such novel electricity markets, how those would interact with power system operation, their real-world implementation (here, in the Svalin community in Roskilde, Denmark), and how it fits the regulatory landscape. The project made a number of significant and high-impact contributions, with many influential ideas and publications that were disseminated broadly and internationally. We believe that future electricity markets will have an important peer-to-peer and community-based component.

Danish: The Energy Collective har det primære mål at udforske nye tilgange til fremtidige elmarkeder med særlig vægt på samfundsbaserede og peer-to-peer rammer. Dette var stærkt motiveret af den seneste udvikling relateret til energisamfund, nye teknologier f.eks. blockchain osv. Til sidst gav Energy Collective-projektet et stort fokus på, hvordan man designer og implementerer sådanne nye elmarkeder, hvordan disse vil interagere med driften af elsystemet, deres virkelige implementering (her i Svalin bofælledsskabet i Roskilde, Danmark), og hvordan det passer til det lovgivningsmæssige ramme. Projektet leverede en række væsentlige bidrag med stor indflydelse med mange indflydelsesrige ideer og publikationer, der blev formidlet bredt og internationalt. Vi mener, at fremtidige elektricitetsmarkeder vil have en vigtig peer-to-peer og samfundsbaseret komponent.

3. Project objectives

NB: The Energy Collective project was originally funded as a ForskEL project, and then transferred to EUDP when the ForskEL programme was discontinued. Consequently, the approach to the design of the project and its implementation might differ from what is normally expected for EUDP projects.

Context, motivations and high-level objectives

The way society perceives energy production and consumption is evolving rapidly. The massive deployment of renewable energy generation capacities and the rise of more proactive energy consumers, the so-called "prosumers", e.g., households with solar panels and storage capabilities (residential batteries, heat pumps and electric vehicles), challenge common practices across the energy sector. Today already, one sees that current ICT developments will enable smart devices to act as sensors and share information. Ultimately, they will be able to directly buy and sell their own electricity. Besides, in terms of regulation, there is a general trend to support a more prominent role of consumers (empowering consumers, improving consumers' choice) and a more flexible electricity market organization that would allow them to get improved energy services at the lowest costs. *Status quo is not an option*, since failing in adapting our electricity markets to such a situation will yield increased investment costs, lower reliability in power delivery, and most likely social discontent. The electric energy sector has evolved from an integrated hierarchical structure to a more deregulated model, but still not entirely up to date with the ongoing transformation of the economy towards more open structures. That transformation may be facilitated by the increased presence of open, shared and collaborative platforms as in various domains of the economy from transport to housing, etc. *The benefits of decentralized and deregulated approaches to energy management are many, and for all actors of the energy system*, including better use of existing assets, shared investment burden, easier billing, as well as increased resilience.

In this context, the Energy Collective project first started by envisaging a future of ubiquitous energy sharing among prosumers, and more generally among all actors of the electric energy system. In practice this translates to reshaping the current electricity market towards ***consumer-centric electricity markets***. We aimed at

- showing how such **consumer-centric electricity markets may be readily deployed** (based on a real-world experiment in Roskilde/Trekroner),
- describe the **novel market mechanisms that will rule energy exchanges** among prosumers and with the existing electricity market
- demonstrate that **power system operation can adapt to, and even benefit from**, consumer-centric electricity markets,
- evaluate the **subsequent benefits for consumers and the system as a whole**.

Technological solutions exist to enable this type of decentralized and community-based management approaches, for instance on the cloud or using a blockchain. Instead of considering a centralized data management approach, a blockchain is a distributed database that allows recording information and transactions without third-party supervision. Experience has shown that managing data and transactions through a blockchain is faster, cheaper and more secure than classical centralized approaches. As an example, the possibility to use blockchain as a backbone for financial transactions is seriously considered by Danish Banks like Danske Bank and Nordea. In the energy sector, blockchain technology provides an opportunity for designing consumer-centric electricity markets, benefiting prosumers while simplifying operations for utilities and grid operators. Such technology is to be seen as an enabler, allowing to think of alternative approaches to consumer-centric electricity markets. Consumer-centric and peer-to-peer electricity markets can exist without blockchain though.

