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0 Executive Summary

The overall goal of the SUSTENANCE project 'SUSTainable ENergy system for Achieving Novel Carbon neutral Energy, is to build carbon-neutral energy communities by establishing local, sustainable, and efficient integrated energy systems. In developing and demonstrating smart techno-socio-economic and eco-friendly solutions and tools for effecting multi-energy systems and collective action in communities' business models play a role. Business models can be understood as the set of practices and relationships through which an organization "creates, delivers and captures value" (Osterwalder and Pigneur, 2010). In this deliverable we focus on the value of the business models for local integrated systems from a citizens' perspective.

This deliverable 3.4 is the main output for task 3.3. Task 3.3 is about developing criteria for attractive and viable business models and a strengthened local economy in more autarkic local integrated energy systems. The SUSTENANCE project is based on seven demo sites across four countries: Denmark (one site), India (three sites), Netherlands (two sites), and Poland (one site). The overall objective of this deliverable was to find, through a literature review and an exploration of the characteristics of the demo sites, criteria for citizen-centred viable business model for a decarbonised local integrated energy system.

What criteria make a decarbonised local integrated energy system a citizen-centred viable business model system? The conclusions in this deliverable focused on three questions that lead us to citizen-centred criteria for carbon-neutral communities.

The first question, w*hat benefits is the decarbonisation of local integrated systems supposed to bring, and to whom,* lead us to three benefits from a consumer individual interests' perspective and two from a collective interest perspective.

From an individual interest perspective, a business model is a more citizen-centred viable business model if it takes into account:

- *Lower prices*, a lower purchase cost for the citizen as a consumer of electricity through the local integrated systems
- *Lower consumption and lower peak prices* for the citizen as a consumer of electricity through local integrated systems.
- *Financial compensation for explicit and implicit value of flexibility for citizens as consumers*

And from a collective interest perspective it should take into account:

- A contribution to *local economies* due to the distributed electricity services.
- *Better services* for isolated consumers and alignment with the social demands in communities.

The second question: *what costs decarbonisation through local integrated systems bring for the citizens, and how do these costs compare with centralized/decentralized fossil-fuel systems,* leads to two conditions. Even if traditional power-on-grid energy services are cheaper, these higher costs for a local integrated system might still be viable in a citizen-centred business model. Some citizens might want to use energy services despite higher costs than alternatives given the benefits. The willingness to pay depends on the specific benefits for the citizens. A condition is that the (future) costs for the citizens are transparent for the citizens for a business model to be a viable citizens-centred business model.

- *In a citizen-centred viable business model citizens investment in equipment and (future) energy service costs should fit within the willingness to pay for specific benefits of local integrated systems.*
- *In a citizen-centred viable business model citizens investment in equipment and the (future) extent of energy services should be clear as well as which citizens' energy uses are part of the cost arrangements, and which benefits the local integrated systems bring to individual and collective consumers.*

The third question is: *What benefits is the decarbonisation of local integrated systems supposed to bring, and what different roles could citizens and local communities play in the business model and how might they interact with other key stakeholders?*

The willingness to pay depends not only on the benefits but also on the influence the citizens have on the decision-making in the business model.

- *In a citizen-centered viable business model attention should be given to the influence the individual citizens have on citizens investment in equipment and (future) energy service costs and should fit with the willingness to pay for specific benefits of local integrated systems.*

1 Introduction

1.1.1 Objective of the deliverable

The key focus of the SUSTENANCE project ‘SUSTainable ENergy system for Achieving Novel Carbon neutral Energy, is to build carbon-neutral energy communities by establishing local, sustainable, and efficient integrated energy systems. The main objective of SUSTENANCE is to develop and demonstrate smart techno-socio-economic and eco-friendly solutions and tools for effecting multi-energy systems and collective action in communities. This is to maximize the local use of renewable energy and enable energy efficiency. In the previous deliverables D3.1 and D3.2 of the SUSTENANCE Work package 3 we placed the local utilization of renewable energy resources within the concept of autarky. Working towards energy autarky is one of the important focus areas of the SUSTENANCE project and an important driver for collective action in communities.

This deliverable 3.4 is the main output for task 3.3. Task 3.3 is about developing criteria for attractive and viable business models and a strengthened local economy in more autarkic local integrated energy systems. The SUSTENANCE project is based on seven demo sites across four countries: Denmark (one site), India (three sites), Netherlands (two sites), and Poland (one site). The transitions of the demo sites local energy systems vary between a transition from either a fossil fuel-based on-grid system to a renewable system on-grid system or a transition from a fossil-fuel-based off-grid or weak grid system to a renewable system on-grid system. This system transition is realised with technical innovations.

To build carbon-neutral energy communities different energy assets and resources in a local area need to be brought together and given specific uses to make them operate in a smarter way. Energy assets, resources, and energy uses are not only technical system characteristics but also have a meaning in the local economic system. Building carbon-neutral energy communities with integrated energy systems is not just about decarbonization but also about cost effectiveness and delivering wider social and economic value for communities. Local energy systems offer an alternative to large-scale energy provision in the transition towards a low-carbon economy. To be able to deliver value to local communities, as they try to decarbonise, new business models are needed. Business models are then understood as the set of practices and relationships through which an organization “creates, delivers and captures value” (Osterwalder and Pigneur, 2010).

What criteria make a decarbonised local integrated energy system a citizen-centered viable business model system? This deliverable is about the following questions that will lead us to citizen-centred criteria for carbon-neutral communities:

- what benefits is the decarbonisation of local integrated systems supposed to bring, and to whom?
- what costs decarbonisation through local integrated systems bring, and how do these costs compare with centralized and decentralized fossil-fuel systems and between the demo site countries?
- what different roles could citizens and local communities play in the business model and how might they interact with other key stakeholders?

To address these questions we will first discuss the economic assessment of local energy systems. The economic assessment cannot be separated from the organization of the (local) energy market and the role in the business model and the local energy market. In the transition towards a new system the existing social organization, self-governance, and economic decision-making position of the citizens is important. This transition is a social innovation that creates an attractive citizen-centred business model through local investments in integrated energy systems, even when the demo sites have weak grid connections or non-existing grids. In the end for the citizen as consumption of energy is a service that can be provided in different ways, with renewable and non-renewable resources or with different market and organizational structuring setting the price and with different decision-making mechanisms that might or might not give the citizens as consumers (and sometimes producer) different costs and benefits. Crucial for creating such business models are organizational set-ups that align with attractive citizen-centered business models in general and which are specific for more autarkic local integrated energy systems, and which are further valuable for citizens; is the position of the citizens in the business model.

An important economic perspective in this deliverable is that energy is considered a service for the private and social interests of consumers in businesses and households. Thinking in terms of energy services is useful for the economic assessment of innovations, including distributed energy systems, leading to new types of energy services for the renewable energy transition. Presently, many fossil fuel energy services involve large private and public expenditures. The fossil fuel energy services cause pollution of fine dust and acidifying emissions that undermine health and nature, as well as CO2 emission that causes climate change.

Organising energy services in a different way comes with different costs and benefits of the energy service. For the new local integrated energy systems we study in the SUSTENANCE project to be economically viable and attractive, particularly for the citizens, we need to look at the different kinds of business models. There is a necessity to find new energy solutions which are cheaper than the current system, which has been intensified by the sharp increase in energy prices since early 2022. However, there might be additional criteria for why a higher price for energy services would be acceptable. The criteria are another operationalization of cost and benefits than the strict economic ones. We primarily focus on the consumers, in particular on energy efficiency, cost-effectivity, and beneficial impacts of decentralized uses. Although new energy services might be more expensive, they can provide substantial consumer and community benefits. This is not just an individual interest in the availability of renewable electricity in general. Locally generated energy strengthens the local economy, particularly more autarkic local integrated energy systems. New energy services enabled new businesses by using electricity and new economic activities that create jobs in manufacturing, installation, and more. Furthermore, there are positive social impacts, such as stronger community solidarity and spirit, as many renewable energy activities take place within the local community. Distributed energy generation can also empower local communities, as they are given the ability to manage and operate decentralized energy systems themselves. Part of task 3.3 is to identify these local economically interesting conditions to boost local energy sources and/or activated local demand-response.

From the consumer's viewpoint, energy services should deliver functional and ethical qualities. Consumers can here be households and smaller enterprises. While functional qualities are usually decisive in the business markets and engineering, ethical qualities are often key in household markets and designs. Some consumers use energy services despite higher costs than alternatives as we will discuss. Some keywords are sustainability, ownership, and democratic control. Here is where these new energy solutions go together with new arrangements for the citizen's involvement in the energy infrastructure and market. These new arrangements follow the objectives of recent EU policies about the necessary change of the role of individual citizens and energy communities and how they can and should play role in the energy transition. One is giving citizens a level playing field to other actors in the energy market and the second one is stimulating the use of financial investments from these citizens. This is only possible if citizens are not only ending user of energy but are part of an explicit (social) business model.

1.1.2 Economic assessment of distributed energy systems.

We discuss in this deliverable the economic assessment of distributed energy systems. We mainly focus on the generation and consumption of electricity. Distributed generation is the term used when electricity is generated from sources, often renewable energy sources, near the point of use instead of centralized generation sources from power plants.

Our discussion on criteria will be besides the literature review be based on new approaches to establish local integrated energy systems in seven demo sites across four countries: Denmark (one site), India (three sites), Netherlands (two sites), and Poland (one site). Given the characteristics of our demo sites (see chapter 3), we have a strong focus in our economic assessment on literature review on PV generated electricity and their interaction with the local consumption. Besides the electricity services with photovoltaics (PV) in our demo sites, we also deal with multi-carrier energy system integration. For instance, heating, previously provided by gas or other sources, will be replaced with heat pumps and facilities for EV-charging will be set up. In the demo sites, more efficient and economical ways for the harmonized operation of heterogeneous energy carriers (electricity, heating, transport, water etc.) and infrastructures in the local integrated systems are considered.

The centralized generation of electricity through large power plants is a specific business model. This business model was developed for the roll-out of the supply of electricity as a co-evolution of technological developments and an economic logic-based market development. In this roll-out technology determined the (economic) organization of the electricity market. Based on the economy of scale and physical rules, an electricity market was built up with some logical characteristics, including economies of scale with large generation units; generation units near load centers; high voltage lines for electricity transmission; interconnection of plants to optimize on different characteristics (natural resources), including lowering the need for costly reserve capacity; interconnecting between rural and urban areas loads to optimize on diversity in demand; central coordination in technical and economical dispatch; and offering low and differentiated rates to cultivate mass consumption (supply creates demand).

The economic perspective also influenced the technological components of the energy systems. The reason that the electricity market was established as a large integrated technological system has to do with costs: many assets in the fossil fuel-based electricity system are specific technologies that are only relevant for the electricity system. From an economic perspective, this creates problems related to the mitigation of financial risks for investors, because many assets require substantial upfront investments. The economy of scale is an important risk mitigator, leading to a natural grid monopoly. Electricity additionally has a low-price elasticity, as there is no substitution product. Furthermore, electricity cannot easily be stored, although this is changing. Combined, this means that there is the danger of monopolies setting high prices for consumers. Governments have a strong interest in guaranteeing the security and reliability of electricity supply and a fair price that reflects suppliers' costs and investments with a reasonable profit margin. This is where monopoly and price regulations in the electricity market came into play.

The liberalization of the energy market in 1996 with the adoption of the first European Directive meant for Europe opening of the energy markets to free competition, breaking up existing monopolies and opening the market to more participants. The aim was to make the electricity supply more efficient and competition would lead to lower prices for the consumers. The existing centralized infrastructure can be a limiting factor for liberalization. The question is in how far new technological developments, like cheaper renewable electricity generation, digitalization, and demand-control that were not available when we started rolling out electricity, can reverse the economic arguments for centralized energy generation since Edison constructed the first commercial electrical generating station in 1882.
Distributed energy services emerge as a global trend in services but limitations are encountered. Small scale can cause high costs, the low energy density of resources may require much space, and energy storage could be needed to counter variability in time. This might lead to the conclusion that the costs of distributed electricity services are about three times higher than the supply costs on-grid but approach the on-grid prices in the EU including energy taxes (see chapter 2 and appendix 1). This is only part of the story as there are several tangible benefits of the distributed energy services for the producers and consumers which largely compensate for higher supply costs. We will discuss this in Chapter 2 that summarises Appendix 1.

Nevertheless, sound designs of distributed energy services are necessary. For the economic assessment in chapter 2, based on Appendix 1, we assume that the proposed designs of demonstration projects are the best combinations of tools and activities with regard to the local resources and demands. Nevertheless, the unit costs could be high regarding those limitations. We therefore will discuss beneficial services to compensate for the higher costs of renewable energy in the distributed mode compared to fossil fuels in large-scale networks. The unit costs and tangible benefits linked to the interests of producers and consumers need to be assessed. Further we will look at the influence that large scale wind power plants and new large scale PV plants might have, through the integration of these renewables in the energy market, on the distributed energy services.

As stated task 3.3 is about developing criteria for attractive and viable citizen-centered (social) business models in terms of new societal innovative models and organizations (see below), also in more autarkic local integrated energy systems. Organizational set-up is needed to create beneficial distributed energy systems, which can be arrangements for a citizen-centred local energy system, that aligns with a more autarkic local integrated energy system and are valuable for position of the citizens in the economic system, the energy market and the specific business model.

To harvest these benefits, local citizens and communities of the new business models need to be involved in the changes made to the local energy system, and informed about different technical opportunities and business cases, so they can make informed decisions about their participation. One of the arguments for a larger role of citizens in the energy transition is that they can economically benefit from it. This relates to both lower energy bills and private citizens' investments. In a distributed local energy system, profits from the production of renewable energy would not only be made by the big market actors, but also by local citizens as (collective) prosumers and active energy consumers.

One could argue that the more autarkic the local energy systems become, this would improve the market role of consumers. Distributed energy systems can be considered deficiencies in the market prices of energy as a commodity caused by monopoly, regulation, insufficient investments, and other market imperfections that should be removed.

The literature review in combination with the characteristics of the demo sites are used to identify and develop criteria for attractive business models that balance costs and benefits. The development of these criteria is done from a citizen-centred perspective. To discuss the criteria on the basis of the demo sites we will look into:
(1) new and alternative organizational configuration
(2) new activities resulting from a new mix of energy sources and services
(3) new cost arrangements
(4) new modes of flexibility.

We start in chapter 2 with a summary of the literature review on the economic assessment of distributed energy systems. The literature review with respect to the characteristics of the demonstration projects in the SUSTENANCE project, focuses on electricity services with photovoltaics (PV). We summarise the costs of those services as assessed in the Appendix 1. This is followed by a summary of the assessment of benefits from the Appendix. Further we give some attention in chapter 2 to the value of new modes of flexibility for citizens. In chapter 3 we will combine our economic questions with the physical and social-economic characteristics of the seven demo sites. In chapter 4 we combine the output from the literature review and the exploration of the characteristics of the demo sites, to suggest criteria for citizen-centred viable business models for a decarbonised local integrated energy system.

2 Costs and benefits of distributed energy services

2.1.1 Introduction

The overall objective of this deliverable is to find, through a literature review and an exploration of the characteristics of the demo sites, criteria for a citizen-centred viable business model for a decarbonized local integrated energy system. Decarbonization depends on producing and using more renewables and organizing the supply and use of renewable energy in a smarter way. Organizing energy services in a different way comes with different costs and benefits of the energy service. The change in costs and benefits only partly can be influenced by the actors in the local integrated system.

Major changes are taking place on the electricity grid because of the trend of a rapidly growing variable production of solar and wind energy and the trend to use more technology with significant electricity demand and a specific demand pattern (such as electric transport and electric heat pumps). The consequences of this for a citizen-centred viable business model are visible in the supply of electricity (as a commodity) and the demand for electricity because of balance maintenance and network congestion (lack of transport capacity). The literature review in combination with the characteristics of the demo sites is used to identify and develop criteria for attractive business models that balance the costs and benefits of new energy services. The development of these criteria is done from a citizen-centred perspective.

In Appendix 1, the literature on the costs and benefits of distributed energy services is reviewed. It is assessed whether the distributed energy services are cost-effective compared to alternatives and if they can provide benefits which can justify their uses. The resources are fossil fuels and renewable energy, the consumers are businesses and households, and the interests are private and social, meaning related to individuals' interests or to communities. With respect to the demonstration projects in the SUSTENANCE project, the review is mostly focused on electricity services with photovoltaics (PV). The review in the appendix sketches the context of distributed energy services. We summarise here the assessment of the costs and benefits of distributed energy in the review in section 2.2.

2.1.2 Costs and benefits of distributed energy services, conclusions literature review

Cost of off-grid and on-grid electricity energy services

The costs of electricity services off-grid are usually higher than supplies on-grid excluding taxes but the services based on microgrids can be cost-effective to reduce the costs of taxes and peak prices and mitigate deficiencies on the grid. Applications of PV with storage are usually costly compared to heat-power generators and diesel generators in large-scale microgrids but they can be cheaper in the small-scale ones if the design of installations and operations are tuned to customer demands. These are findings based on model studies. However, information about experiences with cost-effective applications is scarce despite many publications because the modelling of microgrids captures attention in the academic and professional literature. A major contribution of the SUSTENANCE project to the knowledge pool would be the comparison of the costs and effects of PV-based microgrids in the design stage with realisation during the demonstration. Therefore, an inquiry is proposed to collect basic data for assessments of cost-effective microgrids. Such inquiry should cover three features: (1) main components of the design microgrid with purchase prices, (2) cost of installing the microgrid and hours in development and management, and (3) generation of electricity based on calculations and measurements of generated electricity during the demonstration.

Benefits of distributed energy services

The benefits of distributed electricity services are divided into individual and collective ones for the producers and consumers of electricity. The benefits can be substantial and compensate for their higher costs but not all are well assessable.

Reasonably assessable benefits to the individual producers are risk reduction due to diversification of energy and financial resources, pricing of electricity as a marketing tool, and to the collective interests, they are mitigating impacts and optimisation through deference of costly expenditures. Reasonably assessable benefits to the individual consumer are related to the shaving of the peak prices, and to the collective interests, these are contributions to in local economies.

Less assessable benefits for the individual producer are cost-saving operations and changes of current. For the collective interests of producers, these are lower import-dependency and support of local stakeholders. Less assessable benefits for individual consumers are the prevention of peak consumption and for their collective interests, these are the contribution of the local social interests. However, experiences with valuations of such benefits are scarce and many benefits are difficult to valuate. A major contribution of the SUSTENANCE project would be the benefit assessments based on the demonstration projects which need data and estimates. The data can be provided by the executors of the demonstration project based on an inquiry into the assessable benefits followed by checks of the estimates with regard to local conditions and interests.

Conclusions cost and benefit assessment distributed electricity services

The costs and benefits of the distributed electricity services are assessed based on the literature. The global context is a shift in economic structures from agriculture and industries to services, which also involves the growth of energy services. Whilst the costs of modern renewable energy decline, the value of energy services increase. As a result, modern renewable energy expands, particularly wind and solar energy with PV, despite obstructive policies that support mainly large-scale fossil fuel facilities and obstruct high pollution prices. Variability in energy generation and low energy density associated with the use of those renewable energy resources are compensated by the advantageous availability all over the Earth without pollution and frequent energy storage. These advantageous properties of modern renewable energy are reinforced in applications for distributed electricity services.

The costs of distributed electricity services are compared to the prices on-grid, PV on-grid, PV off-grid and microgrids. The prices per kWh on-grid vary from USD 0.08 in India to USD 0.25 in Denmark including energy taxes, whereas the prices per kWh excluding the taxes are usually about USD 0.05 – 0.07 across many countries and they hardly change over time. An additional share of renewable energy in the resource mix of power generation, in particular additional PV on-grid, has decreased prices on-grid. That price-decreasing impact on the electricity prices turns around at a high share of renewable energy in the resource mix, presumably because renewable energy is less effectively applied. The applications of PV off-grid are scarce in high-income countries while they are popular and growing in low-income countries, particularly India uses much stand-alone equipment.

The costs of PV off-grid are often estimated. These are usually model-based accounts but rarely the estimates of applications during use. The model-based estimates suggest that the PV off-grid is often cheaper than diesel generators and that the costs are similar to the electricity prices on-grid including energy taxes. The estimates also show a large spread in the energy performance of the applications, which implies that sound design and implementation are necessary to attain reasonable costs. Microgrids with fossil fuels and renewable energy emerge in high-income countries, mainly in the USA, from the suppliers' interests for lower the costs of electricity distribution. Estimates show that renewable energy in microgrids does not cause higher costs if the microgrid is well-designed and implemented but a large spread of the costs is observed, which is also observed in low-income countries. The unit costs of microgrids evolve towards USD 0.25 - 0.30 per kWh if designs are tuned to customers' demands and operations are effective. For consumers, the individual costs are the costs of actual equipment like heat pumps, EV chargers, storage as well as the control built for these.

- The benefits are often assessed based on the stated preferences about willingness to pay for power with renewable energy but results show a large spread in the payments and factors that cause this spread is debated. The benefits based on the revealed preferences are specified in various studies but they are rarely quantified though a few estimates show high benefits of USD 0.6 - 0.21 per kWh. Therefore, a checklist for the revealed benefits is constructed for the development of off-grid electricity services and possibilities for the monetary assessments are pinpointed.
- The benefits of the individual producers refer to the moderately assessable advantages in operations (e.g., congestion relief, flexibility, stabilisation of voltage), as well as changes for cheaper DC current; and they refer to well-assessable diversification of energy and financial resources which reduce risks, as well as marketing with the dynamic pricing.
- The benefits of the collective producers can be generated due to the moderately assessable lower import-dependence and using experiences of the local stakeholders; and they address well-assessable risk prevention through mitigation of impacts on health and environment, and optimisation of production, in particular deference of costly equipment as distribution lines to remote areas.
- The benefits of the individual consumers are moderately assessable with respect to the consumption peaks because habits impede change whilst the 'peak shaving' of the prices is well-assessable, but note that the 'peak shaving' of consumers interferes with the marketing benefits of producers.
- Finally, the benefits of the consumer collectives covers the moderately assessable improvements of the social interests (e.g., creating capabilities and serving isolated consumers) and well-assessable economic interests as incentives for local business income and jobs.

The assessment of costs and benefits in the literature review indicates the economic viability of off-grid power applications in many cases if the applications are well-designed and implemented.

2.1.3 Energy demand and flexibility

Above as an answer to the question of what benefits the decarbonisation of local integrated systems can bring to individual consumers we mentioned lower electricity prices, lower consumption and lower peak prices. This was mainly considered from the perspective of distributed renewable energy generation. Distributed renewable energy generation might be more expensive but also might be compensated by other benefits of renewable energy in the distributed mode compared to fossil fuels in large-scale networks.

However, as mentioned to build carbon-neutral energy communities different energy assets and resources in a local area need to be brought together and given specific uses to make them operate in a smarter way. Operating in a smarter way might bring benefits to consumers apart from lower consumption and lower prices. Another value of local integrated systems is the added value of flexibility mechanism for consumers. Smart energy management and provision of flexibility to the grid contribute to a citizen-centred business model besides new energy services in terms of power generation. Apart from the influence flexibility mechanism, in general, have on the cost of energy generation, though for instance capacity reserve costs, and grid investment costs which translate into consumer prices there is also a specific value of flexibility for consumers. Demand flexibility can help make electricity more affordable by helping customers use less power when prices are high. Apart from energy saving through demand, flexibility can also have a value in itself for citizens (Bronski et.al. 2015)

The literature review in combination with the characteristics of the demo sites is used to identify and develop criteria for attractive business models that balance costs and benefits. The development of these criteria is done from a citizen-centred perspective. In the discussion of the criteria on the basis of the demo sites, we will look into new modes of flexibility.

The energy supply is becoming more and more electric. Heat pumps and electric cars will replace gas boilers and petrol and diesel cars. Both the increasing local renewable electricity generation and the increasing need for electricity pose new challenges to the electricity grids. The use of flexibility can help to keep the electricity supply stable and to moderate the overloading of electricity grids. The flexibility of electricity grids can be shaped by shifting part of the demand for electricity, spreading it out over time or using electricity storage. This creates the possibility for new business models for local communities and individual (pro)sumers. From the perspective of what criteria make a decarbonized local integrated energy system a citizen-centred viable business model, also the value of flexibility will lead to different business models when applying flexibility for this citizens-centred perspective. From a citizen's perspective, we will discuss the explicit value of flexibility, by trading flexibility and the implicit value of flexibility through dynamic rates and netting.

Explicit value of flexibility: trading flexibility

There are different 'trading places' with different goals and rules where flexibility can bring money. In the context of this deliverable, we will not discuss the markets that are mainly reserved for the larger players in the electricity sector. However, there are alternatives for smaller players like smaller companies and local energy communities that want to trade smaller amounts of electricity, for balancing services and local marketplaces for congestion management. These alternative trading platforms can have a lower threshold access which makes them also interesting for citizens and local energy communities.

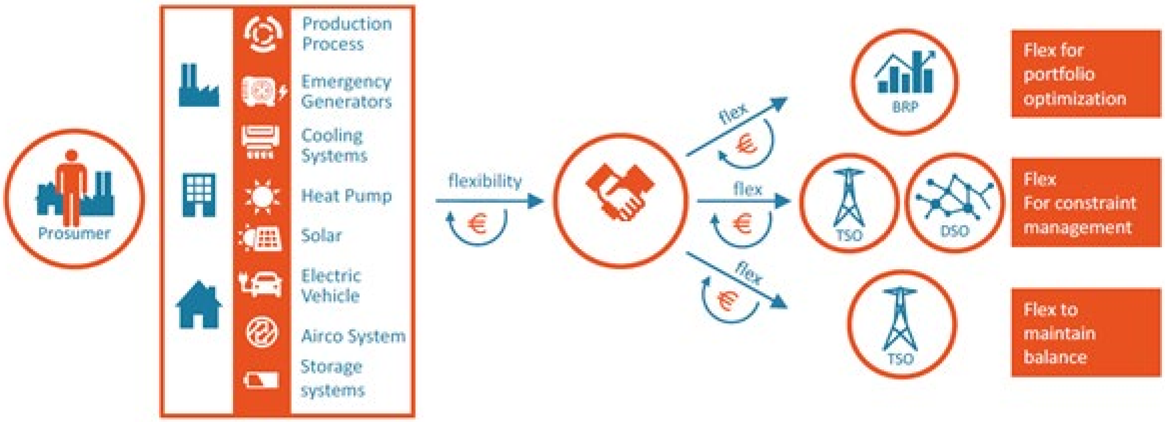

Figure 1. ‘Flexibility Value Chain’. Bron: ‘White Paper Energy and Flexibility Services for Citizens Energy Communities’, USEF, 2019.

In the markets for balancing services, actors make flexibility available to the national grid operator and possibly also to foreign grid operators of transmission networks. These actors can receive compensation for both their promised availability and their energy supply. The time horizon of energy trading and balancing services differs. Where on the intraday market, electricity is traded on a quarter-hour and hourly basis, for the various balancing services often shorter time intervals apply. The use of flexibility for congestion management is intended to keep the supply and purchase of electricity within the limits of the available transmission capacity. With the use of flexibility, network operators can prevent disruptions that require them to make their networks heavier. In this way they can save investment and flexibility has an economic value for them. This in the end also influences consumer prices.

For smaller entrepreneurs, citizens or groups of citizens to earn money on the basis of this value for the operators, specific (local) trading platforms are needed where flexibility to prevent congestion problems can be traded. These possibilities are still in their piloting phase and need rules for when there are congestion management problems, who can be a congestion management service providers and concrete business cases.

In addition to trading electricity as an individual entrepreneur, it is also possible to trade one’s electricity as a collective (possibly via an aggregator) on the electricity markets. This can be both a collective of entrepreneurs and local residents. The collective balances the energy generation and use (and possibly conversion) within a certain area, for example behind one substation. The remaining energy generation can then be traded on the electricity markets. The collective then act for the market as one generating installation, a so-called virtual power plant (VPP). Despite this idea gaining more and more demand, many such initiatives are still in the experimental phase. This is partly due to the fact that this form of action is hindered by current laws and regulations. Energy communities at European level are also receiving increasing attention because they are explicitly included in the EU's Clean Package Deal.

The implicit value of flexibility

In addition to the explicit value in markets, flexibility also has implicit value by using it for optimization behind the meter. These benefits end up with the end user without direct intervention from a supplier or aggregator. At the moment, there are several possibilities for realizing the implicit value of flexibility like dynamic delivery rate, increasing self-consumption, limiting connection capacity and dynamic transport tariffs (Guidehouse, 2021; Presmai et.al. 2021, Li and Pye, 2018).

Depending on the country it is already possible for consumers to choose a dynamic delivery rate. Here is a direct relation to the general energy market. The supplier links the electricity supply tariff to the time of use. The supplier thus covers part of its purchasing risk. If it turns out that he has to buy more at peak hours, he can also charge more to customers at a variable rate. This offers consumers transparency and the opportunity to reduce their energy bills by adjusting their behaviour to the prices paid (CE Delft and ECN, 2017).

Another implicit value of flexibility is increasing self-consumption. Increasing self-consumption is only attractive to households, who can make use of the netting scheme, but they are already attractive to business consumers. This depends on the netting scheme in the specific countries. In the Netherlands for instance the netting scheme will be phased out in stages: every year consumers can net slightly less of their generation.

In addition to a tariff for the supply of electricity, consumers also pay a tariff for the transmission and distribution of electricity. This tariff consists partly (or entirely) of capacity-dependent tariffs. This can be saved by using less grid capacity (a lower capacity of the connection or a lower peak demand).
Limiting the connection capacity (for example via peak shaving) is already an interesting option for especially bigger consumers. For small consumers with a low connection capacity, a possible capacity rate is low compared to the available power of the connection and the transition to a higher capacity class costs a relatively large amount.

There are great expectations of smart energy services for the (temporary) prevention of grid reinforcement, for example with demand management or energy storage. Optimizing devices in one home, for example through an energy management system, can generate value for citizens through demand reduction. However, although technically more and more smart energy services are possible, in practice there are still barriers that make it difficult to build a business model for citizens. Barriers lay in laws and regulations and in the organization of the (energy) market. Examples of barriers are (Royal HaskoningDHV 2021)

- Incomplete and incorrect data from smart meters
- Unclear frameworks and insufficient incentives for grid congestion and grid optimization
- Lack of financial incentives for optimal use of networks (transport tariffs)
- Netting and fixed energy tax limit smart energy revenue model
- Multiple suppliers on one connection.
- Privacy of products, services and systems that need to be connected to the internet.

3 Economic aspects of the energy services in the demo sites

3.1.1 Economic aspects of the system characteristics in the demo sites

In this chapter, we explore the economic aspects as introduced in the previous chapter 2 in the demo sites to support the formulation of relevant criteria for a citizen-centred business model of a decarbonised local integrated system. The SUSTENANCE project explores citizen-centred approaches to business models to establish such energy systems, based on seven demo sites across four countries: Denmark (one site), India (three sites), Netherlands (two sites), and Poland (one site).

To build carbon-neutral energy communities different energy assets and resources in a local area need to be brought together and given specific use in the area, these energy assets, resources, and energy use needs to be made to operate in a smarter way. Energy assets, resources, and energy uses are not only technical system characteristics but also have a meaning in the local economic system.

In the deliverables D3.1, D3.2 and D3.3 we specifically looked to transitions towards more autarkic local energy systems. A fully autarkic system is a distributed energy system that is the completely opposite of a centralised energy system. The lens of autarky is not meant to be normative but looking at the characteristics of more autarkic system brings out the differences between a distributed energy system and a centralised energy system. In the previous deliverables a typology for autarkic energy communities was developed as part of work package 3 within the SUSTENANCE project. This analysis is based on the notion of local energy transitions as socio-technical system change and guided by a two-dimensional typology that combines physical-technical and socio-regulatory characteristics of the different sites. Part of these characteristics have a particular relevance for criteria that make a decarbonised local integrated energy system a citizen-centred viable business model system.

As a characteristic of the physical-technical dimension, *technological dependence* addresses the degree to which the local energy system depends on the larger energy grid to function, related to both the transmission and the storage of energy. Economically a more autarkic system with weak or no grid connection changes the costs and benefits of the energy service compared with a centralised energy system, particular a micro-grid in which community members can share energy with each other and where a local energy storage is used. But also selling electricity back to the grid in case of temporally or seasonal overcapacity of renewable electricity generation has an economic relevance.

The availability of *local renewable energy sources* determines whether local energy demand can be met from the renewable energy sources available to the system. For the exploration of the economic aspects of the demo sites not only the currently installed renewable energy generation is relevant but also the potential and/or increase in the renewable energy generation. The complexity of *energy uses* captures the range of users and associated uses that need to be covered by the local energy system. Household or business uses in the energy system and the flexibility of different uses have economic relevance.

The first characteristic of the socio-regulatory characteristic is the social organisation within this dimension that refers to the networks and social structures within the community, including, but not limited to those related to energy, that provide insights into the relationships between members of the community. These relations might have an economic relevance or support economic decision-making. The position of the citizens depends on the organization of the (local) energy market and the role of the citizens in the business model and the local energy market. In the transition towards a new system the existing social organization, self-governance, and economic decision-making position of the citizens is important. Different market and organizational structuring setting the price and with different decision-making mechanisms might or might not give the citizens as consumers (and sometimes producers) different costs and benefits. This also relates to *self-governance*. The sophistication of self-governance covers the type, structure and 'weight' of the governance system within the energy community, including decision-making processes and associated sets of rules. It gives insight on the ability of the local community to govern its local energy affairs and on its relationships with other energy governance stakeholders outside of the local system. The ultimate citizen-centred energy business model is a group of citizens who collectively organize decentralized energy actions, in the form of more or less formal local energy communities. But if decision-making powers lies with other actors, the influence of the citizen on the decision-making of these other actors is important. A particular aspect of the economic relevance of economic decision-making are the energy values and economic values the citizens have. The energy values and their economic motivation decided about the energy services the citizens wish for. An overall plan with more autarky aspirations has economic consequences in terms of specific values and benefits, but also in terms of costs. We have brought the relation between the economic aspects of energy services and the physical-technical and socio-regulatory dimension together in some specific questions in the table below.

Characteristic	**Relation to economic aspects of energy services**
Physical-technical dimension	
Technological dependence	• Can grids within the demo site be characterized as (1) power on-grid, (2) PV power on-grid, (3) PV power off-grid, or (4) PV – microgrids?
Availability of local renewable energy sources (RES)	• What is the economic relevance of the current installed capacity for energy production from RES and planned expansions, compared to the energy demand?
Complexity of energy uses	• What is the economic relevance of the main energy uses, and flexibility mechanism in the project site?
Social-regulatory dimension	*Relation with energy services*
Social organisation	• From an economic perspective on energy services does the social organisation play a role in the energy market within the project community?
Sophistication of self-governance	• Is there a formal citizens' representation within the community, and are community members able to influence economic energy services and energy market-related decision-making?

Alignment of energy values	• Is there an economic motivation for the community members in the project site to (1) switch to local, renewable energy and (2) become as self-sufficient as possible?
Scope of autarky aspirations	• Does the project community strive for full energy independence and do economic motives play a role in this?

3.1.2 Denmark

The demo site Voerladegård

Voerladegård is a village of ca. 550 inhabitants in the municipality of Skanderborg in the Central Denmark (Midtjylland) Region. The demo site includes 20 existing houses within Voerladegård and the neighbouring small village Dørup, which will be retrofitted with new technology to make use of local renewable energy sources. A new integrated community energy system with active citizen participation is envisioned to provide opportunities for energy sharing between households. Voerladegård and Dørup are rural villages at the edge of the municipality of Skanderborg with predominantly residential buildings.

Key stakeholders in this demo case as identified by project partners are the local prosumers (with heat pumps, phase change material-based thermal storage tanks, solar-PVs and electric vehicles), the local aggregator (Neogrid), and the distribution system operator (AURA). Neogrid will take the central position in the envisioned use case for SUSTENANCE, which includes establishing contacts to other economic players.

3.1.3 Economic aspects of the physical-technical characteristics of the Voerladegård demo site

Technological dependence
Can grids within the demo site be characterized as (1) power on-grid, (2) PV power on-grid, (3) PV power off-grid, (4) PV – microgrids?
The houses included in the demo site are individually connected to the larger municipal energy grid, whereby some houses are consumers only, while others have a reciprocal connection to the grid and provide surplus electricity from their local PV installation to the grid. The local distribution system operator and electricity supplier to the demo site is the company N1.

The demo site can be characterized as a combination of (1) power on-grid (consumers only) and (2) PV power on-grid (prosumers). There is no microgrid within the community, and a grid specifically connecting the 20 demo houses would be difficult to construct, as they are spread out across Voerladegård and Dørup.

Local renewable energy resources
What is the economic relevance of the current installed capacity for energy production from RES and planned expansions, compared to the energy demand?