From high-level objectives to work themes

The higher-level objective of the **Energy Collective** project was to adapt current market design towards ***consumer-centric electricity markets****.* There may be alternative market models to consider (fully decentralized, i.e., peer-to-peer, or organized through collectives), with their respective advantages and caveats. These may require different data sharing and communication infrastructures, also having an impact on power grid operation. However, besides impact on grid operation, such an organization brings new opportunities in terms of mobilizing customer's flexibility through increased awareness and involvement. Finally, we aim to demonstrate that such a proposal can be readily deployed by building an Energy Collective (see the-energy-collective-project.com) at a community housing site (”bofællesskaber” in Danish) in Trekroner, Roskilde, Denmark.

To realize this higher-level objective, the lower-level objectives of our research then included:

- Building on most relevant **data sharing and communication infrastructures**, as a backbone to consumer-centric electricity markets,
- Proposing a set of **alternative market designs**, for energy exchanges among prosumer communities and out to current electricity markets,
- Appraising **impact on grid operation** practice and its potential adaptation,
- Understanding the **societal and policy implications** of decentralized electricity markets enabled through distributed database technologies such as blockchain
- **Deploying** one of more consumer-centric electricity market**s** and demonstrating their practical interest,
- **Disseminating the concept** broadly for this concept to spread in the future.

Our work was organized in work themes with these various objectives in mind.

Such trends in power systems operation and markets are to be placed in a broader perspective of digitization and increased acceptance of sharing economy principles in our daily lives. The vision of consumer-centric electricity markets and the concept of Energy Collectives build on that background to propose a new paradigm in electricity market organization. The Energy Collective project took a holistic and multi-disciplinary approach to the analysis of this future trend in electricity market development.

Firstly, we took a ***market angle***, by proposing and analysing various consumer-centric electricity market designs, ranging from a fully decentralized approach where each and every actor of the system is an agent of its own directly interacting with all others, to flexible community-based approaches, with virtual energy communities managed by a community manager working in the best interest of its community members (the same way energy cooperatives like *elforbundet.dk* negotiate prices for their members). This novel market organization may support the development of new business models for equipment providers (solar panels, residential and larger-scale batteries, etc.), but also for energy retailers.

In parallel, we took a ***power system operation angle***, to show that, while the challenges brought in by consumer-centric electricity markets and prosumer communities can be identified and accommodated, those may also bring new opportunities. Indeed, one might be critical with the way these markets would operate on existing power grids with their numerous operational constraints. Since power exchanges may be more easily localised, new ways to think of grid tariffs (for instance, as a function of electric distance and most-likely usage of the grid) additionally incentivize further investment in distributed energy management solutions and localised self-balancing.

Finally, we took a ***practical angle***, to show how such markets can be deployed, organized and operated readily, while also illustrating its functioning. For that, we used a practical setup based on community housing site (Svalin bofælledsskaber) in Trekroner. As of today, surplus electric power from the solar power installation from the community housing site is sold back to the grid, while power has to be bought back from the grid at the same time for their shared facilities and electric vehicle charging, or by those houses that do not have solar panels. Here in practice, we showed how that community housing site can locally work on self-balancing and how peer-to-peer transactions may be recorded and valued (i.e., monetized directly or indirectly through Local Exchange Trading Systems).

4. Project implementation

As for any other project, the Energy Collective project had some evolution during its course, some being due to external conditions (e.g., Covid-19, evolution in smart metering solutions, etc.), and some being due to internal aspects of the project (delays in implementing the first metering setup at the demonstration site, international partners changing their level of commitment to the project, etc.). All in all, the project plan was adapted accordingly every time some challenges were faced, in order to insure delivering on the various objectives for the project.

5. Project results

The project achieved tremendous results in many different areas, with high impact internationally. It additionally attracted a lot of attention, mainly on the type of market solutions being developed. The project also became an opportunity to generate synergies with other activities e.g. at DTU, with projects partially supported by EUDP (EnergyLab Nordhavn) and others. It finally brought some opportunities for further development and demonstration at the EU level, e.g., with the EU project EMB3Rs focusing on generalizing the solutions of the Energy Collective project for heat and electricity jointly, with demonstration in, e.g., Nordhavn, Copenhagen.

In the following, we focus on a number of project results related to markets, operations, feasibility of the concepts proposed and their practical implementation, as well as regulatory aspects. A final part covers the dissemination efforts and impact of the Energy Collective project.