Of the 20 houses included in the Voerladegård demo site, nine houses already have solar PV installations for electricity generation, and one house is equipped with a solar collector for hot water. Across Voerladegård and Dørup, there are photovoltaic systems with an estimated capacity of 50 kW, with an additional 50 kW planned in the foreseeable future. Energy for heating currently originates from individual natural gas boilers, however, houses will switch to individual heat pumps as part of the SUSTENANCE project.

Energy uses

What is the economic relevance of the main energy uses, and flexibility mechanism in the project site?
The Voerladegård demo site includes residential houses only, making heating and domestic electricity consumption the primary energy uses. These are private houses. In addition, eight of the 20 houses in the demo site reportedly have EV charging stations.

The SUSTENANCE project will explore opportunities for synergies between different energy sources and uses, particularly between the electricity-consuming heat pumps and EV chargers and the electricity-producing PV systems, by applying battery and smart management of the energy consumption. In the Voerladegård demo site the smart energy management and provision of flexibility to the grid means a flexible control adapting to fluctuating power generation, which is important for the energy use.

3.1.4 Relation between energy services and the social-economic characteristics of the demo site Voerladegård

Social organisation, self-governance, and economic decision making

From an economic perspective on energy services does the social organisation play a role in the energy market within the project community? Is there a formal citizens' representation within the community, and are community members able to influence economic energy services and energy market-related decision-making?

Voerladegård is a socially active community with a range of different clubs and associations, although there does not seem to be any clubs with a specific focus on energy or sustainability yet. Nevertheless, this provides social platforms and networks to upscale SUSTENANCE innovations for a larger citizen-centered energy community. The local residents' association (Voerladegård Borgerforening) acts as a platform for local communication and citizens' initiatives and includes a number of organisations that focus on key aspects of daily life in Voerladegård, such as the Voerladegaard Community House Organisation and the local sports club (Voerladegård IF). Community members can participate in the annual general assembly and be elected as board members, decision-making is ruled by the association's statutes. Voerladegård Borgerforening is also represented in Skanderborg's village community (Landsbyfællesskabet), which cooperates with the municipality on issues related to rural development.

From an economic decision-making perspective, although there's a local residents association and they have a system with a General Assembly and elected board members, residents that do not want to participate simply do not participate because they are independent house-owners. However, there is a local community of households in the community, and for the test houses in the project, most of them (80/90%) are active in the local community, but it's not organized. They participate actively, but it is not like they have to be somewhere or do anything collectively based on a majority vote, but they have a strong community.

In principle in the demo case, all the investments are from the private owners. The private owners pay the equivalent of what they would usually pay to have just a heat pump installed. But since this system is more complex, the added complexity is covered by the SUSTENANCE project.

Other actors through subsidies and government policies influence the economic perspective of the house owners. Within SUSTENANCE, the key actors involved with project implementation in the demo site are Skanderborg Municipality, which is involved in project planning, the company Neogrid, which will take the central position in the envisioned use case for SUSTENANCE by managing the smart energy system, and Voerladegård Borgerforening, which plays an important role for the communication with citizens and their acceptance of the project. Energy provider Aura Energi and Aalborg University are involved in the project to simulate the local grid system for analysing and mitigating possible congestions. The municipality is the local authority for heat systems, including, but not limited to district heating. However, the heating system in the case of the SUSTENANCE demo site is so small that it does not require a permit from the municipality. Overall, the relationship between the different key organisations is good, and citizens are reported to mostly trust these organisations. Overarching rules, e.g., on the relationship between the municipality and the residents' association via Skanderborg's village community, shape the interactions between actors.

Energy values and motivations

Is there an economic motivation for the community members in the project site to (1) switch to local, renewable energy and (2) become as self-sufficient as possible?

The primary motivation for the people in Voerladegård to switch to a RES-based energy supply and pursue local self-sufficiency is economic. New energy solutions need to be cheaper than the current system, which has been intensified by the sharp increase in energy prices since early 2022. The way the taxes on electricity are structured in Denmark make it cheap to heat your house with a heat pump (strong economic argument) compared to oil and gas burners. Basically, in economic terms, any form of a heat pump is better than fossil fuels.

Other motives, mostly related to environmental concerns and the political or social statement of becoming independent from fossil fuel imports since the onset of the Ukraine war, are also common within the community. However, community members reportedly agree on economic motives being the main driver of the local energy transition in this demo site. Accordingly, interventions will have to be more cost-effective than current energy solutions in order to be broadly accepted.

The main focus from the project community is on the economic benefits of being a renewable energy community, with little emphasis on self-sufficiency as such. It is therefore unlikely that the community would want to pursue autarky in other sectors or go beyond the level of self-sufficiency that is cost-effective in the energy sector. Economic motives do not play a role in a demos site community to strive in any way for full energy independence.

3.1.1 India

3.1.2 The demo site Barubeda village

Barubeda is a remote agricultural village in Jharkand state with around 50 households. The village is not connected to any larger energy grid, and only has limited access to water. Inhabitants primarily use firewood for cooking, and kerosene-based lamps for lighting. There is no access to public transportation services, and the nearest road is located 3 km away from the village. For several months each year, the men of the village migrate to the closest city for work.

The goal within SUSTENANCE is to develop an off-grid integrated energy system based on local renewable energy sources. Specific utilities provided in the new local energy system include electricity, a domestic water supply system, a transportation system based on e-rickshaws, biogas- and biomass-based cooking, and a multi-utility-based heating, cooling and drying facility. Planned energy sources include solar PV systems, wind and biogas, supported by a new battery system for energy storage.

3.1.3 Economic aspects of the physical-technical characteristics of the Barubeda village demo site

Technological dependence

Can grids within the demo site be characterized as (1) power on-grid, (2) PV power on-grid, (3) PV power off-grid, (4) PV – microgrids?

Barubeda is a remote off-grid village. To improve living standards, the goal is to supply electricity to the local community through a local off grid-based generation and distribution system. While the system will initially be an islanded off-grid system, it will be capable of interfacing with the main grid in the future if that gets extended to this location. The type of grid integration implemented here is a collective connection with autonomous internal distribution mechanisms, whereby locally produced energy is being fed to the grid. Specifically, the goal is to ensure a reliable power supply to match local demand by sourcing electricity from Solar PV supported by small wind turbines and a biogas generator with battery storage system. The local islanded grid will optimise the use of different generation technologies in electricity vector and across other energy vectors including water pumping system, transportation and cooking. A smart energy management and scheduling tool will be used to operate the off-grid system in an optimal and economic manner.

Local renewable energy resources

What is the economic relevance of the current installed capacity for energy production from RES and planned expansions, compared to the energy demand?

Because there is currently no installed capacity for any local energy source in Barubeda, the economic impact is expected to be significant. For SUSTENANCE, the plan is to install wind turbines and solar panels for local energy production, along with a biogas generator and battery energy storage system. Specifically, solar PV system of around 30 kW and small wind turbine capacity of 9 kW. It is to be noted that, while there is high photovoltaic power potential in Jharkhand State, wind speeds are quite low in this area.[1] Therefore, the SUSTENANCE project team will develop and test a prototype for innovative low-speed wind turbines. It is expected that local renewable energy generation will meet the current energy demand, however, in the future with expansion of energy requirements, additional RE sources would be required to meet the future energy demand locally.

Energy uses

What is the economic relevance of the main energy uses, and flexibility mechanism in the project site?

The Barubeda village consists mostly of residential houses. There are currently no systems in place to supply water and electricity, nor to treat wastewater. Therefore, primary energy use is for domestic load including residential load. Additionally, energy will be used for the water supply system and for charging e-rickshaws; there will be two charging stations in the demo site. The energy will be supplied by the wind and solar installations, combined with a battery. Besides this, biogas will primarily provide power for cooking applications along with electricity supply through the biogas generator. The Biogas plant will meet the cooking demands of the villagers replacing the current use of firewood. The water pumping system is expected to cater for the domestic water needs of the village. In addition, multi-utility heat pumps will also be deployed at the site.

The SUSTENANCE project will explore several opportunities to synergise different energy vectors by optimally integrating and operating such energy carriers in order to exploit the flexibility offered by different energy carriers. For example, biogas-based electricity generation will be used during peak load hours to support the rising load due to lighting and other household load and falling solar PV generation. Similarly, water pumps will be operated to store the water in local storage tanks during off peak hours during the day when solar PV generation will be high. Therefore, all the energy carriers will be controlled to operate in an optimal manner. Secure and stable operation of the energy system by maintaining generation-load balance under intermittent and variable RE generation is a very important target of the energy management system that will be deployed at this site.

3.1.4 Relation between energy services and the social-economic characteristics of the Barubeda village demo site

Social organisation, self-governance and economic decision making

From an economic perspective on energy services does the social organisation play a role in the energy market within the project community? Is there a formal citizens' representation within the community, and are community members able to influence economic energy services and energy market-related decision-making?

Barubeda is a tribal village, so there are no formal clubs or associations within the community, neither on energy or sustainability topics, nor on unrelated topics. However, the under SUSTENENACE project, a village energy committee (VEC) has been constituted which officially represents the project community. The primary motivation around the energy sector that binds the local village community is the need for electricity, water, cooking and transportation utilities that this village is keenly looking for,

[1] *Photovoltaic power potential and wind speeds were retrieved from Global Wind Atlas and Global Solar Atlas.*

as a local energy system will elevate their economic status by improving their agriculture (cattle etc.), giving access to the nearest market for selling their locally grown vegetables and other agricultural products due to easy market access and provision for drying and storing the milk and other agriculture products increasing its shelf life. Therefore, the VEC is currently the primary community group which represents the village inhabitants.

The local VEC is expected to manage the billing for different utilities including electricity, water, cooking and transportation. Through the VEC, the billing of different utilities collected from each house will be manage through the VEC bank account which will be locally managed. All the utilities provided to each household are planned to be metered, and accounting is expected to be done by the VEC. Moreover, villagers will have the choice to provide raw material, for example cow dung for the biogas plant that is to be deployed in the local energy system, and such raw material contribution from the villagers will be accounted for in their monthly utility bills. Post project period, it is expected that industry partners and/other relevant industries would be interested to manage the local energy system. An adequate business model will be developed for sustainable operation of the local energy system, particularly beyond the project period.

Energy values and motivations

Is there an economic motivation for the community members in the project site to (1) switch to local, renewable energy and (2) become as self-sufficient as possible?

There are three common motivations across the Barubeda community for establishing a local, renewable energy system and becoming self-sufficient. The first and most important motive is economic: the residents of Barubeda are economically poor and therefore appreciate measures for cost saving. Simultaneously, ecological and social motives also play a role to some extent. There is a common aim or interest across residents to reduce carbon emissions and to take charge of their own energy system. Overall, there does not seem to be any disagreement in the community, implying that these motives are generally not disputed.

The main focus of the project community in Barubeda is to provide reliable access to energy and to do so in a cost-efficient manner. Since the village is remote and currently off-grid, and its residents are relatively poor, an energy system with micro-grid and locally produced energy is simply the most desirable option. Hence, autarky and self-sufficiency are not objectives as such but are aspirations in line with the technical and social conditions within the Barubeda community.

3.1.5 The Borakhai village demo site

Borakhai is a village in Assam state in eastern India, located close to the city of Silchar. The village is partially electrified, but electricity is only available for a limited number of hours each day. Domestic water supply is unreliable. Inhabitants primarily use firewood for cooking and kerosene-based lamps for lighting, although some houses have a liquefied petroleum gas (LPG) connection. The transportation system is very limited and unreliable.

The demo site in Borakhai village comprises around 80 houses, split across two locations that are close to each other. Within SUSTENANCE, a multi-energy cluster based on renewable energy sources will be developed for the village, which will include electricity and domestic water supply systems, an e-rickshaw-based transportation system, and a biowaste-to-manure conversion facility. Power generation will be based on solar PV systems and wind, coupled with a battery storage system.

3.1.6 Economic aspects of the physical-technical characteristics of the Borakhai village demo site

Technological dependence

Can grids within the demo site be characterized as (1) power on-grid, (2) PV power on-grid, (3) PV power off-grid, (4) PV – microgrids?

Borakhai village is partly and temporarily electrified; and has a weak and unreliable grid connection. To further improve the living standards of the villagers, the goal is to connect all the circa 40 households to a more reliable partial grid. This is a micro-grid or subnet for internal distribution, which in turn is connected to the larger grid. The type of grid integration is a collective connection with autonomous internal distribution mechanisms, whereby locally produced energy will be fed into the grid. Specifically, the goal is to ensure reliable power supply to the local demand by sourcing electricity from Solar PV supported by small wind turbines and battery storage system. The local islanded grid will optimise the use of different generation technologies in electricity vector and across other energy vectors including water pumping system, and transportation. A smart energy management and scheduling tool will be used to operate the off-grid system in optimal and economic manner.

Local renewable energy resources

What is the economic relevance of the current installed capacity for energy production from RES and planned expansions, compared to the energy demand?

Since there is currently only partial and temporary electrification in the village, the economic impact could be significant. Some houses only have a connected load of less than 200 W, limited to a few hours a day. For others, it is a maximum power of 0.5 kW. Overall, the villagers are getting electricity for less than one-third of the day. For SUSTENANCE, the plan is to install wind turbines and solar panels for local energy production, alongside a battery energy storage system. Specifically, a solar PV system of around 32 kW and small wind turbine with a capacity of 7 kW. It is to be noted that, whilst there is high photovoltaic power potential in in Assam State, wind speeds are quite low in this area[1]. Therefore, the SUSTENANCE project will develop and test a prototype for innovative low-speed wind turbines. It is expected that local renewable energy generation will meet the local energy demand currently, however, in the future with expansion of energy requirements, additional RE sources would be required to meet the future energy demand locally.

Energy uses

What is the economic relevance of the main energy uses, and flexibility mechanism in the project site?

The Borakhai village consists mostly of residential houses. Except weak grid connection of some of the villagers, there are currently no systems in place to supply water and electricity, nor to treat wastewater. Therefore, primary energy use is for domestic load including residential load. Additionally, energy will be used for the water supply system and for charging e-rickshaws; there will be two charging stations in the demo site. The energy will be supplied by the wind and solar installations, combined with a battery. Besides this, biowaste plant will be used to produce manure for local farming. The water pumping system is expected to cater domestic water needs of the village. Further, multi utility heat pumps that will be deployed at the site.

The SUSTENANCE project will explore several opportunities to synergies different energy vectors by optimally integrating and operating such energy carriers to exploit the flexibility offered by different energy carriers. For example, biogas-based electricity generation will be used during peak load hours to support the rising load due to lighting and other household load and falling solar PV generation. Similarly, water pumps will be operated to store the water in local storage tanks during off peak hours during the day when solar PV generation will be high. Therefore, all the energy carriers will be controlled to operate in an optimal manner. Secure and stable operation of the energy system by maintaining generation-load balance under intermittent and variable RE generation will be very important target of the energy management system that will be deployed at this site.

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3.1.7 Relation between energy services and the social-economic characteristics of the demo site Borakhai village

Social organisation, self-governance and economic decision making.

From an economic perspective on energy services does the social organisation play a role in the energy market within the project community? Is there a formal citizens' representation within the community, and are community members able to influence economic energy services and energy market-related decision-making?

Since Borakhai is such a remote village, so there are no formal clubs or associations within the community, neither on energy or sustainability topics, nor on unrelated topics. However, under the SUSTENENACE project, a village energy committee (VEC) has been constituted which officially represents the project community. The primary motivation around the energy sector that binds the local village community is the need for electricity, water, and transportation utilities that this village is keenly looking for, as a local energy system will elevate their economic status by improving their agriculture, providing access to the nearest market for selling their locally grown vegetables and other agricultural products and providing provisions for drying and storing the vegetables and other agriculture products increasing their shelf life. Therefore, the VEC is currently the primary community group which represents the village inhabitants.

The local VEC is expected to manage the billing for different utilities including electricity, water, and transportation. Through the VEC, the billing of different utilities collected from each house will be manage through the VEC bank account which will be managed by the VEC. All the utilities provided to each household are planned to be metered, and accounting is expected to be done by the VEC. Moreover, villagers will have the choice to provide raw materials, for example cow dung for the biogas plant that is to be deployed in the local energy system, and such raw material contribution from the villagers will be accounted for in their monthly utility bills. Post project period, it is expected that industry partners and/other relevant industries would be interested to manage the local energy system. An adequate business model will be developed for sustainable operation of the local energy system, particularly beyond the project period.

Energy values and motivations

Is there an economic motivation for the community members in the project site to (1) switch to local, renewable energy and (2) become as self-sufficient as possible?

There are three common motivations across the Borakhai community for establishing a local, renewable energy system and becoming self-sufficient. The first and most important motive is economic: the residents of Borakhai are economically poor and hence appreciate measures for cost saving. Simultaneously, ecological and social motives also play a role to some extent. There is a common aim or interest across residents to reduce carbon emissions and to take charge of their own energy system. Overall, there does not seem to be any disagreement in the community, implying that these motives are generally not disputed.

The main focus of the project community is to expand the existing energy system to make it more reliable access to energy, and to do so in a cost-efficient manner. Since the village is remote and its residents are relatively poor, an energy system with micro-grid and locally produced energy is simply the most desirable option. Hence, autarky and self-sufficiency are not objectives as such but are aspirations that are in line with the technical and social conditions within the Borakhai community.

3.1.8 IIT Bombay campus demo site

The IIT Bombay campus is located within the urban area of Mumbai, the second most-populous city of India with a population of 12.5 million. The campus itself houses more than 10,000 people and receives 24/7 electricity from the main grid. It also has a solar PV system of 1 MW installed capacity. The objective of the demo site is to set up a smart integrated energy system comprising a smart electric building with its own micro-grid and EV charging infrastructure, including vehicle-to-grid (V2G) services.

3.1.9 Economic aspects of the physical-technical characteristics of the IIT Bombay campus demo site

Technological dependence

Can grids within the demo site be characterized as (1) power on-grid, (2) PV power on-grid, (3) PV power off-grid, (4) PV – microgrids?

The IIT Bombay campus in Mumbai provides a significantly different demo site, compared to the two rural villages of Barubeda and Borakhai in India. The IIT campus already has a connection to the grid, through a dedicated 22 kV feeder. This results in 24/7 power supply from the main grid. Moreover, the campus already has a rooftop solar PV system of around 1 MW installed capacity. The plan for IIT Bombay is to expand the energy system with an intelligent electric vehicle charging infrastructure, utilizing local renewables, which will be coupled with a smart electric building system.

Local renewable energy resources

What is the economic relevance of the current installed capacity for energy production from RES and planned expansions, compared to the energy demand?