MARKETS

Electricity markets are traditionally organized in a way where electricity supply and demand meet through wholesale markets, which are only for large quantities. This means that, in practice, the final consumers like households do not actively participate in those electricity markets. They are active in retail electricity markets instead, where they may have a choice of the retailer they have a contract with, possibly with some extra information on type and origin of electricity. With the advent of prosumers, who may be able to both produce and consume electricity, the starting point of the project was to look at ways to rethink profoundly electricity markets, so that even small consumers may be able to directly negotiate on electricity exchange. A consequence would be that electricity consumers then would readily choose who they buy electricity from, and the type of electricity they would like to consume. Obviously, one cannot control the electrons involved, but from a market point of view, this would still comprise a fundamental change compared to the current situation.

On the market side, the Energy Collective project has proposed some of the first ideas worldwide for the functioning of electricity markets in the novel framework. These two ideas were for instance focused on (i) the specific case of community-based markets (taken direct inspiration from Svalin, but also generalizing to other types of communities) as described in Moret *et al.* (2019), and (ii) the more general case of peer-to-peer markets where each producer or consumer is on his/her own to negotiate electricity exchange, as described by Sorin *et al.* (2019). Eventually, we showed mathematically that such approaches could all be generalized within a unique framework, which additionally generalized the current pool-like electricity markets (Moret *et al.*, 2018; Pinson *et al.*, 2020). The interest of such a novel market framework is that all producers and consumers may directly negotiate with each other, while retaining some of the desirable properties of current electricity markets. An open-source version of the code for such general electricity market setups was also released at https://gitlab.com/fmoret/P2PApp.git.

A disadvantage of those markets, compared to the case of current electricity pools (and with a retail market connection to end-consumers e.g. households), is scalability, since direct negotiation among all actors of the electricity system necessarily becomes intractable. Consequently, the Energy Collective project investigated various ideas and angles that would allow to find the right balance between centralized approaches and the full decentralization that peer-to-peer markets entail. Different hybrid designs can be feasible, and a hierarchical "Russian doll" approach appears to be the most relevant (Sousa *et al.*, 2019). In parallel, we investigated approaches that were more focused on the computational and mathematical aspects, and which may allow to support such large-scale decentralized negotiation. This led to a focus on rethinking the core optimization framework within an online and asynchronous environment (Guo *et al.*, 2021a; Guo *et al.*, 2021b), with the benefit of substantially lightening the computational burden, and allowing for agents to negotiate in an asynchronous manner.

In parallel, we looked at how novel assets may be considered in such markets, in view of the feedback we got from industry, e.g., in relation to storage and P2X/hydrogen. This led to a number of works, where we looked at how the design of local electricity markets may jointly consider electricity and hydrogen (Xuo *et al.*, 2018), but also how to design market mechanisms to optimally utilize shared storage within a community or a peer-to-peer setup (Thomas *et al.*, 2019).

On a final (and more exploratory) note, emphasis was placed on two aspects of the markets that are normally not considered, while they are clearly of importance when it comes to prosumers – these are risk and bounded rationality. For instance, the work in Moret *et al.* (2020) looked at the impact of heterogenous risk preferences of prosumers in a peer-to-peer market, and their impact on market-clearing. It then proposes an ideal mechanism and set of hedging mechanism that allows counter-balancing the unfairness that may arise due to such varied risk preferences. In parallel, whole the assumption that market agents are rational may be acceptable when looking at wholesale markets, when considering prosumers in such community-based and peer-to-peer markets, the fact they are rational is highly unlikely. Consequently, the work in Radoszynski and Pinson (2020) was a first try at assessing how bounded rationality could be modelled, and what its impact may be on the flexibility of prosumers. As the problem is quite complex, the setup was highly simplified to get some interesting insights – however, much more work may be needed to fully appraise the impact of bounded rationality in such electricity markets.

Operations

It may be seen as challenging to design and deploy community-based and peer-to-peer electricity markets, even if considering the market component only (i.e., the set of transactions among agents). However, electricity is a special commodity, with stringent operational constraints – hence, implementing such markets while accounting for operational aspects is much more complex. This is actually one of the reasons why, so far, most foresee the deployment of such market structures at the local level (low-voltage level, community under the same electric bus, etc.), while those countries who regulated towards trying out those new market structures have also restricted themselves to such levels. Only a few business models e.g. for PowerPeers in the Netherlands, overlook those operational aspects and do not restrict themselves to a certain type of agent in the system or physical location.