As mentioned, the IIT Bombay campus already has a rooftop solar PV installation that makes up for 1 MW. This installed capacity for solar energy will not be expanded. However, the plan is to add a wind turbine for 3 kW electricity along with a small battery storage for a local smart electrical building. Although, while photovoltaic power potential in Mumbai is quite high, wind speeds are relatively low in the area. The local energy generation from Solar PV system is currently not meeting the local demand which is predominantly met from the local grid.

Energy uses

What is the economic relevance of the main energy uses, and flexibility mechanism in the project site?

The energy uses on the IIT Bombay campus are mostly for providing educational services, and hosting students and employees. Besides this, energy use is for the more than 10 charging points that will be installed at the IIT Bombay campus.

Therewith, the SUSTENANCE project will mostly explore synergies between energy and mobility, and local smart electric building based controllable load and generation. The project focuses on expanding the existing energy system with an intelligent electric vehicle charging infrastructure. Besides, in the smart electrical building, the local energy will be met from existing rooftop PV generation of 10 kW capacity and wind energy along with a Battery storage of around 30 kWh capacity. Further the local controllable load through the appliances in the house will be controlled to exercise the flexibility and demand side response at household level.

3.1.10 Relation between energy services and the social-economic characteristics of the demo site IIT Bombay campus

Social organisation, self-governance and economic decision making

From an economic perspective on energy services does the social organisation play a role in the energy market within the project community? Is there a formal citizens' representation within the community, and are community members able to influence economic energy services and energy market-related decision-making?

The IIT Bombay campus is managed by the administration of the Institute. Besides, there are several local communities repressing residents and student community separately, some of them being officially recognised forums. Moreover, there are a few clubs/forums which promote carbon free system. There is a high degree of consensus regarding the energy system to be installed (see section on values and motivations), which does hint at some degree of social organization.

As with the social organization of the community, the governance network does not include many actors or organizations. Besides the SUSTENANCE project team, there is the IIT Bombay campus administration, which is a public organization. The two IIT Bombay campus administrations cooperate with the SUSTENANCE team wherever this is required, for example for administrative approvals. There is no formal representation of the users of the building or energy system. Simultaneously, there appears to be very strong trust throughout the community in the project team to implement the local energy system.

Energy values and motivations

Is there an economic motivation for the community members in the project site to (1) switch to local, renewable energy and (2) become as self-sufficient as possible?

There is a focus on developing a sustainable energy system. The main focus of the project community at IIT Bombay is to develop an intelligent electric vehicle charging infrastructure, utilizing local renewables, which will be coupled with a smart electric building system. Autarky and self-sufficiency are not objectives as such, though the related aspirations fit with the technical and social conditions at the IIT Bombay campus.

3.1.11 Netherlands

3.1.12 Vriendenerf

Vriendenerf is a community-led eco-housing project in the village of Olst in Overijssel. It comprises 12 residential units and a community building, all built between 2016 and 2017. The houses were constructed according to ‘zero energy building’ standards and are equipped with solar panels, heat pumps and ground thermal storage. The community recently also constructed an EV charging station.

Within SUSTENANCE, Vriendenerf aims to explore ways to exchange energy and flexibility within the community, with the underlying objective to increase the community’s sustainability and achieve a higher level of renewable energy generation.

3.1.13 Physical-technical characteristics Vriendenerf

Technological dependence

Can grids within the demo site be characterized as (1) power on-grid, (2) PV power on-grid, (3) PV power off-grid, or (4) PV – microgrids?

The Vriendenerf community is integrated into the larger municipal electricity grid via a reciprocal, i.e., two-way, connection, meaning it receives electricity from outside of the community, while also providing locally produced electricity back to the grid. Each residential unit is connected to the electricity grid via its own meter and feeds the surplus electricity from its solar panels back to the grid individually. Residential units are not connected to the gas grid, only the common building currently receives gas for heating purposes (see ‘Local renewable energy resources’). The houses in the Vriendenerf community are served by three different energy suppliers that supply ‘green’ energy: Greenchoice (9 residential units plus common building), VandeBron (2 residential units), Pure Energie (1 residential unit).

Vriendenerf does not have its own micro-grid or local battery capacity, meaning it is dependent on the municipal grid for the facilitation of all energy transactions and the storage of surplus energy.
The demo site is PV power on-grid.

Local renewable energy resources

What is the economic relevance of the current installed capacity for energy production from RES and planned expansions, compared to the energy demand?

The local electricity demand is met with solar PV systems on the three residential units with a total installed capacity of 6,360 – 5,565 – 6,360 Wp, respectively. After covering the local in-unit electricity demand, an estimated surplus of 2,000-3,000 kWh is provided to the grid per residential unit each year. Due to building characteristics, there is a low energy demand, which simplifies the full coverage of energy demand from local RES.

Residential units have individual ground source heat pumps to cover their energy demands with regards to heating, passive cooling and domestic hot water. The electricity needed to operate these heat pumps is provided by the solar PV system. The common building, however, is still connected to the gas grid and uses a high-efficiency boiler for heating and warm water. The community is planning to replace this boiler with an electric ground source heat pump in the foreseeable future to eliminate the need for gas.

Energy uses

What is the economic relevance of the main energy uses, and flexibility mechanism in the project site?

Vriendenerf is a small residential neighbourhood, with the main energy uses being domestic heating and hot water, both of which are covered by individual heat pumps in each residential unit. Electricity is used for the standard domestic uses and for the operation of the heat pumps. Some surplus electricity is used in a local EV charging station, allowing for electric mobility. As the Vriendenerf community is planning to expand its EV charging infrastructure, this energy use will likely increase in the foreseeable future.

Given that there are no commercial or industrial users with significant energy demand or complex usage patterns, the energy uses in Vriendenerf are relatively simple and easy to predict. They also provide some degree of flexibility to react to fluctuations in the local electricity production from solar PV, as community members can adjust their use of large household appliances or limit EV charging during times of low electricity production. This does, however, require the information networks to create awareness for such fluctuations and the willingness of community members to adjust their behaviour accordingly.

Energy sharing with other actors in the municipality is foreseen in the near future.

3.1.14 Relation between energy services and the social-economic characteristics of the demo site, Vriendenerf

Social organisation, self-governance and economic decision making

From an economic perspective on energy services does the social organisation play a role in the energy market within the project community? Is there a formal citizens' representation within the community, and are community members able to influence economic energy services and energy market-related decision-making?

The Vriendenerf community consists of the 21 residents living within the neighbourhood. From its inception, the project was specifically designed for and by people older than 50 years. The community has formed a wide range of groups to organise daily life and various activities within Vriendenerf. There is an homeowners' association (Vereniging van Eigenaren / VvE) with a General assembly, a Daily Board and association rules and activity focused groups. All these groups consist of inhabitants, with participation being voluntary. They act when needed and report to the general meeting or in the meeting of inhabitants and contribute to the yearly report of the association. The wide range of groups activating community members, as well as Vriendenerf's nature as a community-driven project indicate a high level of social organisation and strong community cohesion, centred around sustainability issues.

The community has no formal relations with other organisations or actors; however, they do maintain contact with the municipality Olst-Wijhe and coordinate where needed, and interact with other communities who are interested in increasing their sustainability and self-sufficiency. In addition, community members are active in various other organisations, such as the local energy cooperative "Goed Veur Mekare," and contribute to ecological activities in the broader Olst community.

Energy values and motivations

Is there an economic motivation for the community members in the project site to (1) switch to local, renewable energy and (2) become as self-sufficient as possible?

There is broad agreement among the Vriendenerf community on energy values and the motivation to be as sustainable and self-sufficient as possible. To a large degree, this is due to the nature of the Vriendenerf project, which was motivated by environmental values from the onset: the goal of the project was to provide a "house for life" for people of the age of 50+, using building techniques as environmentally friendly as possible and showing an energy performance of at least zero-energy (Vereniging Vriendenerf, 2012). Only people who agreed on these plans and values joined the initial group and later became members of the community. New potential residents are selected by the current community members to fit this profile as well.

Next to environmental values, some people also have social motivations to be part of the community, mostly related to being able to take charge of their own energy system. According to the SUSTENANCE spokesperson of the Vriendenerf community, economic motives compared with sustainability motives, do not play a large role for the community members.

The Vriendenerf community largely prioritizes sustainability and self-sufficiency, with the goal to maximize local production beyond energy, for example by growing vegetables and fruit in the community garden. At the same time, however, there appears to be a strong vision to share the surplus of locally produced resources with the larger community around them, indicating that while self-sufficiency is desired, off-grid is not.

3.1.15 Slimpark Living Lab

The demo site Slimpark

Slimpark is a small EV charging station of 0.1 ha, including with nine parking spots. It is located on the suburban University of Twente campus, in between the cities of Enschede and Hengelo. It is a self-sufficient EV charging station, powered by a 27 kWp solar panel rooftop and equipped with battery storage. It is a living lab used by researchers to study self-sufficient energy systems and user interactions with the system and will be used to explore new methods of direct interaction between user and energy system, e.g., via innovative apps or business models.

3.1.16 Physical-technical characteristics of the SimPark demo site

Technological dependence

Can grids within the demo site be characterized as (1) power on-grid, (2) PV power on-grid, (3) PV power off-grid, or (4) PV – microgrids?

Slimpark is outfitted with its own micro electricity grid for distribution within the project area. The micro grid is connected to the larger campus grid of the University of Twente, for which the university itself acts as distribution system operator (DSO). The local energy infrastructure allows the Slimpark grid to internally balance the locally produced electricity and the EV charging stations, combined with a battery for electricity storage (capacity 30 kWh / 10 kW).

One of the objectives of the Slimpark project is to minimize grid usage of the combined assets. Having both its own microgrid, and for the time being, sufficient electricity storage capacity via the local battery, supports this objective. Although here is minimum grid usage, there is still the option. The best description would be a PV power on-grid microgrid.

Local renewable energy resources

What is the economic relevance of the current installed capacity for energy production from RES and planned expansions, compared to the energy demand?

The Slimpark roof is fully covered with a solar PV system with 27 kWp installed capacity, serving the nine EV charging spots included in the project. This is currently sufficient to cover the electricity demand of the project, due to the combination with electricity storage and a smart charging system. However, the PV system alone would not be able to supply sufficient electricity if all nine EV charging stations were to request full power at the same time. No expansion of the solar PV system is currently planned.

Energy uses

What is the economic relevance of the main energy uses, and flexibility mechanism in the project site?

The primary electricity use at Slimpark is for e-mobility, with nine EV chargers (22 kW AC). A small office building is attached to the carport, which is also supplied with electricity from the PV panels.
The available electricity storage in combination with the flexible use of the EV charging stations provides Slimpark with the ability to react to fluctuations in the local electricity production by adjusting the amount of electricity used to charge the parked vehicles. Part of the Slimpark living lab research projects indeed focuses on developing models to optimize the allocation of electricity based on local production and storage availability.

3.1.17 Relation between energy services and the social-economic characteristics of the demo site Slimpark

Social organisation, self-governance and economic decision making

From an economic perspective on energy services does the social organisation play a role in the energy market within the project community? Is there a formal citizens' representation within the community, and are community members able to influence economic energy services and energy market-related decision-making?

Users of the EV charging facilities are registered participants in the Slimpark project. They participate in the project by charging their electric cars while using a specifically prepared smartphone app to indicate available energy flexibility. The current cohort of users act as a test group within the living lab setting. At present, there is no information available on the characteristics of these users (e.g., socio-economic status, motivations to drive an electric vehicle), and the Slimpark research team is currently designing a survey to gather this data.

Specific social networks and organisational structures within the Slimpark project will most likely depend on the experiments with user interaction and different business models throughout the SUSTENANCE project. This includes considerations of whether the Slimpark project will be connected to the wider University of Twente community or remain a mostly stand-alone project with some university community members being users/customers.

There are two kinds of relationships between the Slimpark project team and other actors that are important to consider from a user decision influence perspective. There is a relationship between project team and users. Users need to register via the project website[2], according to the rules determined by the project team. Users can then provide feedback and share their experiences to the project team, which accounts for these inputs in the further development of the Slimpark project.

Second, the relationship between project team and external partner organisations. The key partners engaged in the Slimpark project are the University of Twente as owner of the carport and the local distribution system operator (within the campus), and the private businesses that supply technology to the project, namely AmperaPark, Mennekes and Kiwatt. The cooperation with these partners is in the context of different research projects, where project and data contracts describe the rules of interaction and the responsibilities of each actor.

Governance in the Slimpark project is therefore primarily formal and clearly defined in project contracts or user agreements. The research team is at the center of the governance system, while also dependent on the collaboration with external partners and the Slimpark users. At present, there is little community influence in shaping governance mechanisms.

Energy values and motivations

Is there an economic motivation for the community members in the project site to (1) switch to local, renewable energy and (2) become as self-sufficient as possible?

As of now, there is no information on the values and motivations of different users to participate in the Slimpark project or to use an electric vehicle yet. The research team is currently preparing to conduct a survey to fill this knowledge gap and learn more about the social profiles of the Slimpark users.

The research projects linked to Slimpark generally try to combine ecological and economic motives, trying to develop new technologies and management configurations that both decrease carbon footprints and create economic value. Slimpark is designed as a fully autarkic EV charging station, i.e., with the goal of not using any electricity outside of what is produced on-site.

3.1.18 Poland

3.1.19 The demo site Mickiewicza Street

The demo site in Poland focuses on Własnościowa Spółdzielnia Mieszkaniowa (WSM), a housing cooperative in Mickiewicza Street in Sopot, comprising five residential apartment buildings and one commercial building. Within the housing community, a micro grid-based integrated local energy system will be developed, that aims to include solar PV systems and heat pumps, as well as battery storage and EV installations. Smart control, monitoring and management systems will be applied to optimize the operation of the local system. As a first step, the SUSTENANCE project focuses on one apartment building, building number 59.

3.1.20 Physical-technical characteristics Mickiewicza Street

Technological dependence

Can grids within the demo site be characterized as (1) power on-grid, (2) PV power on-grid, (3) PV power off-grid, or (4) PV – microgrids?

The buildings in WSM are partially integrated into the larger electricity grid via a substation across the street and each apartment unit has its own meter. Electricity is supplied to the buildings by Energa Operator, which is part of the SUSTENANCE project team.

Gas is provided by the Polish Oil Mining and Gas Extraction S.A. company (PGING) via the regular gas grid as well, directly to each apartment with its own gas meter. As there is no direct supply of hot water to the apartments, each unit uses a gas oven to heat water individually.

There are currently no storage facilities for electricity or gas available within the project area, making both supply and storage of energy dependent on the larger grids.

Local renewable energy resources

What is the economic relevance of the current installed capacity for energy production from RES and planned expansions, compared to the energy demand?

WSM currently does not produce any energy from renewable sources. Over the course of the SUSTENANCE project, a PV system with an estimated capacity of 24.4 kWp will be installed on the roof of Building 59, with an expected annual electricity production of 20 MWh. Similar installations would eventually be installed on the other four apartment buildings as well. It is yet unclear whether this is sufficient to cover the overall energy use of all buildings.

Building 59 is like the other apartment buildings eleven storeys tall, built from concrete and insulated with polystyrene in the early 1970s. Water and wastewater services are provided by the municipality via the public network, however, the water pressure in the municipal network is not sufficient to reach the upper floors of the buildings. Instead, water is sent via a local hydrophore system for the upper floors, which makes the modernization of the domestic hot water system somewhat more complicated.

The 77 apartments in the Building 59 are currently heated (incl. hot water) by individual gas boilers. These will be replaced with central heating based on an air heat pump, which will also require the abovementioned modernization of the hot water system, as water is currently heated via the gas boilers within each unit.

Energy uses

What is the economic relevance of the main energy uses, and flexibility mechanism in the project site?

The primary energy uses in WSM are domestic, as most units are residential apartments. Within each flat, some energy is needed for common areas, including elevators and staircases. For the pilot building 59, this amounts to ca. 5400 kWh per year, based on data from 2018-2021. Additional electricity is needed for the commercial building and to light the walking paths within the project area, as well as for the hydrophore system to pump water to the upper floors of the buildings (ca. 9695 kWh per year). As part of SUSTENANCE, options for EV charging within the premises of WSM will be explored, adding another energy use.

3.1.21 Relation between energy services and the social-economic characteristics of the demo site

Social organisation, self-governance and economic decision making

From an economic perspective on energy services does the social organistion play a role in the energy market within the project community? Is there a formal citizens' representation within the community, and are community members able to influence economic energy services and energy market-related decision-making?

Across all five apartment buildings, the project area along Mickiewicza Street houses is several hundred households, giving the demo site a relatively large community. However, there is no indication of significant social cohesion or social life within the community. The housing cooperative itself is primarily concerned with the facility management and daily logistics of the buildings but does not seem to offer social activities or platforms for informal dialogue among tenants. There do not seem to be any specific activities related to energy or sustainability either.

The housing cooperative Własnościowa Spółdzielnia Mieszkaniowa (WSM) is the central governance actor in this demo site. It is led by a management board and a supervisory board and includes several committees in charge of different tasks related to facility management. The General Members Assembly is WSM's highest decision-making body, allowing community members to voice their opinions and to vote on the boards and other relevant decisions. The cooperative has a set of statutes and regulations that govern life in the WSM flats, related to conduct towards other tenants, water and energy supply, waste management, fire protection, and others.

Within SUSTENANCE, project partners next to WSM include the Institute of Fluid-flow Machinery at the Polish Academy of Sciences (IMP), the energy supplier Energa Operator, and the companies KEZO and STAY-ON, both of which are involved in the provision and management of new energy system technology.

Energy values and motivations

Is there an economic motivation for the community members in the project site to (1) switch to local, renewable energy and (2) become as self-sufficient as possible?

The primary motivation for WSM's move towards renewable energy generation and autarky is economic, i.e., to reduce energy costs. There is broad agreement on this within the community. At the same time, ecological motivations have become more common as well, and the community considers 'going green' as an important step and wants to set an example locally. While the main focus of the demo site is on the economic benefits of local energy production from RES, the idea of being a local frontrunner for ecological energy transitions could be an entry point for further development in the direction of autarky.

4 Analysis and conclusions

4.1.1 Characteristics of the demo sites and business model criteria

In deliverable D2.1 the overall perspective of the technical specifications, requirements, and system architecture to establish integrated local energy systems at the various demo sites in the SUSTENANCE project are described. In this deliverable, we focus on the energy services for consumers, both households and businesses, in the demo sites. In the seven demo sites, the end energy users are mostly households in residential houses or apartments or EV car drivers. An exception is the educational services on the Bombay campus. It is not clear the extent to which in the residential areas, particularly in the Indian villages, there are small businesses using the energy.