On the operational side, a first challenge that was identified early in the project is that for prosumers to participate in community-based and peer-to-peer markets, they need to use their marginal utility functions. They most certainly do not know their marginal utility functions, as they are simply to complex to design and estimate. We have therefore investigated approaches to design markets that would not require agents to use marginal density functions to participate, while also developing some novel ideas to automatically learn and estimate those marginal utility functions (Ziras *et al.*, 2021).

Considering this idea that community-based and peer-to-peer markets may only be localized, we have investigated alternatives organization approaches. For instance, Figure 1 shows what the community-based and peer-to-peer approaches look like, while these may be generalized into a hybrid approach, also shown in that Figure. Eventually, we have managed to generalize all those potential organizations and architecture into a single unifying framework (Moret *et al.*, 2018; Pinson *et al.*, 2020). An extensive overview of that work, also touching connections with business models is given in Sousa *et al.* (2019).

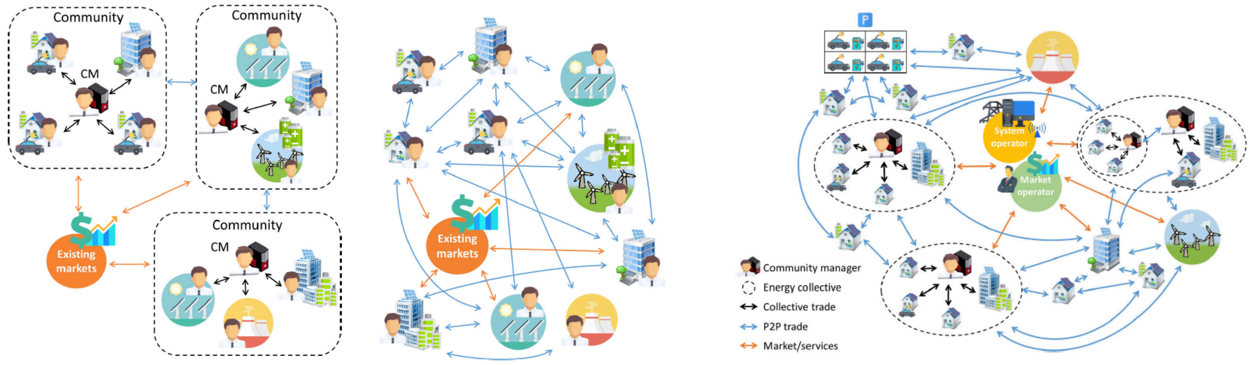

Figure 1: *Community-based (left), peer-to-peer (middle) and hybrid (right) organizations*

Obviously, one of the main aspects of concern to systems operators (at both transmission and distribution levels) is about how such novel market mechanisms may affect operations. Therefore, in the frame of the project, a co-simulation environment was developed in order to be able to look at how *(i)* market layer, *(ii)* communication layer, and *(iii)* operational layer, may interact with each other. This environment then allows to simulate how energy communities may locally affect power grids, but also may be used to see how communities may provide services to system operators.

In practice, it means that operational aspects and restrictions should also inform community-based and peer-to-peer electricity markets. We have formulated and analysed an original proposal, which makes that the network charges (i.e., grid-related costs, but could also consider policy-related costs) are made a function of the stress induced by each and every trade, between the prosumers (or, more generally, producer and consumer) involved. As of today, network charges are socialized in the sense that they are not a function of the actual network usage, expect for the proportionality on energy quantities. However, in a community-based and peer-to-peer electricity market, one may actually localise the trades, which means that one may readily assess the impact of that specific trade on grid operations. Our proposal then consisted in using electric distance between agents (since it is that distance which is of relevance, and not geographical distance only) in order to re-define network charges – see Baroche *et al.* (2019). The two consequences are that grid-related costs are allocated in a way that may be seen as fair, but also that agents in the market engage in trade that decrease the stress on the power grid and its operation. We have then generalized that idea looking at various types of assets, network levels (transmission and distribution), and loss allocation rules, as described and discussed in Tosatto *et al.* (2020).

As mentioned in the above, a large part of the work related to operations was focused on looking at how energy communities (bound together through a community-based electricity market) may be able to provide services to system operators. Interestingly enough, one realizes that those may readily function as aggregator, with the only difference that aggregators act as for-profit agents, while energy community managers do not – hence, all potential profits coming from service provision are re-distributed in a fair manner to all community members who, de facto, are those providing those services. A specific example is that of prosumers, within community-based and peer-to-peer markets, negotiating on both energy and reserves (i.e., on allocating parts of their capacity to accommodate deviations from original schedule). This proposal by Guo *et al.* (2021a) may then be seen as a generalization of current processes for the procurement of reserves. Another one was to consider that prosumers may be aggregated within that system in order for them to act as a retailer, or more generally as a single entity within wholesale markets (Xiao *et al.*, 2020).

Feasibility and practical implementation

Some of the methods developed during the project were investigated in the context of a co-housing community called Svalin. Svalin is a modern danish neighbourhood in the vicinity of Roskilde. It was designed as sustainable co-housing community of 20 private house and a common house collectively owned by the 20 households. To achieve the goal of being energy self-sufficient on a yearly basis, each house and the common house were equipped with solar PVs, and a collective ground heat pump located in the common house. 2 hot water pipes, one for ground heating, and one for hot water as well as an electrical cables connect all the houses energetically to the common house forming a micro-grid. The common house itself is connected to the public electrical network. Because the houses are independently privately owned, and of the public danish regulation on electricity, each house were equipped with private electrical meters and are forced to buy and sell electricity to different actors in the national electricity system.

During the project several additional energy systems were installed to measure and control some of the aspects of the energy activity in Svalin. 17 houses and the common house were equipped with smart meters systems to measure the electricity going inside and outside the houses. Two types of smart meters were investigated. In the first phase of deployment, 5 houses were equipped with custom designed micro-computers with IR probes extracting data from the existing electricity meters installed originally in the houses. This worked quite well until Radius, the local district operator responsible for the deployment and maintaining the meters, decided to upgrade the meters to a new technology able to be remotely probed by the company. Unfortunately, the new meters were equipped with an encryption technology making it impossible to read locally the data using an IR probe system. Instead, we had to use another smart meter system to get access to the electrical data of the house. The only practical way we could find, was to use a system designed by Smart-Me, a German start-up offering a cloud-API to the data. This had several implications for the project, both in delaying and shortening the experimental phase of the project and on the applicability of blockchain technology, as we will be discussed later in this section. The project also installed common smart charger connected to the common house. The smart charger, developed by another group at DTU Elektro, could identify the car owners using a RFID sensor, and modulate the charging amplitude programmatically.