To build carbon-neutral energy communities, different energy assets and resources in a local area need to be brought together. PV electricity generation dominates in all the demo sites. Therefore, our literature review of distributed energy systems focussed on PV generation. Only in the three Indian demo sites, are there plan for wind power. In the Barubeda village biogas will also be provided for cooking applications. And in the Borakhai village demo, a biowaste-to-manure conversion facility will be created. The demo site user cases are all at varying stages of development. In the Vriendenerf demo, the IIT Bombay campus demo, and the Slimpark demo the PV generation is already installed. In the IIT Bombay demo, the plan is to add a wind turbine. In the Voerladegård demo, nine of the twenty houses already have PV installed. In the Indian rural villages, PV and wind generation capacity need to be created. Most residential Indian village houses are not suited for PV on roofs. In the Polish Mickiewicza Street, a PV system will be installed on the roof of the demo building 59.

For a carbon-neutral business model, the carbon-neutrality of the demos depends on the availability of renewable power-on-grid or power off-grid. Only the Barubeda village demo might be in a fully off-grid situation. In some of the other demos electrical storage is present (Slimpark) or planned (Barubeda, Borakhai, and Mickiewicza Street). It is currently unclear if this will enable the complete avoidance of using non-renewable electricity from the grid. Only in the Vriendenerf demo, is there an overall surplus of PV electricity to the grid, in all other cases there is just a temporary or seasonal surplus.

In the business model, the exact use of renewable and non-renewables needs to be calculated. This determines the costs of energy use if we take into account the investments in renewable energy generation, storage, and the market prices for the (non-)renewables in the demo case. The existing situation is the benchmark for the (partly) carbon-neutral demo to be created. The cost of the (PV) energy generation in the new demo sites are determined by (1) the main components of the PV-on grid or microgrid design with purchase prices, (2) the cost of installing the PV-on grid or microgrid and hours in development and management, (3) the generation of electricity based on calculations and measurements of generated electricity during the demonstration.

Studies show numerous benefits of distributed electricity services with renewable energy. The benefits in the business models of such a distribution this can be divided into individual and collective ones for the producers and consumers of electricity. The benefits can be substantial and compensate for the higher costs of distributed electricity services with renewable energy compared to traditional power-on-grid, but not all are well assessable. Without distinguishing if the benefits can be assessed we discussed in Chapter 2 the following benefits.

- Benefits for individual larger producers' interests (not prosumers) are risk reduction due to the diversification of energy and financial resources, pricing of electricity as a marketing tool, cost-saving operations, and changes of current.

- Benefits in the collective interests of the large producers (not prosumers) are the mitigation of impacts and optimization through deference of costly expenditures, lower import-dependency, and support of local stakeholders.
- Benefits to the individual consumer (not prosumers) are the shaving of the peak prices and the prevention of peak consumption.
- Benefits to the collective interests of consumers (not prosumers) are the contributions to local economies and the contribution to local social interests.

We also discussed the willingness to pay for renewable energy on the grid and for off-grid uses. For citizens, what they are willing to pay depends on the energy service they will get in the new situation against which costs. And on which (part of the) energy service is replaced. This depends on what is actually replaced or added in terms of the main components of the microgrid design. This needs a calculation of the main components' purchase prices, cost of installation, hours in development and management, and the actually generated electricity during the demonstration. Which can be used for a comparison of how much more (or less) costs need to be paid in the new situation compared with the old situation. The calculations and measurements of generated electricity during the demonstration depend on the (future) energy use. New energy uses, like EV charging, lead to a different comparison with the old situation.

A particular value of the new situation for the business model is the carbon neutrality of the demo site. It is not just about a new distributed energy service but a renewables-based energy service. This means we eventually need to know what fossil fuel energy use is actually replaced in the demo site. In the Indian village demos, there is simple and basic energy use. Local fossil fuel generators, and in the Borakhai site limited power from the grid, will be replaced with PV and Wind-generated electricity. In the Voerladegård demo, it is the household grey electricity from the grid and the heating gas. In the Vriendenerf demo, the gas heating of the common building is replaced. In the Mickiewicza Street demo site, the heating (incl. hot water) by individual gas boilers will be replaced with central heating based on an air heat pump for the apartments. In the IIT Bombay case, fossil fuels used by educational services and housing were already is already replaced. In the Slimpark demo, there was no previous use. Apart from the EV loading as a prime goal in the Slimpark demo also in some other demos EV charging is planned, for public transport or private cars. During the demonstration period, we have to see in how far the carbon neutrality of (part of) the demo site as a particular value in the business model is reached, against which costs

Further, energy use can be made smarter, so (renewable) energy use is lowered. In all demos either in the individual households or in the system as a whole there are measures to use energy smarter and eventually save energy through energy management systems and flexibility measures. While comparing the old and new situations in the business model, in the energy use calculation this energy saving needs to be taken into account. The business model needs to show if the new energy services are more expensive than the old situation, where the old situation needs to be extrapolated into the future to make a comparison possible.

For all demo sites, we asked the question if from an economic perspective on energy services the social organization plays a role in the energy market within the project community. In most demo sites there is no new and alternative organizational configuration yet. In the demo with apartment residents (Mickiewicza Street) there is an existing housing cooperative. In the Vriendenerf demo, there is an existing homeowner association. In the Voerladegård demo, there is a geographical neighbourhood organization. But this community is larger than the group of houses in the project. In the Indian demos, there is some inhabitant organization. In the Indian villages, the neighbourhood organization overlaps with the representation for the project, but the grade of organization related to the energy project is not yet clear. In the Slimpark demo, the car drivers are mainly voluntary project participants and customers. A strong social organization, particularly if there are in the demo sites specific clubs that represent the individual and collective citizens' interests, might lead to social norms on renewable energy use, investments, and savings (Coenen and Hoppe, 2021). The way the community is socially organized relates to the question if: *there is also a formal citizens' representation within the community, and if community members are able to influence economic energy services and energy market-related decision-making.*

In the Voerladegård demo site, it is the private house owners who decide to invest. The private owners pay the equivalent of what they would usually pay to have just a heat pump installed. But since this system is more complex the added complexity is covered by the SUSTENANCE project. That there is a neighbourhood organization does not mean the private owners have to follow the decisions of this organization. In the Vriendenerf demo site, through the home-owners association, the citizens decide together about investments. In the Slimpark demo, there is little community influence on the demo decision-making. In the Mickiewicza Street demo, the citizens have influence through their membership in the housing cooperative. In the Indian demos, the influence is not yet clear. The Borokai village demo has a Village Energy Committee (VEC).

To understand how far citizens bear the costs of new energy services and/or get benefits from the new arrangements in delivering the new energy services, we also must see if new activities result from a new mix of energy sources and services. A main new activity seems to be EV charging. In the Indian demos, it is not clear yet if there will be economic activities due to the expansion of energy services in the communities. Another aspect that needs to be considered is to assess the business model from a citizen's perspective on potential new cost arrangements. Except for the private house owners in Voerladegård and the Vriendenerf demo sites, and in Mickiewicza Street by the housing cooperative, the investments were not done by the residents or residents cooperative but by other stakeholders. What does this mean for the energy cost the residents have to pay? Are there new costs arrangement through which residents pay part of all energy investment costs or arrangements where they will profit from lower future prices of renewable energy?

A related question for the business model is who profits from the new modes of flexibility. Does it lower the energy costs of the residents? If one party pays while the other benefits from new energy services this is a condition known as "split incentives", which mostly is a situation between owner and tenant. In the case of collective decision-making in the house owners or housing cooperation, this is not a problem. In the Slimpark demo, the citizens are not residents but customers of the EV charging. In the Indian demos, the cost arrangements need to be cleared.

4.1.2 Criteria for citizen-centred viable business models

The goal of this deliverable was to find, through a literature review and an exploration of the characteristics of the demo sites, criteria that make a citizen-centred viable business model for a decarbonised local integrated energy system.

Business models can be understood as the set of practices and relationships through which an organization "creates, delivers and captures value" (Osterwalder and Pigneur, 2010). In a citizen-centred viable business model of a local integrated system, the benefits should outweigh the cost for the citizens, which does not have to be an economic cost-benefit balance. The created values relate to the different benefits local integrated systems can have. In chapter 2 the benefits of distributed electricity services are divided into individual and collective ones for the producers and consumers of electricity. We concluded that these benefits can be substantial and compensate for their higher costs but not all are well assessable. From the perspective of the citizens the individual and collective benefits for the producers are less relevant. They are only relevant when the citizens are besides consumers also producers (prosumers) or if the citizens are members of a local energy community who produces energy.

This brings us to the first question relevant for citizen-centred criteria for business models for carbon-neutral communities: *What benefits is the decarbonisation of local integrated systems supposed to bring, and to whom?*

Based on the benefits found from a consumer individual interests' perspective, a business model is a more citizen-centred viable business model if it considers:

- *Lower price*, a lower purchase cost for the citizen as a consumer of electricity through the local integrated systems
- *Lower consumption and lower peak prices* for the citizen as a consumer of electricity through local integrated systems.
- *Financial compensation for explicit and implicit value of flexibility for citizens as consumers.*

Based on the benefits found from the consumer collective interests' perspective a business model is a more citizen-centred viable business model if it takes into account:

- Contribution to *local economies* due to the distributed electricity services.
- *Better services* for isolated consumers and alignment with the social demands in communities.

The second question relevant for citizen-centred criteria for carbon-neutral communities for business models is: *what costs decarbonisation through local integrated systems bring for the citizens, and how do these costs compare with centralized/decentralized fossil-fuel systems and between the demo site countries?*

Even if power-on-grid energy services are cheaper, these higher costs for a local integrated system might still be viable in a citizen-centred business model. In chapter 2 we discussed *t*he costs of electricity services off-grid in comparison to energy services on-grid. And of specific PV applications, with and without storage, compared to alternatives like heat-power generators and diesel generators. From the review we were not able to draw a unanimous conclusion about what costs decarbonisation through local integrated systems brings for the citizens and if these costs are higher than compared with centralized and decentralized fossil-fuel systems

For a citizen-centred viable business model, it is important were the higher cost land, with the citizens as consumers or with the producers, and the willingness to pay more costs by the citizens. A condition is that the (future) costs for the citizens are transparent for the citizens for a business model to be a viable citizens-centred business model. In a citizen-centred viable business model the (future) extent of energy services and which citizens' energy uses are part of the cost arrangements, and which benefits the local integrated systems bring to individual and collective consumers should be clear. During the demonstration period for transparency also the revealed costs and benefits are important to show to the citizens

- *In a citizen-centred viable business model citizens investment in equipment and (future) energy service costs should fit within the willingness to pay for specific benefits of local integrated systems.*
- *In a citizen-centred viable business model citizens investment in equipment and the (future) extent of energy services should be clear as well as which citizens' energy uses are part of the cost arrangements, and which benefits the local integrated systems bring to individual and collective consumers.*

The third question relevant for the citizen-centred criteria for carbon-neutral communities is: *What benefits is the decarbonisation of local integrated systems supposed to bring, and what different roles could citizens and local communities play in the business model and how might they interact with other key stakeholders?*

Some citizens might want to use energy services despite higher costs than alternatives given the benefits as we have seen above. A distributed energy service might be related to the will to belong to a specific social group or the community's commitment to the climate cause. But specific benefits might come with a different willingness to pay. The willingness to pay depends also on the influence the citizens have on the decision-making in the business model. The most far-reaching influence would be a formal local energy community with co-ownership and membership voting. But even in a democratically led energy community, there might be a discussion about individual and collective interests. For instance, does voting mean that individual citizens must give in to the majority vote.

- *In a citizen-centered viable business model attention should be given to the influence the individual citizens have on citizens investment in equipment and (future) energy service costs and should fit with the willingness to pay for specific benefits of local integrated systems.*

We have seen in the overview of the energy values and motivations of the demo sites that the main motivation for citizens to want to switch to local energy is reducing energy costs. Except for the Vriendenerf demo, other motivations are secondary and there are no specific motivations to become as self-sufficient as possible unless this is cheaper. Although willingness to pay might even be related to autarky and self-sufficiency as the ultimate form of decision influence. Only in the Vriendenerf demo self-sufficiency and autarky would be a value for the business model. This is not to be said that from an economic perspective, this might not change in the future for the other demo sites. A business model based on energy sharing among the community members might create a specific economic value for citizens, For the time being, the inability to legally construct and operate a microgrid and to locally store energy without formally becoming an energy supplier (with all associated obligations and market regulations) are the main impediments for sharing energy within a local energy community on a peer-to-peer basis (Butenko, 2016).

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[1] Photovoltaic power potential and wind speeds were retrieved from Global Wind Atlas and Global Solar Atlas.

[2] As of September 2022, the project is not accepting new registrations as it has reached the maximum number of participants. Interested EV owners can request to be added to the waiting list.

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0 Appendix 1

A literature review on costs and benefits of distributed energy systems

1. Introduction

This introduction defines the distributed energy systems and the scope of this literature review. While local energy systems, decentralised energy services, embedded energy and similar terms are used interchangeably without agreement about definitions, all these refer to generation and consumption of energy at an operational unit or several units in vicinity of each other, as opposed to centralised energy systems with energy transfer on large distances (Alanne and Saari, 2006).[2] Herewith, it is focused on electricity at households; electricity and power are used in alternation. An additional term is introduced by the European Union (EU) regulation: a network based on the distributed electricity system is referred to as a community energy network (EU, 2019).[2] This regulation allows under several conditions distribution of electricity by the private entities: firms, social organisations and individuals. A community energy network covers persons, who generate, distribute and bundle loads, along with other energy services delivered to a network under the conditions that the community membership is open, voluntary and provides the right to use energy and be paid for deliveries. For example, in the Netherlands permits could be provided by the authority on consumers and markets (ACM) to the networks within a geographic area, below 500 customers on the net, without non-household customers, if technical and production activities pose no safety risks (ACM, 2023).[2]

In this literature review, the distributed electricity systems are compared to the centralised electricity network, called grid. A distributed energy system can refer to a household, group, a neighbourhood in city, or a village, that operate an electricity network based on generated fossil fuels (coal, oil, gas, and nuclear) and renewable energy (biofuels, hydropower, geothermal, wind, solar, and marine). Main difference between those systems is the scale of activities. The centralised systems generate electricity in large-scale power plants (a few to hundreds MW capacity), transmit high voltage power (hundreds kiloVolt – kV) across tenths kilometers, distribute mid-high voltage power (tenths kV) and deliver low voltage for consumption (usually 220 V in Europe and India). A community electricity network can generate and consume electricity in a mini-grid within households, which can operate stand-alone when grid is unavailable, or deliver excess of power after consumption to the grid (hybrid), distribute electricity in local mid-high voltage networks within a few kilometers area (microgrid), and combine those alternatives. It can serve a few citizens up to a few thousands in dense cities. In the EU, spatial limits are required for obtaining a permit, but the requirements vary across countries. For example, that limit refers to the postal codes in the Netherlands, to private distributors in Denmark, and is 'local' in Sweden (Maldet et al, 2022);[2] the regulation is pending in Poland and India. Another requirement is the non-discrimination of consumers, which means that all consumers must be able to use the community electricity networks (EU, 2018).[2] While interpretations of this requirement is unclear it can be an issue when a community network causes costlier distribution on-grid because some consumers switch to cheaper community networks.

Various technological, institutional and operational issues of the distributed electricity systems are covered in a comprehensive, open-source checklist, which can be useful for setting up of a project (Bjarghov et al, 2021).[2] This literature review is purposed in support of socio-economic criteria for demonstration projects in the SUSTEANCE project. It focuses on costs and benefits of the renewable energy-based distributed electricity systems as a whole with references to realised and professionally proposed projects. Insofar the transactions between power generators, transmitters and distributers are relevant for the whole system, these market interests are briefly touched in the Section 2. That focus on costs and benefits is justified by the consumers' and suppliers' prime interests in the cost-saving and value addition, respectively. They can face high costs caused by small scale, low energy density of renewable energy resources that requires much space, energy storage to counter variability in time, and others. Costs of the distributed electricity systems are indicated in Section 3. A multi-carrier system integration can reduce the costs; for instance, power along with heating through air conditioners and heat pumps, EV-charging, and others. Furthermore, the cost is only a part of the story as there are several tangible benefits to be considered in decision making about the centralised or distributed electricity system. The benefits are discussed in Section 4.

To avoid misunderstandings a few economic terms are defined beforehand. All power services involve subsequent efforts in generation of knowledge, constructions and purchases of equipment, followed by operations with maintenance and management, ending with disposal. During such life time, those efforts cause expenditures in materials, capital, labour and knowledge. Expenditures on equipment and constructions that are used for several years, called investments, are depreciated to obtain the annual capital costs, whereas operations involve labour and materials costs, called operational costs; similar holds true for expenditures in maintenance. The sum of capital costs and operational costs in a period, usually a year is considered, constitutes the total costs. The total costs can be divided by the total deliveries of energy to obtain the marginal costs, or unit costs. In the Anglo-Saxon literature on energy the unit costs are often labelled as the levelized cost of energy (LCOE) when the costs and energy deliveries are considered in the life time but costs assessments rarely cover all activities in the life time. Below, the term unit cost is used. If the total costs address the past, they can be corrected for inflation to obtain the real, or constant costs. The expected expenditures in the future are discounted in time at an interest rate in order to obtain the present value of future expenditures. A business model is a concept how an organisation can generate benefits to cover costs and make profit.

2. Market interests

2.1 Centralised systems (on-grid)

The centralized electricity systems encompass a value chain of generated alternating current in power plants that is transformed into high voltage loads transmitted on long distances to distribution units from where mid-voltage and low-voltage electricity is delivered to consumers. In this business model based on economies of scale, power supply determines demands. Central coordination of the technical and economical dispatch is necessary for all those power generation units; load units for high voltage transmission; interconnection of the generation plants to optimize on various characteristics of energy resources along with lowering the need for costly reserve capacity; and offering low and differentiated rates to cultivate mass consumption. That coordination is fulfilled by the state in most countries. While the electricity generation in the EU is largely privatised from 1990s onward, the transmission and distribution are operated by the public companies, utilities, which are obliged to deliver electricity to all citizens. Exceptions exist, for example, large power generator in Sweden is public (Vattenfall); small-scale private distributors also operate, and large firms that are permitted to generate, transmit and distribute power. In India, the electricity value chain is usually public; the generation and transmission of electricity is usually managed by the federal authorities and distribution by the states.