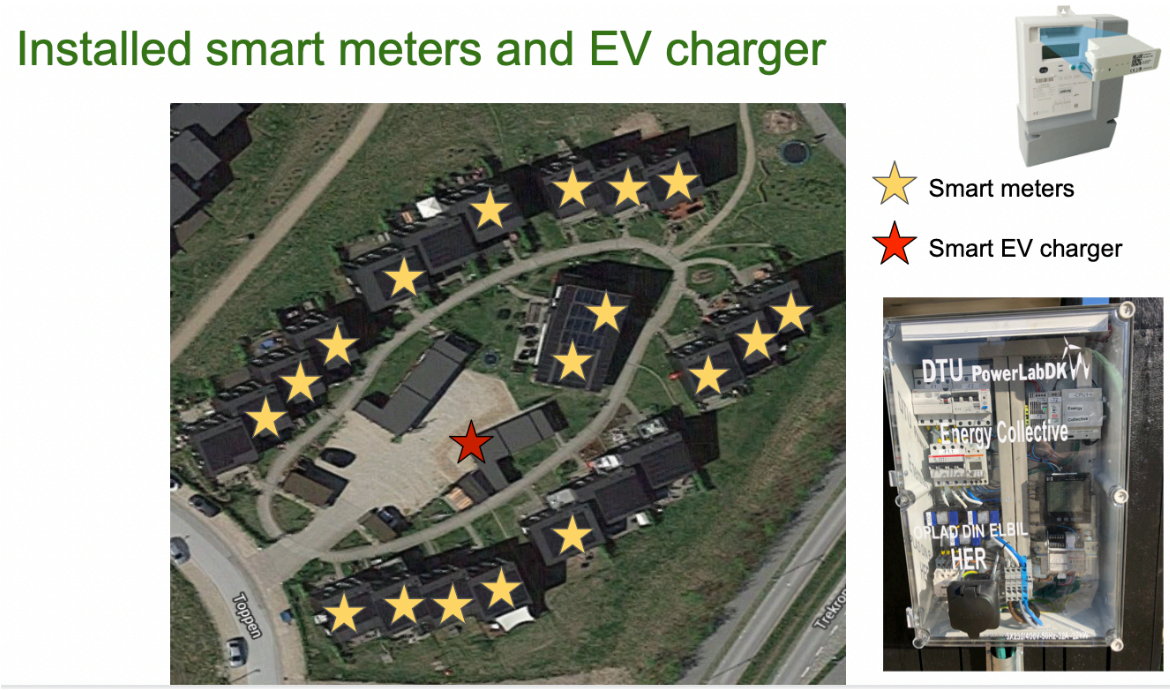

Figure 1 Installed smart meters and EV charger in Svalin

One of the technologies we wanted to test in the context of this project was the blockchain technology, which promised the possibility to create a decentralized p2p energy market between houses. At the time of the project, the technology was still very young and immature, with limited toolsets and frameworks available to develop on it. Moreover, the characteristics of the blockchain platform investigated (i.e. Ethereum) at the time, meant that recording data on it was prohibitively expensive and the blockchain itself had a carbon-footprint very high per transaction. While the Ethereum blockchain programmers have promised for many years to move to a different consensus mechanism than Proof-of-work, which is responsible for the extremely high electricity cost of the network, and to develop scalable solutions, very limited solutions were available at the time of the project. As the blockchain technologies mature, there is common trend of moving away from proof-of-work consensus mechanism to proof-of-stake, which offer a major decrease in computational expenses. Ethereum blockchain, for instance, has planned to release a new version that will expend both the number of transactions per seconds and move to proof-of-stake. This will most likely significantly reduce the cost of transactions both in currency and in energy. At the time of the project, however we could only test a so-called “layer-2” solution, called the Raiden Network, which enable us to quickly trade between two parties’ tokens representing energy transactions. This offered limited capability to develop a decentralized energy market, as most of the market-maker mechanism would have to be operated off-chain in a centralized sever, and thereby requiring centralizing a lot of the information. Additionally, because of the data-gathering service, Smart-me, that we had to use, the data itself was being centralized in a third-party cloud solution. This undermined the whole premise of using a blockchain for decentralisation purpose. Finally, it was found that in the context of Svalin, where there is a lot of trust in-between the neighbours and already a centralisation of part of the community economy through an administrator, there was little need for a decentralised solution.

Once the prototype of blockchain solution was put on hold, we focussed on developing a centralized solution based on internal database. The concept we developed was to have each house running an automatized agent, trading energy through a local peer-to-peer energy market. The agents retrieved the energy data from the smart-me cloud service, predicted their next 5-minute consumption needs and production, and would bid on a local market. A market-maker would then take in all the bids and settle the transactions every 5 minutes. The market-maker could also include virtual actors, like the neighbouring community (Bakketoppen), the common-house heat-pump and shared smart charger, and a virtual wind turbine. Several prototype of real time trade illustration system were designed and presented during workshops.

The method was deployed live on a server localized in the common house of Svalin and has run autonomously for the last 10 months of the project. Some proof-of-concepts were developed on the system, to showcase how the market maker could start/stop the common charger based on various criteria (e.g. if there is enough local energy in Svalin). The market maker can also derive from its trades a local CO_2 intensity metric, characterizing the theoretical amount of gCO_2/kWh at any given time in the micro-grid of Svalin. The metric characterize how green is the electricity by merging data from the national grid (based on a value accessible through the ElectricityMap.org server), with the data from the trades of energy between the different agents. This metric was then illustrated in Svalin by changing the colour of the outdoor pathway lights, visible from each house kitchen windows. A green colour would indicate if the electricity was of low CO_2 intensity, and red would indicate a high CO_2 intensity. This enabled the inhabitants of Svalin to adapt their electricity consumption according to the colour of the outdoor lights.