Injections of generated electricity and withdrawal for consumption must be continuously balanced on the networks. If electricity injections and withdrawals deviate from each other within seconds, the alternation frequency starts to depart from its reference value, which is 50 Hz in Europe and 60 Hz in the US. A deficit of injections with respect to withdrawals results in a frequency drop, while a deficit of withdrawals with respect to injections results in a frequency increase. If the frequency deviates too much from its reference value, protection devices start to disconnect power generation and loads within minutes. Such disconnections can lead to a cascading failure that can result in a system-wide blackout. To avoid that transmission system operators (TSO) and distribution system operators (DSO) put in place procedures for load frequency control, called ‘electricity balancing’, to manage real-time power balances for load frequency control. Voltage and alternation frequencies on the transmission lines must be balanced throughout the cross-countries interconnections, while power excess is stored. The transmitted high-voltage is transformed by the distribution companies into mid-voltage power and distributed to customers (Schnitkatte and Pototschnig, 2022).[2] There is usually one TSO in a country and several DSO’s as shown at the end of this Appendix; similar situation is in India with the interstate transmission and state-wise distribution.

Costs are covered by charges of transmitters and distributers for injection of power into the grid, for connections, reactions, time-of-use network. All together, they constitute the networks tariffs paid by final consumers; those charges are usually averages of the past costs and expected future costs which are usually passed from transmitters to distributers and then, to the final customers (ACER, 2023)[2]. The wholesale prices, it is the prices paid by the distributers is set on the electricity auctions within a few minutes, which evolves largely with automated bidding. The wholesale prices fluctuate per hour mainly depending on the balance between electricity injection and consumption. More than fifty times large monthly price variations are observed across countries; for example, from € 0.01 per kWh to € 0.5 per kWh in 2022.[2] Those annual average wholesale prices in the EU are about € 0.12 per kWh, out of that about 75% are directly linked to transmission, 25% are other costs. The transmissions operate efficiently as the wholesale prices did not change much from 2017 to 2020, whilst the share of the costs directly linked related to the transmission did steadily increase (ENTSO, 2018).[2] Given that the distributed electricity systems avoid transmissions, these costs can also be avoided. However, those wholesale costs constitute only 20% to 23% of the network costs paid by consumers to the distributers (DSO) and taxes. It implies that the hybrid models of distributed electricity systems hardly save costs of the centralised electricity systems.

The reason that the electricity market was established as a large integrated technological system has much to do with costs; many assets are specific technologies that are only relevant for the fossil fuel-based electricity system. This creates problems related to the mitigation of financial risks for investors, as those assets require substantial upfront investments. The economy of scale is an important risk mitigator, leading to a natural grid monopoly. Electricity additionally has a low-price elasticity as there is no substitution product. This implies that people keep consuming power despite higher prices, given that electricity is difficult to hoard during high prices for uses during low ones. Combined, there is risk of monopolies setting high consumption prices. Governments have also interest in guaranteeing the security and reliability of electricity supply at fair prices that reflects suppliers' costs and investments with a reasonable profit margin, as well as income from taxes. Hence, monopoly and price regulations in the electricity market came into play. The liberalization of the energy market in 1996 with the adoption of the European Directive meant for Europe opening of the energy markets to competition in the private participation but the networks remained public. The aim was to make the electricity supply more efficient. Market competition would lead to lower prices for the consumers, which only partially occurred as infrastructure vested in the past limited the envisaged effects of the liberalization. A question is in how far cheaper generation of renewable energy, along with digitalization of power balancing on grid, electricity storage, better demand-control, and other emerging innovations can reverse the economic arguments for the centralized electricity systems which expanded since Edison constructed the first commercial electrical generating station in 1882.

As fluctuations in power supplies increase with the growth of intermittent generation from wind and solar energy, and the loading of voltage and balancing of frequencies becomes costlier. Therefore, more automation, and larger and more flexible storage of power on grid are required. In addition, the consumer demands for electricity increase as fast, or faster than the economic growth, while the transmission and distribution systems do not keep pace with the demands. In effect, congestions on the power lines becomes a pressing issue; for example, entry of the industrial consumers cannot be served in a few regions of the Netherlands. Larger investments in the transmission and distribution are necessary but even those cannot preclude power scarcity in Europe. This scarcity is observed in India more than a decade ago along with recommendation for larger investments in the networks, and changes in fees and responsibilities of federal and states government (IEA, 2002);[2] however, progress is slow compared to fast economic growth, thereby even faster growing demands for electricity. Given more fluctuations in electricity supplies with respect to the envisaged renewable energy in the next decades and the growing consumers demands for electricity, alternatives to the centralised system are searched.

Regarding slow increase of transmission and distribution vis-à-vis those challenges, two non-exclusive strategies are pursued. One strategy involves more automation for balancing on grid and expansion of flexible power storage during excess of energy injections. In particular, growth of large-scale batteries at the load units in distribution is envisaged (DOE, 2020).[2] This needs huge investments because about 97% of global power storage involves inflexible water storage, while the remaining 3% cover flexible storage with roughly half-half mechanical and chemical devices, such as compression and batteries, respectively (DOE, 2021);[2] similar percentages hold true for Europe. Storage in hydrogen is envisioned but it covers presently only a small fraction of all battery storage. Another strategy is decentralisation of the grid towards the distributed electricity systems linked with the centralised electricity system, it is hybrid devices, as well as with low dependency on the centralised one through mini-grids and microgrids. That second strategy is addressed below.

2.2. Distributed electricity systems (off-grid)

The global capacity of distributed electricity systems is small despite high scientific interest – solely in 2021 more than 200 scientific publications (Boche, 2022). In 2021, that global capacity was 11 GW, which was below 0.4% of all renewable energy capacity, and the annual average growth 2018 - 2021 was below 12% global growth of all renewable energy. Within renewable energy, the share of PV in the distributed systems increased from 14% to 43% in that period. Whilst biobased energy resources were also much used, hydropower, geothermal, and wind energy were rarely applied as the power supplies; marine energy is small scale, as yet. Main reason is that modern installations with capacities of a few MW or larger usually exceed household consumption in a neighbourhood or village, though India has small-scale hydropower. The capacity of distributed electricity systems in Europe with the global capacity is small. Presumably more can be learned from the Indian experience as 22% of the global distributed electricity systems are located in India, even 28% of all PV-based ones, and those capacities have grown in time (IRENA, 2022). These percentages are manifold higher than the Indian share of a few percent in global renewable energy, which means that the Indian power system as a whole is more decentralised than in other countries.

The distributed electricity systems are often initiated and developed by the electricity distributers (DSO’s) confronted with higher costs of balancing on grid caused by larger injections of intermitted supplies in combinations with growing demands for secured power. Particularly, DSOs in a few states of the United States of America geared to this development though the distributed electricity systems can be considered rival to the centralised ones as they capture a market share. Consumers have also interest in the distributed electricity systems when the electricity services on-grid are unavailable, or they are not satisfactory because of frequent blackouts, high peak prices, and other issues. In such cases, consumers express interests in the distributed systems. Three different, non-exclusive manners are observed. One option is decentralised electricity generation with connection to the centralised grid, called ‘hybrid’, which is by far the most popular option; for example, all uses electric cars can be considered as ‘hybrid’ system. Another option is a stand-alone business model. In this case, renewable energy is generated and stored in a mini-grid for one or a few households near each other. Third option is distributed power generation with mini-grids that are interconnected with other mini-grids of power suppliers and consumers into a microgrid. Given strict regulations in Europe, scarcity of mini-grids and microgrids in Europe is not surprising; mini-grids are mainly used for telecom, lamps, signs and other solitary devices, as well as by environmentalists aiming at energy-independence (energy-autarchic). Hybrids, mini-grids and microgrids as business models are non-exclusive because each model can be connected to the centralised grid but is not per se needed as both latter can operate autarchic. Business models for market transactions between peers with regard to those options are also hypothesised, though other labels for those options are used (Sousa et al, 2019).[2] Simulations suggest that the individual transactions between peers provide most efficient outcomes but consumers preferences are neglected though such transaction require knowledge about power generation, distribution and transactions.

For the deliberation about those business models, Table 1 illustrates the number of key devices that are needed for operations, which indicates an increasing complexity, thereby larger investments and higher operational costs. PV is used as an example for the power generation though it can be a biofuel co-generator, or less probably a windmill, hydropower, geothermal or marine power plant. The costs are considered from the consumer perspective, given consumed scale of electricity.

Table 1 Options for business models in the distributed electricity systems with PV generation

Models	Main elements	Payments: capital and operational costs
Centralised	Connector to the grid	Fees for generation+ network+ taxes
Hybrid	PV + Inverter + connector PV-Grid	Costs of power generation + fees, or incomes for the electricity injection.

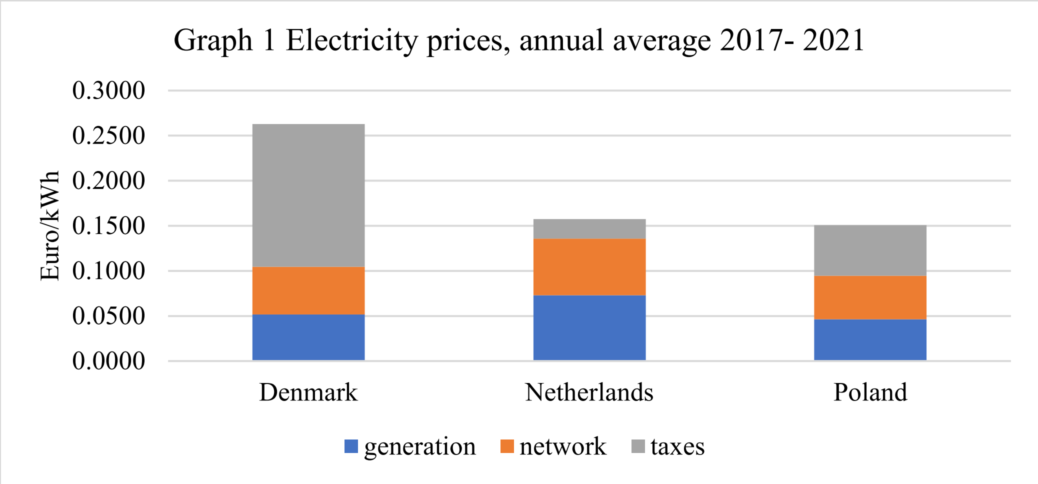
Mini-grid	PV + Inverter + Power storage (Battery) + connectors PV – Battery – Grid	Costs of power generation + storage + (lower) fees, or (higher) incomes for the electricity injection+ lower peak prices.
Microgrid	PV's + inverters + batteries + distribution network + network management + connectors to grid	Costs power generation + storage + power lines + balancing + (lower) fees, or (higher) income for the electricity injection + lower peak prices.

Compared to the fees paid for a given consumed scale of centralised electricity, the consumer costs of hybrid business models largely depend on the payments for its power generation. Most countries in the EU support the hybrid business model with subsidies and feed-in tariffs for injection of renewable energy into the grid whilst DSO's and TSO's make additional costs of balancing power. As those costs increase, those power injections can be fees, which undermines this option. The costs of a mini-grid are higher because of additional power storage but the centralised electricity could be used during low prices on grid and fees for the power injections could decrease; the latter cost-saving is presumably modest because all transmission and distribution costs of the centralised networks remain. Avoiding high prices during consumption peaks, so called 'peak shaving', is the main cost-saving. The microgrid requires even higher costs caused by the loading units, distribution lines and networks management. This could reduce the need of transmission and distribution, thereby save costs, even avoid these costs when the microgrid operates independent of the grid. Incomes could be generated when power is injected during low power supplies and cost-saving is attained through the peak-shaving. Whether those incomes and cost-saving outbalance the additional costs compared to the centralised electricity system is estimated below.

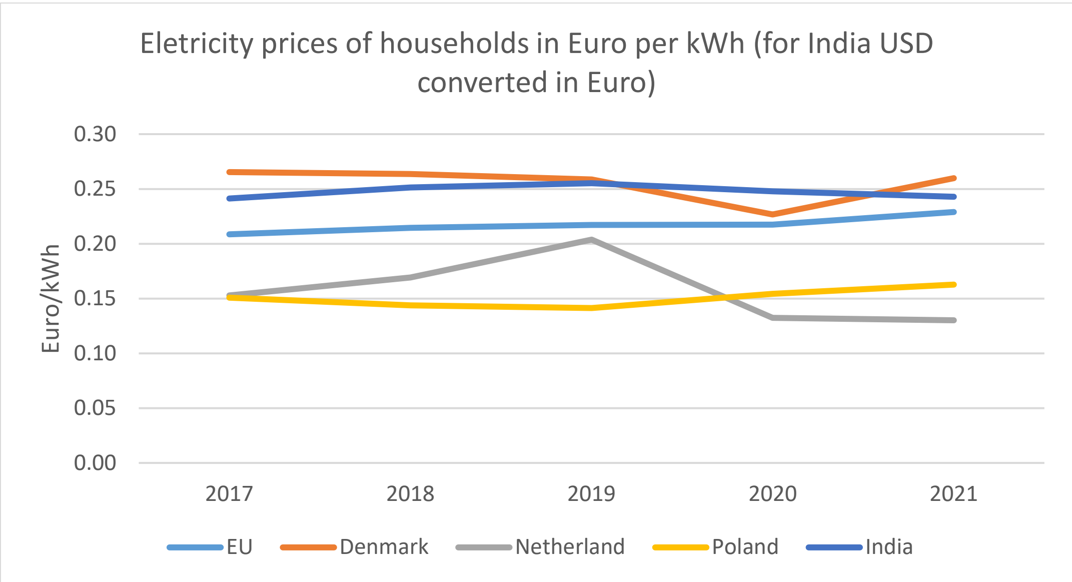
3. Costs

3.1 Power on-grid

The price of centralised electricity systems (on-grid) provide a benchmark for the costs of decentralised systems (off-grid). The prices on-grid cover three main components: power generation costs, network tariffs for distribution and taxes. As those components differ across countries, they are shown for Denmark, Netherlands and Poland; similar statistical data for India are not found. Graph 2 shows the average costs per kWh (unit costs) in the period 2017 - 2021. The unit costs of power generation were about € 0.05 in Denmark and Poland up to € 0.07 in the Netherlands whilst the network costs were about € 0.05 in Denmark and Poland, and € 0.06 per kWh in the Netherlands. Taxes on the household electricity consumption were € 0.05 average in the Netherlands and Poland, which includes the negative taxes during COVID epidemics in 2020 and 2021 in the Netherlands, while Danish tax of € 0.15 remained throughout those five years. The costs of power generation in India costs similar to Europe,[2] but the statistical data about the costs of network and the energy taxes on households are not found. The Indian taxes are 6% - 10% in most of the Indian states; a few exceptional states have 20% energy tax, similar to the Netherlands, and even 40% taxes similar to Poland (Bankbazaar, 2022). Whether the Indian price tariffs vary with respect to the consumption scale is unknown but the Indian households and farmers pay lower taxes than industries that are usually large consumers (Voxdev, 2022). This is another way around in Europe where large consumers pay substantially lower energy taxes per kWh; in most countries these taxes are lower long for larger household consumption.



Given the variation in cost components across countries, a question is if a single reference price for off-grid can be found. For an answer, the real prices in time are estimated. The European statistics (Eurostat, 2022)2 are used for Denmark, the Netherland and Poland. For India, the costs estimates of the International Energy Agency in 2017 and 2018 are used (IEA, 2022).[2] The Eurostat shows the averages of price tariffs for all scales of household energy consumption. All prices are in €2010 per kWh including taxes for the period 2017-2020; inflation correction is done with the World bank data (World Bank, 2022). The Indian prices are in US Dollars converted into Euro (Wise.com, 2022); Graph 2 shows the prices.



The EU average prices of electricity increased only from € 0.21 in 2017 to € 0.23 per kWh in 2021. While the Danish prices of € 0.23 – 0.25 per kWh exceeded the EU average, the Polish prices around € 0.15 remained below the EU average. Meanwhile, the prices in the Netherlands fluctuated annually between € 0.13 to € 0.20 per kWh; it is between the Polish and EU average. High prices in Denmark, low in Poland and fluctuations in the Netherlands can largely be explained by the taxation. In addition to variation in taxes, the price tariffs in Europe vary with scale of consumption; a scale is expressed as a 'band' in the Eurostat. When measured by the purchase parity prices excluding taxes during 2007-2021, the prices declined with larger scale of consumption below 5000 kWh a year, but above that the prices jump up, followed by decline with larger scale. This implies that larger energy consumers face lower prices on-grid. The wholesale electricity prices increased from November 2021 to November 2022 in most European countries due to higher prices of gas and coal, but thereafter, the prices declined to the former level (Statista, 2023).[2] The consumer prices increased manifold during that peak but declined in line with the wholesale prices. By January 2023, the prices reached the level of 2021 year (GMK, 2023)[2]. Regarding, similar costs of energy generation and consumer prices but lower taxes in India, the costs of networks in India are presumably higher than in Europe.

In conclusion, for the cost assessments of the off[-grid power services one single benchmark across countries is not realistic. Also in time, the benchmark can change in some countries mainly caused by changes in the energy taxes. To be competitive by prices, the off-grid services should deliver power below € 0.20 – 0.22 if they are not taxed, but if they are also taxed the off-grid costs should not exceed € 0.12 per kWh in Europe.

3.2 Competitiveness off-grid

A question is whether the cost-reducing technological change in the centralised systems may impede progress in the distributed electricity ones. The issue is if additional renewable energy injected by consumers off-grid and injected into the grid remains competitive compared to technological changes with renewable energy on-grid in the next decades. In answering this question, particular attention is given to electricity generation with PV which is presently the main energy source for the distributed electricity systems. It is focused on the technological change in power generation on assumption that this progress in the power networks on-grid and off-grid is similar.