Apart from the light indicator, there was little involvement and interest of the neighbours in the project. The project participants organised several workshops and events around the project to disseminate the activities and finding of the project to the inhabitants, but few inhabitants were interested enough to attend to the events. Part of the reason could be attributed that the experiment was delayed due to the smart-meter deployment technology. This meant that there was not enough time to apply demonstrate how the measurements and p2p-market system could be used to inform the decisions around energy made by the inhabitants. Another reason for not being able to involve more the inhabitant of Svalin in the project was that during the last year of the project the COVID-19 social restrictions seriously reduced the amount of social activities organised in the community.

Figure 2 Colour changing pathway lights indicating the current CO2 intensity in the micro-grid

Despite these unfortunate limitations, the involvement and interest from inhabitants in the project were not as high as we could have hoped for. Considering that Svalin is a community with quite an exceptional focus on energy matters, as per their original goals, it is likely that similar concepts would have even less interest from the general population in a different setting. While the theoretical results from the project indicate that the concept of local p2p energy market could make sense in the context of a large city-building with roof-top solar, or a larger neighbourhood, or even at a city scale, it seems likely that the concept would have to be based on economic incentives in order to motivate the users to act differently. Unfortunately, the current regulations in Denmark do not allow to create such economic incentives yet. There is however hope that the recent EU directive about energy communities will enable and incentivise these types of setup in the future.

Finally, as a more general contribution, the Energy Collective project participated in an international comparison of similar experiments towards energy communities and community-based electricity markets, resulting in an interesting overview summarized in Weinhardt *et al.* (2019).

Regulatory aspects

On the regulatory aspects, the Energy Collective project was lucky enough to start before all the discussion on implementation of the EU Clean Energy Packages was initiated. Hence, the project was in a very good position to interact with a number of relevant stakeholders within academia, industry, as well as regulatory bodies, in Denmark and abroad. Also, by contributing to many events e.g. conferences, seminars, etc. abroad, this allowed us to look into those aspects of novel market structures oriented towards prosumers from a more international perspective.

On the regulatory aspects, a large focus was placed on governance models for the underlying energy communities, individual prosumers in the case of peer-to-peer markets, since such markets are based on individual agents only. Obviously, the strong towards the use of blockchain in energy systems was also a component, though the project made it clear from the start that all aspects towards future consumer-centric electricity markets do not require blockchain. If it can help bring some momentum, it can obviously be seen as a good thing – however most of the developments within the Energy Collective project are to be seen as technology-agnostic and hence not depending upon the use of blockchain, or not.

An important aspect is that the development of such novel electricity markets goes along the digitization of energy systems. And, actually, the original idea behind the Energy Collective project was that in the future, electricity markets should be decentralized, while jointly considering energy and data. A famous article by The Economist in 2017 argued that data is now more valuable than oil. For energy systems, where the marginal cost of energy generation is clearly going towards zero (with renewable energy sources), it is clear that it may be the case that data (and more generally information) is more valuable that the energy itself. The project therefore placed a large focus on looking at governance models for energy and data together. There also, the advent of GDPR has highly influenced the project. However, one of our conclusions is actually that one should instead think of ways for all agents of the energy system to be incentivized to share relevant information, since this would be instrumental in increasing social welfare, while not really affecting the privacy of individual prosumers.

Dissemination and contribution to research-based education

The Energy Collective project has been extremely active on the dissemination side, as well as in terms of research-based education. This was certainly helped by the fact that the topics covered by the project are broadly appealing to students, scientists, industry, etc. As an example, the topic of community-based and peer-to-peer electricity markets was added to the curriculum of a M.Sc. course on "Renewables in Electricity Markets" at DTU, for the period 2017-2020, with more than 100 students attending the course every year. Similarly, the more advanced methods that have been developed were taught at the occasion of PhD Summer Schools, e.g. that organized summer at DTU. In addition, a large number of special courses and MSc thesis projects were ran linked to the project, with focus on novel business models, the mathematics of electricity markets, the linkage between those markets and power system operations, etc.

To reach a broad audience, we developed a web-based app with R-Shiny, for which the code is openly shared at https://github.com/ppinson/P2Papp - this may then be a nice basis for others to see what those new electricity markets are about, but also to use that app as a basis for their own further development. This app was developed in collaboration with students at DTU, who were keen to get involved on that topic.