Nearly all renewable energy in Europe is linked to the grid; it is less pronounced in India where much bioenergy is used for heating and cooking. Renewable energy has grown in the EU and India; particular fast in solar and wind power consumption. In the EU, the share of solar and wind power consumption grew from close to nil in 1990 to 13% of all electricity in 2020; meanwhile, Denmark attained 41%, the Netherlands 20%, while Poland 13% in that year. The growth of PV capacity in Poland started in 2004, which is later than in Denmark and the Netherlands, but grew fast toward 20 GW in 2022 (Meza, 2022). The growth of PV in India is faster but also started mid-2000s. If larger renewable energy on-grid reduces electricity prices, the cost of off-grid activities must decline even faster in order to remain competitive in the future. Prices do change and they are reduced with larger renewable energy; based on the Eurostat data, correlation of annual average changes in renewable energy and prices across 27 countries in the period 2017 - 2021 is observed (R2 = -0.4). Inter alia, the decreasing prices in the EU are mainly driven by large scale wind turbines on-grid, which delivered much more electricity for consumption compared to PV. When the share of renewable energy is high and increasing as it is in Denmark and the Netherlands the prices decline. Meanwhile, in Poland with low share of renewable energy higher prices are observed, which can be caused by less experience with the integration of PV on-grid. Additional renewable energy in India also reduced the electricity price but a policy assessment on renewable energy instead of statistical data is used (Kumar and Majid, 2020) because proper statistics on India is not found. The conventional explanation for the decreasing prices on-grid as renewable energy grows is that the costs of power generation with renewable energy declined as technologies for PV and wind became cheaper. Indeed, the costs of these technologies for energy generation declined in USD per kWh from 2010 and 2020 from 0.1 - 0.15 to 0.03 - 0.05 for wind power and from 0.23 - 0.27 to 0.03 - 0.04 for PV (Lazard, 2022). Those unit costs seem reliable regarding similar data shown by IRENA, NREL and other institutions for 2020, though the rates of change differ. This cost-reducing technical change is largely

due to introduction of cost-effective technologies. This process can continue in the future with regard to growing number of patents in renewable energy, which enable more effective technologies, and growing scale of implementation, given policies for nil CO2 by 2050 in the EU and 2060 in India, which can reduce the supply costs of technologies due to economy of scale.
However, an extrapolation of the cost-reducing technical change may deliver false results if the energy performance of installed technologies declines. The energy performance of applications can decline as technologies for wind and solar power disseminate because of deficient selection of location, less effective operations and management. The installed technologies are indicated by the energy capacity of applications. This input of energy technologies is measured in kW. The energy output of energy technologies is measured in kWh. The energy performance of applications is measured in annual average kWh energy output per kW installed capacity. Table 2 illustrate the performances of solar energy in 2010 and 2020 in Denmark, Netherlands and Poland; similar information is not found for India. It shows the additional installed capacity of PV in MW, additional electricity generation in GWh, and the energy performances of PV applications in MWh/MW.

Table 2 Energy generation, installed capacity and energy performance of PV applications

PV added from 2010 to 2020 year	Capacity in MW(*)		Generation in GWh		Performance in MWh/MW	
	2010	2020	2010	2020	2010	2020
EU27	13470	19930	8462	21027	628	1055
Denmark	2	220	2	217	1014	988
Netherlands	29	3289	11	8720	378	2651
Poland	1	2619	0	1247	0	476

(*) https://en.wikipedia.org/wiki/Solar_power_in_the_European_Union

The energy performances in the EU27, Netherlands and Poland increased but it declined in Denmark. For example, the scale of installations declined in Denmark; the number of PV installations boomed in 2012 to 70,221 units with 406,661 MW, but steadily declined towards 2,340 units with 71 MW in 2016, which means changes toward small-scale of 50 to 100 panels per installation (Ahm, 2016). As the scales of applications decline, the installation costs increase despite cheaper and more effective PV technologies. The cost decrease of PV applications seems to evolve toward an asymptote between the unit costs in the EU and Denmark.
In conclusion, renewable energy technologies on-grid become more effective and cheaper in time but they are not necessarily more cost-effective during applications. For competitiveness assessment of distributed electricity systems compared to the centralised ones it is not solely relevant to assess the cost and effect of technologies but also the energy performance of particular applications. In case of power generation with PV, which is the main off-grid technology, the distributed electricity systems remain (presumably) competitive compared to the centralised systems if the distributed applications of PV are well designed and implemented.

3.3 Mini-grid

Power off-grid can be generated with use of fossil fuels in engines and microturbines, and with renewable energy technologies as fuel cells, PV, small wind turbines, bioreactors, small hydropower and so on. Herewith, it is focused on PV with storage and external connectors to grid. Though PV can be generated at nearly any place on Earth, the generated power fluctuates with respect to the solar

inflow during day and night, seasonal conditions and irradiation on earth. Hence, the PV installations are not instantly dispatchable and power generation is variable in time, whereas the installations based on combusted fossil fuel can provide continuously dispatchable heat for power generation. Those fluctuations in the power generation with PV are largely mitigated by linking to the continuous on-grid power generation with fossil fuels, hydropower and biomass, or through storage in batteries. For a similar quality of power off-grid with the PV installations a mini-grid must be installed that links that installation to the local electricity storage, which is usually a battery along with inverters for the stabilisation of voltage and conversions of the Direct Current (DC) and the Alternating Current (AC). The implementation of that mini-grid adds to the costs of PV applications.
Despite additional costs of PV off-grid these applications grow. Several motives drive PV off-grid. An obvious one is lack of connectivity to power grid because network is unavailable, or often distorted while electricity service in buildings, lamps and other applications on remote sites are demanded. In most EU countries, the connectivity has been nearly hundred percent during the last decades but it is still lower in some rural areas; for example, in Poland. In India, the connectivity has been below 80 percent ten years ago, which means that nearly two hundred million people missed electricity but meanwhile, the connectivity percentage is substantially higher. Another motive is high electricity price on-grid. When the prices on-grid strongly fluctuate throughout a day and seasonally as a result of fluctuations in supplies and demands of power, a mini-grid can reduce the peak prices in power consumption on-grid. Such peak shaving is popular in many areas in the USA where high prices on-grid are faced every morning and evening. Peak shaving could also be interesting in the case of high energy taxes; for example, in Denmark, and in particular regions; such as islands where infrastructure is costlier than on mainland. The economic perspectives for mini-grid improve because those price peaks increase, whilst the costs of components for the mini-grid applications decrease. Third motive for the off-grid PV is the use of mobile applications. This motive is usually related to a personal status and social engagement. This motive invoke PV-based boats (e.g., Sunyacht, 2022)[2] fancy electric car (e.g., Lightyear One, 2022),[2] driving and living an autarchic bus (Youtube, 2022),[2] and other mobile applications; nearly autarchic housing is in development.

Such mini-grids usually include: (1) several PV panels for conversion of solar irradiation into DC with, (2) storage of DC, (3) hybrid inverter for stabilisation of voltage and conversion of DC into AC with (4) switchbox for applications at home, and (5) links to another power generator, power storage and to grid (Newkirk, 2016).[2] Various websites provide information about elements of the PV off-grid systems, among others about the energy-efficiency of solar panels (Clean energy reviews, 2022a),[2] and solar panel costs (Greenmatch, 2022)[2], costs of batteries alone Climate Bizz, 2022),[2] and hybrid invertors (Clean Energy reviews, 2022b).[2] Appendix shows several examples of PV off-grid and microgrids found in literature; a lot of examples can be found but the presented ones are selected with regard to sufficient data about capacities and generated power, as well as total costs or unit costs. Most examples are estimates done with the HOMER software without verification of the calculations and comparisons with realisation after the installation during uses. It is surprising that higher costs of diesel generators than PV off-grid are often estimated. Experienced experts argue that the diesel generators are much cheaper ,[2] and diesel generators are widely used for the stand-alone power generation, which puts some doubts about qualities of those assessments. Experienced experts argue that the diesel generators are much cheaper ,[2] and diesel generators are widely used for the stand-alone power generation, which puts some doubts about qualities of those assessments.

Those exemplary assessments suggest that the unit costs of the PV-based mini-grid are typically in the range of USD 0.2 – 0.3 per kWh with a few higher and lower exceptions. Typical unit costs are supposed to be within the range of electricity prices in Europe including taxes, but they are twice costlier excluding taxes. This range can be realistic regarding popularity of such mini-grids in the USA where average electricity prices including taxes are lower than average in Europe, similar to the prices in Poland, and where high peak prices are experienced in many areas. While PV-based mini-grids are rare in the EU, contrary to fast growth of PV on-grid, those applications In India are widespread. In India, they serve, among others, 7.8 million lamps, 1.7 million homes, 0.8 million street lights and nearly 0.3 million water pumps (Statista, 2022).[2] Table 3 shows Indian PV capacity in GW and percentage off-grid. However, the popularity of PV-based mini-grids should not be overestimated as the total PV capacity grows much faster than those mini-grids.

Table 3 PV in India: total and off-grid (based on IEA, 2022)				
In GW	2019	2020	2021	2022
Total	9	4	12	14
% off-grid	20	21	11	12

Whether the unit costs of the PV-based mini-grids decline fast in the near future is difficult to assess given large spread in the costs of installations. Illustrative for the spread of those costs are the USA data such installations. Per installed kW of the mini-grids, the costs are USD 3000 – 5000 for PV below 10 kW, and USD 2500 – 4500 for PV 10-100 kW. Such estimates are also done for the wind-based mini-grids but these are twice costlier when small-scale wind turbines are used, and the spread in the costs is even larger than in the PV cases. Even larger spread in the unit costs of mini-grids is found for the biomass heat-power generators; the unit costs vary from USD 3000 to nearly 10000 even though their capacity is usually larger (NREL, 2016 (2022)). Regarding that large spread in costs per kW, it puzzles if the PV-based mini-grids are well designed and implemented. This is difficult to assess as many model-based estimates are found but hardly any evaluation of the realised applications throughout the period of uses. Design and implementation are essential for energy performance; for example, two-digit rate higher speed of racing solar boats with prescribed capacities of PV and batteries is observed (Krozer, 2015), which is also observed in solar race cars but data is unavailable. Cheap options for power storage are also insufficiently considered though storage is the costliest component of mini-grids on the annual basis; for example, closed water storage is neglected even in the assessment of the PV-based mini-grid at a water pumping station (Emmanouil et al, 2021).

In conclusion, in addition to the choice of technologies for mini-grids, design and implementations of these technologies are major features for the cost-effective uses. Assessments of costs and effects of the realised mini-grids in a few countries would be a major novel contribution of the SUSTENANCE project because such evaluations are rare.

3.4 Microgrid

When several mini-grids are interconnected into a network, their individual supplies and demands must be continuously balanced within the network in order to control voltage and frequency. While a mini-grid is usually installed in order to satisfy a particular demand, the microgrids are often driven by the electricity suppliers when aiming to reduce costs. By far, most microgrids and the largest capacities are installed in the USA. There were about 160 microgrids with 1600 MW in 2016, mainly in Alaska, California, Georgia, Maryland, New York, Oklahoma en Texas, and projected 4300 MW in 2020.[2] Their drivers are typically: prevent losses of power caused by harsh weather, cascading outages, cyberattacks and other distortions, thereby liabilities for the disruptions on the networks. Another major driver is deference of investments; in particular, large cost-saving can be reached when additional mileage of infrastructure can be avoided because lengthy transmission and distribution are costly. A distributed energy systems can be economic on islands and remote areas because an additional kilometre grid costs USD 9,730 -11,120 while even larger ranges are found: from USD 3,058 in India to USD 25,020 in Mali (Levin and Thomas, 2016). Microgrids can also be attractive when ancillary power services involve large or unpredictable expenses for the congestion relief, frequency regulation, and suchlike network management on-grid; for example, when the installations for power generation and distribution are obsolete (Hirsch et al, 2018).

There are also impediments. In addition to the legal limitation for operating networks mentioned in the introduction, main impediment is high costs of microgrids. An assessment suggested that the use of renewable energy is main cost factors. It compared 9 microgrids in California based on PV with storage (153 kW to 13.5 MW capacity) with 10 microgrids in North America based on biogas (78 kW to 15.6 MW capacity) and 7 microgrids in other countries based on fossil fuels generators (206 kW to 112.5 MW capacity). The costs per MW of the microgrids with renewable energy in California and North American were USD 3.5 - 3.8 million, whilst the costs were USD 2.1 million in other countries (Asmus et al, 2018). A different result is found based on an inquiry into the costs of 80 microgrids in the USA, This one has shown that the design of microgrids are decisive for the costs, not the energy source (Giraldez, 2018). Table 4 summarizes results.

Table 4 Costs of microgrids in the USA (Giraldez, 2018)

Complexity of a system	Main elements of the designs	Costs in USD million per MW	
		Quartile between lowest and highest quartiles (outliers*)	Mean
Level 1	Standard generation, on-grid	2.856 (0.931)	1.981
Level 2	+ distributed automation & distributed generator(s)	4.871 (2.179)	3.463
Level 3	+ microgrid controller & thermal asset & renewables & storage	3.821 (1.941)	3.054
Level 4	+ load management	5.143 (3.727)	4.437
Level 5 (**)	+ weather forecast & generation forecast & economic dispatch	3.701 (2.920)	3.310
Level 6	+ coordination & optimal control of multipurpose microgrids	Not Available	

(*) outliers - outside the lowest or higher quartile (**) Only two projects found

These results indicate that the costs of microgrids based on fossil fuels, measured in USD million per installed MW, are typically 36% to 81% costlier than the conventional centralised systems. Better control, use of thermal residues and implementation of renewable energy with storage, it is level 3 complexity of the systems, provides cost-savings compared to simplified microgrids, levels 2, and with more complex microgrids, level 4. The forecasting of weather, power generation and demand, level 5 of complexity, could also be helpful but it is too rarely applied for robust conclusions. Generally, the microgrids are costlier than on-grid but well design combinations of thermal technologies with renewable energy provides cost-savings in comparison with complex microgrids based on gas co-generators and diesel generators.

The costs of the PV-based microgrids are shown in an assessment of the World Bank (Greacen, 2019), though unclear if the data are estimates based on models or realised grids, and if the calculations are verified. Those costs are based on 53 microgrids in Asia and Africa, out of these 38 are based on PV-diesel power generation and hybrid on- and off-grids network. Large range in the unit costs is observed. The installation costs per kW range from USD 1400 to USD 22000, median is USD 4800. There is cost-reducing change as the costs decline by average USD 800 a year. As several customers participate in a microgrid, the installation costs per customers vary. Per customer kW, the costs of small grids are above USD 4000, middle-large ones USD 2400 - 3300, and large grids with more than 200 customers USD 700 -2000. Particularly, fast cost-reducing change is observed in large microgrids: the costs of microgrids above 100 customers decline by USD 68 per customer kW. These data suggest that the installation costs decrease with the scale and that the improvements in design, installation and operations are worthwhile attention. Moreover, the unit costs of electricity consumption in USD per kWh could be lower in small-scale microgrids if these designs would be tuned to the customer demands because more effective services would be generated compared to large-scale microgrids. Getting experience is relevant: as expenditures in microgrids increases from USD 13 billion in 2018 to 16 billion in 2021 the unit costs declined from USD 0.55 per kWh to 0.38 per kWh. A load factor of 22% is usually observed at many customers but higher load factor due to better design is found possible with the unit costs of USD 0.28 per kWh (ESMAP, 2022). The scale of installations can reduce the costs of capacity whereas design and implementation tuned to the demands can reduce the costs of that capacity utilisation; and the scale and design could cause trade-offs in decision making about the microgrids.

Total capacity of microgrids in India is about thousand times smaller than in the USA. In India, 63 villages run a with microgrid with nearly 2 MWp capacity in 2020 data and the projected additional capacity for 2024 was 500 MW. Main objective is empowering of rural communities that lack grid (Businesswire 2020)[2]. Manifold smaller capacity is in Europe. A compilation in 2021 in a database shows 13 microgrids, all experimental and small scale. For example, Poland has one microgrid for 94 households on former mine area, the Netherlands also one for 46 households in the harbour of Amsterdam, each one with several kW capacity; no microgrid is found in Denmark (Smart Energy International, 2023).[2] Other publications suggest many initiatives with labels as ‘energy communities’ and ‘local initiatives’ which are possibly various initiatives, but not the energy community networks as defined in the EU regulations (Tarpani, 2022).[2]

A review of several proposals microgrids in various countries (Egypt, Iran, India, Bangladesh, Rwanda, Peru and Panama) show a huge range in performances despite estimates with HOMER, which is the most popular model for assessing cost-effectiveness of the microgrids, though not necessarily the best model. These seven project proposals out of a few dozen others are selected because they clearly indicate the expected capacity and capacity utilisation. Table 5 shows results with references. The performances in the capacity utilisation range from 2000 – 40000 kWh/kW which indicates ample possibilities for improvements in the effective performance the microgrids. There is also progress in the scale and design of microgrids, if to rely on the cost estimates with the HOMER model. The estimated unit costs during the 2010s were USD 0.55 – 0.85 per kWh, whereas the recent estimates were USD 0.20 – 0.35 per kWh. Whether that fast cost-reducing technical change in microgrids, above 90% annual cost reduction, continues for decades is doubtful because the components whose costs decrease fast – PV, batteries, and inverters - cover about one third of the total costs. Fast cost reduction can be expected in small-scale microgrids and mini-grids where batteries constitute up to 39% of the installation costs per kW, whilst other main cost components are PV modules and inverters. In the large-scale microgrids, however, only a third of the installation costs per kW decrease fast: PV modules cover typically 11%

(usually below USD 600 per kW), Li batteries 15% (below USD 400 per kWh), and inverters 9% (about USD 90 per kW). Two-third of the installation costs hardly decrease. One third of the costs in large-scale microgrids are linked to distribution 14%, installation 8% and project development 9%, whereas the remaining third of the costs covers housing, measurements and miscellaneous. The installation costs in large-scale, complex microgrids may even increase as shown above in the Level 4 microgrids; for example, a large-scale microgrid is proposed for the Chennai harbour with 25 GWh power (of it 5.65 GWh solely for harbour), with PV 5 MW, Wind 6.5 MW, Biogas generators 500 kW, and compressed air storage (Misra, 2017).

In conclusion, rather than larger scale of microgrids, better designs and implementations tuned to local demands would be cost-effective options. Regarding the range 2000 – 40000 kWh/kW there are ample possibilities for improvements in the capacity utilisation of microgrids.

3.5 Conclusions and follow-up

The costs of electricity services off-grid are usually higher than supplies on-grid excluding taxes but the services based on microgrids can be cost-effective to reduce the costs of taxes and peak prices and mitigate deficiencies on grid. Applications of PV with storage are usually costly compared to heat-power generators and diesel generators in large-scale microgrids but they can be cheaper in the small-scale ones if design of installations and operations are tuned to customer demands. These are findings based on model-studies. However, information about experiences with the cost-effective applications is scarce despite many publications because modelling of microgrids captures attention in the academic and professional literature. A major contribution of the SUSTENANCE project to the knowledge pool would be comparison of the costs and effects of PV-based microgrids in the design stage with realisation during the demonstration. Therefore, inquiry is proposed to collect basic data for assessments of cost-effective microgrids. Such inquiry should cover three features: (1) main components of the design microgrid with purchase prices, (2) cost of installing the microgrid and hours in development and management, (3) generation of electricity based on calculations and measurements of generated electricity during the demonstration.

3.6 Benefits of distributed energy systems

3.6.1 Introduction

Benign qualities of the distributed energy systems related to the market and policy deficiencies may not be reflected in the energy prices; for example, environmental qualities, local welfare, and sense of autonomy. Given the costlier off-grid power services than the on-grid ones, a few questions arise as: what are those under-priced qualities, do they justify additional expenditures on the distributed energy systems and how suppliers and consumers can benefit? In this section, the beneficial qualities are assessed, valued, and compared to the on-grid ones. It is indicated whether the benefits can be estimated in monetary or similar terms in a reliable manner; for instance, without double counting of costs and savings. In mainstream economic thinking, it is assumed that the under-priced benefits can be assessed by asking people about their individual preferences for particular qualities. In order to assess those preferences, inquiries into the individual willingness to pay for a quality, or to accept the degradation of a quality are recommended and various techniques are used, which can be found in many manuals for cost-benefit assessments (e.g., Boardman et al, 2010). However, this approach is biased. Major concerns are that individuals cannot assess their preferences for services when they are abstract or need expertise, and that the individuals usually express socially prevailing arguments rather than their preferences. This bias causes large discrepancies between their statements about the preferences and the preferences revealed in purchases and behaviour (Kahneman and Kletsch, 1992). Inquiries into personal opinions can be useful for the assessments of preferable attributes in energy services but obtained results are dubious with respect to the monetary benefits. A brief literature review of the willingness to pay for the distributed electricity service below illustrates those discrepancies. Instead of inquiries, it is proposed to assess what benefits can be revealed with regard to the private and social interests of suppliers and consumers.

3.6.2 Willingness to pay

Numerous studies are done on the willingness to pay for renewable energy on-grid and for off-grid. Several reviews are discussed. A high willingness to pay for electricity off-grid is expressed in low-income countries with poor electricity infrastructure (IEG, 2008). But the preferences for electricity on-grid are also stated in low-income countries (Wilson et al, 2010), and in high-income ones mainly because the latter is more convenient for the consumers (Scarpa and Willis, 2010). While job creation and starting businesses were often stated as preferential activities based on the off-grid electricity services, evaluations of projects showed mainly uses for leisure, which brought the evaluator to conclude that the monetary benefits of such services would be low (FMO, 2022). Studies on the willingness to pay for renewable energy also provided confusing results. Although the stated preferences for renewable energy are widely assumed to be higher than the revealed ones in purchases, a study showed the opposite result in the USA as the household payments for renewable energy in electricity consumption were higher than their willingness to pay in inquiries (Farhar, 1999). In the Korean Republic, however, consumers prioritised the cheapest electricity option but their statements were not verified with purchases (Kim, et al, 2013). There is also no agreement about why the results differ. Several scholars underline differences in methods (Ma et al, 2015), but others point out differences in income, education, age, and other sociocultural factors of respondents in high-income countries (Ntanos et al, 2018), and in low-income ones (Entele, 2020). A cautious conclusion could be that willingness to pay for electricity is usually somewhat higher than the market price, while the preferred option is on-grid with use of renewable energy.

How much higher the willingness to pay for renewable energy in electricity has also been estimated in many studies. Several literature reviews show various ranges. A comprehensive review shows that the highest willingness to pay is more than 100 times higher than the lowest one (Zorić and Hrovatin, 2012), but in another review it varies from a few dollars-cent to a few dozen dollars-cent per kWh (Streimikiene et al, 2019), and still another one shows only USD 10 – 37 per month (Grilli, 2018), which is equivalent of 3 - 11 dollars-cent per kWh assuming 300 kWh a month. A cautious estimate of the willingness to pay could be 10 dollars-cent additional payment for renewable energy in electricity services if energy taxes are low. Some social groups say to prefer off-grid services with respect to their individual autonomy but estimates of preferences may cause biased decisions; for example, a study estimated several thousand customers for the PV-powered electric car, but a study on the PV-powered boats heavily overestimated sales, followed by flop of business.

3.6.3 Revealed benefits

Studies show numerous benefits of distributed energy systems with renewable energy. However, the empirical valuations of those benefits are rare. Even a USA review on nine implemented state policies aiming at distributed energy systems show only three reliable reports (ICF, 2018). That review is focused on the suppliers' benefits, and shows the benefit range from USD 0.06 per kWh to USD 0.21 per kWh. The latter is sufficiently high to close the gap between the prices of PV off-grid and on-grid, which justifies the benefit assessments of distributed energy systems. For illustration Table 5 lists the benefits envisaged in those three reports; below somewhat different methodology is proposed.

Table 5 Benefits of microgrids in a few states in the USA, excluding avoided costs of gas pipelines

	District of Columbia	Mississippi	Maine
	USD/kW (*)	USD/kW (low value)	USD/kWh
energy saving	53		0.081
avoided capacity costs			0.04
avoided reserve cap. cost			0.05
generation capacity	16		
transmission capacity	8	16	0.016
distribution capacity	10	23	
energy capacity wholesale	7		0.066
compliance policy	7		
subsidies	8		
lower losses	19		
risk avoidance	8		0.037
integration	-1		-0.005
societal energy policy	18		
societal Cost of Carbon	36	15	0.021
societal Cost of SO2			0.062
societal Cost of NOx			0.013
Total	136	54	0.21

*levelized value of solar (3% interest 2017-2040), utility and societal (italic) ** lowest value

Below, main benefits of the distributed energy systems are reviewed based on literature, and it is indicated whether the benefit can be estimated in monetary terms. In line with the 'stacking approach' in a valuation of distributed energy resources, which means enumeration of benign impacts for the producers and consumers (Littell, 2019), the benefits are divided into four categories: interests of producers and consumers as individuals and as collective. Within each category, the benefits are ranked starting from the internal features towards external ones while possible double counting is avoided. A benefit can be specified in detail and assessed with several valuation techniques as shown for possible cost-savings of price peaks in consumption (Rana et al. 2022); however, this may suggest false confidence in reliability of result. The presented benefits constitute a non-limitative list though it is based on a comprehensive literature review; note that the list below is somewhat different and longer than in the USA review on state policies mentioned above. Rather than making a longer list, possibilities for external valuations in the monetary terms are indicated; the terms are euro per kW capacity or euro per kWh.

3.6.4 Producer individual interests

Operations

Many scholars argue that improvements in operations of electricity generation, transmission and distribution would generate benefits, meaning that the cost-savings would exceed the additional costs. In particular, larger storage capacities would be beneficial (Schiermeier et al, 2008; Eyer and Corney, 2010; Richter, 2012; Denholm et al, 2013; Burger and Luke, 2016). It is pinpointed that congestion of electricity on grid is relieved when power is temporarily stored because production and distribution can be more flexibly utilised; herewith, cheap storage with water for long-term uses and costly storage with batteries for short term uses are considered relevant. Another type of benefit due to larger storage is flexibility in production because costly production capacity for the demand peaks can be reduced. It is also observed that short-term storage with batteries is supportive to stabilise voltage and balancing of frequency in the networks; herewith should be noted that storage in large-scale batteries on-grid is usually cheaper per kW than storage in smaller batteries off-grid. Another type of benefits refers to lower power losses in distribution. These benefits can be valued with internal costs of electricity suppliers but they are hardly assessable by the external experts. Possibilities for valuations of benefits are modest (+/-).

Diversification

Several scholars point out that the distributed energy systems enable to diversify energy resources, which can mitigate scarcities and high price caused by economic crises, political conflicts, speculations and other irregularities on markets; it is called fuel price hedging. It is also argued that the financial resources can be spread, thereby mitigate bottlenecks in liquidity (NREL, 1997; Awerbuch, 2004; Resch et al, 2008; EPA, 2011; Adamec et al, 2011). In the valuation of benefits, those resource scarcities in energy and finance can be considered as business risks. Based in this assumption, avoidance of the economic risk per installed capacity or unit energy service approximates the benefits of distributed energy systems; herewith, the risk estimate is occurrence of scarcity multiplied by additional costs in a period. Possibilities for valuations of benefits are reasonable (+).

Marketing

It is often argued that introduction of renewable energy has influenced the suppliers' market mix, in particular the price of supplies (Awerbuch, 2004; Schiermeier et al, 2008; Adamec et al, 2011; EPA, 2011; Richter, 2012; Schleicher-Tappeser, 2012; Eid et al, 2016). One argument is that lower prices would be possible because additional renewable energy would reduce sensitivity of purchases with respect to the resource prices. Another argument is that additional renewable energy could invoke flat rate pricing, which are easier to manage, but it also enables dynamic pricing with respect to variability of wind and solar energy. The flat rate can be expected in the public wholesale and dynamic one in the private retail but current practices in the EU are opposite to that expectation as the wholesale prices are determined on nearly continuous auctioning whilst the retail prices based on annual or longer-term agreements between distributers and consumers. It is also suggested that certification based on renewable energy enables to reduce costs imposed by regulations, but regulations are often driven the larger scale of renewable energy consumption. It is also plausible that market entry of suppliers dedicated to renewable energy trigger higher prices, thereby benefits. Based on this argumentation, the benefit of distributed energy systems could be valued as price mark-up of the firms dedicated to renewable energy compared to the statistical average multiplied by the scale of supplies. Possibilities for valuations of benefits are reasonable (+).

Change of current

It is also assumed that the distributed energy systems can supply DC instead of AC on short distances (Pepermans et al, 2003). This way, elevating voltage and transformers in electronic products can be avoided. The DC distribution on short distances could be cheaper because the costs of transforming stations for high-voltage AC would be avoided though estimates for large-scale PV installations suggest that the AC distribution is cheaper (Li et al, 2017). In addition, many products apply transformers. While the costs per transformer are only a few euro per products many transformers are daily used. Such benefits of DC depend on their specific applications, which is difficult to assess. Possibilities for valuations of benefits are modest (+/-).

3.6.5 Producer collective interests

Mitigation of impacts

A benefit of the distributed energy systems with use of renewable energy and storage is reduction of impacts on health and environment. Severity of the impacts caused by the generating and distributing of electricity based on fossil fuels is widely observed (Vohra et al, 2021), and there is a broad consensus about prevention of the impacts due to the distributed services based on renewable energy (NREL 1997; Schiermeier et al, 2008; EPA, 2011; Eller and Gauntlett, 2017; Rickerson, 2019). The valuation of benefits can be based on assessment of the damage costs or the costs of preventing impacts. The damage cost approaches depend on the scales and causes of damage which vary (Markandya and Wilkinson, 2007); for example, the damage cost per ton CO2 vary from USD 5 to USD 800 (Tol, 2005). The costs of preventing impacts depend on targets for the impact reduction; a possibility compared to the distributed energy systems with conventional ones is based on far reaching demands for pollution reduction (Krozer, 2008). Possibilities for valuations of benefits are reasonable (+).

Import dependency

In addition to the impacts on health and environment, several scholars addressed the consequences of energy services on political and economic relations. An issue is lower import-dependency thanks to renewable energy based on local resources which is pursued with regards to international conflicts and competition (NREL, 1997; Resch et al, 2008; Eller and Gauntlett, 2017). Whilst the benefits of domestic production and distribution are widely acknowledged the valuations of benefits pose difficulties because trading is usually least costly, except during the collisions; hence, policies embrace the domestic production during a conflict but dismiss after its resolution. However, the international prices of energy fluctuate heavily. Given the fluctuations, it is difficult to define a price that would provide a reference for the estimate the benefits due to lower import-dependency. Comparison of the scale of energy services during low and high fuel prices throughout decades is possible but doubtfully relevant for the distributed energy systems. Possibilities for valuations of benefits are modest (+/-).

Local stakeholders

The distributed energy systems also enlarge capabilities of local stakeholders which can reduce costs of execution due to better knowledge of local conditions (NREL, 1997; Schiermeier et al, 2008; EPA, 2011; Eller and Gauntlett, 2017). For assessing such benefits, comparison of local and external interests is needed, which in turn, requires specification of prices and quality performances in tenders. It is also pinpointed that the distributed energy systems in remote areas enhance energy consumption which contributes to sales, thereby to the suppliers' benefits. The additional sales due to additional services for remote areas can be assessed based on local energy demands and experiences with energy consumption in suchlike areas elsewhere but there can be double counting with the benefits in optimisation mentioned below. Possibilities for valuations of benefits are modest (+/-).

Optimisations

A major benefit of the distributed energy systems is attained when construction and maintenance of large scale, high-voltage distribution network are avoided, it is when investments in infrastructure are deferred. The deference of high-voltage grid is widely advocated with regard to high costs per mileage and power losses in lengthy distribution grid (Adamec et al, 2011; EPA, 2011; Busch and McCormick, 2014; Bronski et al, 2015; Burger and Luke, 2016; Rismanchi, 2017). Those benefits can be based on cost assessment of distribution lines in manuals for investments and loss prevention in distribution (e.g., IEA-ETSAP, 2014; MISO, 2019; ENTSO-E, 2019; Euelectric, 2021). A few other benefits are also envisaged. One is optimalisation of energy resources when locally available renewable energy and human capabilities to use them are considered. Another benefit is economic use of polluted and wasted land for local energy generation but these valuations need assessments of the local conditions. Possibilities for valuations of benefits are reasonable (+).

3.6.6 Consumer individual interests

Prices

Main consumer benefits of the distributed energy systems, as argued by scholars, are lower purchase costs of electricity (Pepermans et al, 2003; Adamec et al, 2011; Richter, 2012; Schleicher-Tappeser, 2012; Eid et al, 2016). Major benefits emerge when consumers store renewable energy and use this storage for the cost reduction during the price peaks, if the variable pricing applies. This 'price shaving' generates large benefits, it is expected, because the peak prices are several times higher than the average prices. This way, consumer can also avoid high charges for the decreasing power consumption, monopoly price caused by suppliers' mergers and high taxes. In cases of microgrids, consumers can settle prices based on local power nodes rather than mimic the prices on-grid. As shown in simulations of PV with battery storage compared to on-grid consumption, consumers can gain but suppliers that miss sales can react by lower on-grid prices and differentiation of tariffs (Neubauer and Simpson, 2015). Possibilities for valuations of benefits are reasonable (+).

Consumption

In addition to lower peak prices, the distributed energy systems can reduce costly peaks in consumption. The peaks can coincide with high price in case of the variable pricing and can also be costly when the flat rate is used. It is argued that large benefits could be obtained through monitoring of energy, which would provide incentives for prudent, low-cost energy consumption (Pepermans et al, 2003; Adamec et al, 2011; Bronski et al, 2015; Tuballa and Abundo, 2016; Rismanchi, 2017); thereby avoiding peaks in consumption. In addition, local waste heat and other scattered energy resource could be assessed for consumption. Whilst the peaks in energy consumption are widely observed and assessed, the benefits are disputed because vested habits usually prevent energy savings. Studies on the factors that drive toward lower consumption are indecisive (Frederiks et al, 2015). Smart meters for monitoring of energy consumption are often recommended, which give sense of control to the consumer, but they do not necessarily invoke reduction of energy consumption. Even more difficult is to assess the benefits of individual and social autonomy due to the distributed energy systems though this perception is widely observed. Possibilities for valuations of benefits are modest (+/-).

3.6.7 Consumer collective interests

Economic interests

Several authors point out that distributed energy systems contribute to local economies (NREL, 1997; Richter, 2012; Busch and McCormick, 2014). Various positive impacts are mentioned. Such services would enlarge local business income due to constructions and operation on sites rather than ones far away. More jobs would be created given that local small-scale firms are generally more labour-intensive than large scale companies. Due to more incomes of firms and jobs taxes would enlarge. Moreover, when local energy services expand, external energy services are attracted due to positive image, entailing diversification of energy services which generates investments and provides price stability. These train of thoughts are attractive, but risks a wishful thinking. The direct benefits for income and jobs are well-assessable but follow up is disputable. Possibilities for valuations of benefits are reasonable (+).

Social interest

Various scholars mention the social interests in favour of distributed energy systems (Adamec et al, 2011; Akinyele and Rayudu, 2014; Busch and McCormick, 2014; Tuballa and Abundo, 2016). Benefits of such services are better services for isolated consumers, increasing social capabilities to deal with energy issues and services tuned to the social demands in communities. The benefits for the isolated consumers are well-assessable as an additional electricity consumption but it is disputable how to define the contributions to social capabilities and tuning to the demands in communities compared to the electricity consumption on-grid. Possibilities for valuations of benefits are modest (+/-).

3.7 Conclusions benefits of distributed energy systems

The benefits of distributed energy systems are divided into individual and collective ones for the producers and consumers of electricity. The benefits can be substantial and compensate for their higher costs but not all are well assessable. Reasonably assessable benefits to the individual producers are risk reduction due to diversification of energy and financial resources, pricing of electricity as a marketing tool, and to the collective interests, they are mitigating impacts and optimisation through deference of costly expenditures. Reasonably assessable benefits to the individual consumer are related to shaving of the peak prices, and to the collective interests, these are contributions to in local economies. Cost saving operations and changes of current are less assessable benefits of individual producer, whereas lower import-dependency and support of local stakeholders are less assessable collective producers interests. Less assessable benefits for the individual consumers are prevention of peak consumption and for their collective interests these are contribution of the local social interests. However, experiences with the valuations of such benefits are scarce. A major contribution of the SUSTENANCE project would be the benefit assessments based on the demonstration projects which needs data and estimates. The data can be provided by the executors of demonstration project based on inquiry into the assessable benefits followed by checks of the estimates with regard to local conditions and interests.

Table 5 A few illustrative examples of project with PV off-grid and microgrid

Country	Location	Customer	PV	Battery, or KW generator	Other sources	Annual power	Total cost	PV USD	Other	kWh	Perform-ance PV	reference
			kW	kWh		MWh	USD	/kWh			kWh /kW	
Egypt	National Agricult. Center (Niubaeya)	autarchic (generator)	41	*20*	10 kW wind	683	184374	0.32		0.27	16563	Fouad et al 2019
Iran	north of Tehran	remote residential house	10	*50*		*361*	70072	0.19			36120	Guan, 2021
India	rural area across states	10000 households + commerce	172	4000	circular batch	1371	1212000	0.12	diesel	0.42	7969	Raman, 2022
Bangladesh	St Martin	coral island 8000 persons	340	*730*	240 kW wind	1058	361147	0.25	diesel	0.34	3112	Masrur, 2020
India	Hyderabad	campus hostel	150	250	grid	362	278400	0.05		0.07	2415	Iqbal, 2017
Rwanda	Mukungu vilage	stand alone	20	584	none	222	1166898	1.26			11086	Chang, 2021
Peru	Laguna Grande	50 to 200 persons fluctuating (installed)	8	38	3 kW turbine	62	23467	0.23	larger scale PV	0.35	7756	Canziani et al, 2021

Notes

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