On the scientific dissemination side, the Energy Collective project made a substantial impact internationally, with talks and lectures given at some of the most prestigious institutions worldwide including for instance:

- Massachusetts Institute of Technology (MIT), USA
- University of Yale, USA
- University of Oxford, UK
- University of Cambridge, UK
- ETH Zurich, Switzerland
- EPFL Lausanne, Switzerland
- Tsinghua University, China
- Etc.

In addition, the project led to the publication of a non-negligible number of scientific publications, in high-impact scientific journals. A list of those publications is gathered in the following. Among those papers, some (3) are already on the list of ISI/Clarivate highly cited papers, i.e., the 1% most impactful papers of their year and field. Together, in 2 years only, those papers have gathered more than 600 citations.

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6. Utilisation of project results

The main aims of the project were to extensively explore all aspects of community-based and peer-to-peer electricity markets, so as to develop the necessary know-how towards their adoption and deployment. The project led to a considerable number of advances in view of the project objectives that were originally stated. Project members were regularly contacted by numerous companies aiming to develop new business models within that field, for advice and interaction.

The project main coordinator, DTU, originally proposed this project idea in the frame of the ForskEL programme. The project was then transferred to EUDP when the ForskEL programme was discontinued. The project did not aim at the development of a specific technology to be sold.

It should be noted though that the ideas and concepts developed within the project will serve as a basis for future developments in the field, while some of those are already being adopted and replicated by some companies working in the field. In addition, the scientific advances will be highly valuable towards the proposal and development of future electricity markets, in systems that are more decentralized, dominated by renewable energy sources, and with a prominent role of digitization.

The project led to the graduation of 3 PhD students, one at DTU, one at Aalborg University, and one at ENS Rennes (France) who was associated to the project. Those 3 PhD students actively contributed to the work and developments in the project, while also doing a tremendous contribution towards the dissemination of the project results to students and peers.

7. Project conclusion and perspective

Over the 4-year period of the Energy Collective project, a lot has changed in the landscape of energy markets and with energy communities, owing to intensive developments internationally, e.g. related to the EU Clean Energy package. Similar developments were also observed in other parts of the world, with some iconic projects related to community-based and peer-to-peer electricity markets in various parts of the world, e.g. Perth in Australia, New York in the USA, etc. The Energy Collective made a significant contribution in that direction, by developing some relevant expertise related to regulatory conditions, relation with power system operation, and use of relevant technologies. Most importantly, it made a number of important contributions to the design and negotiation processes within such novel electricity markets, with high impact.

As of today, there is still an ongoing debate about whether opening up towards community-based and peer-to-peer approaches to electricity markets makes sense or not. This is while the extent to which one allows for such approaches may actually have a non-negligible impact on investment and regulation, eventually supporting (or not) the further decentralization of our energy systems. Based on the experience from the Energy Collective project, as well as interaction with other similar projects internationally, it is clear that technology could be ready in the case those new energy markets were pushed forward, through a political choice and the adaptation of the regulatory framework. It would actually also give us the opportunity to rethink some of the aspects of the current regulatory framework for energy systems, as well as the cost structure, which have been with a centralized energy system in mind, and a centralized top-down approach to its operations in mind. It is not the case anymore today, that we want it or not: energy systems are bound to be more decentralized and with more decentralized approaches to their operation.

One of the aspects which is key when looking at those new market structures is that the role of the consumer and prosumers become more important. In a classical wholesale-retail view of electricity markets, consumers and prosumers are at the end of the line – they are unlikely to influence the system as a whole. With more decentralized approaches, e.g. peer-to-peer, consumers and prosumers will readily have more influence on the system, for instance by expressing preferences in real-time. However, they may not be fully rational in their preferences and way to express them, or not even know them yet… Consequently, this would require ways for the broad audience to better appraise their relationship to energy usage, while simplifying the process by having bots within households that translates those views and preferences into ways to participate in peer-to-peer and community-based markets.

We do believe that such novel market structures have a role to play in the green transition and in future energy systems.

8. Appendices

All of the publications and documents mentioned in that report are available at the DTU repository DTU Orbit (www.orbit.dtu.dk) and on the webpage of the project coordinator Pierre Pinson (www.pierrepinson.com).