AKADEMIA GÓRNICZO-HUTNICZA IM. STANISŁAWA STASZICA W KRAKOWIE
WYDZIAŁ ENERGETYKI I PALIW

KATEDRA ZRÓWNOWAŻONEGO ROZWOJU ENERGETYCZNEGO

Praca dyplomowa

Feasibility study of Demand-Side Management in microbreweries

Studium wykonalności zarządzania stroną popytową w mikrobrowarach

Autor: *Haoran Zhang*
Kierunek studiów: *Energetyka Odnawialna i Zarządzanie Energią*
Opiekun pracy: *dr hab. inż. Artur Wyrwa, prof. AGH*

Kraków, 2022

Abstract

Green, organic and sustainable are becoming important marketing labels for European microbreweries to attract consumers. As an energy-intensive industry, nearly 8% of production costs in a brewery are attributed to energy consumption. Recent studies focus on heat resource management, but for microbreweries, the thermal process is powered by electricity and therefore not applicable. This thesis develops a simulation tool to assess the feasibility of electricity Demand-Side Management in microbreweries. Case studies show that a Krakow-based microbrewery can be expected to save more than a quarter of its monthly electricity bill under a Demand Response scenario with a PV-battery system. The investment cost is expected to be fully recoverable after the 13th year of operation. A Lifecycle Cost analysis shows that the modelling system can achieve a cumulative savings of 106344 PLN in the 20th year compared to business as usual. In addition, another case study argues that the involvement of an Energy Service Company can enhance the feasibility of microbreweries participation in a Renewable Energy Community project.

Streszczenie

Słowa: ekologiczne, organiczne i zrównoważone stają się ważnymi znakami marketingowymi dla europejskich mikrobrowarów, przyciągają konsumentów. Browarnictwo należy do przemysłu energochłonnego, prawie 8% kosztów produkcji związane jest ze zużyciem energii. Ostatnie badania koncentrują się na zarządzaniu procesami cieplnymi w mikrobrowarach, natomiast niewiele badań dotyczy zarządzania energią elektryczną. W pracy opracowano narzędzie symulacyjne do zarządzania stroną popytu na energię elektryczną w mikrobrowarach. Studium przypadku w krakowskim mikrobrowarze doposażonym w instalację fotowoltaiczną z magazynem energii wykazało, że poprzez odpowiednie zarządzanie urządzeniami można zaoszczędzić ponad jedną czwartą miesięcznych wydatków za energię elektryczną. Czas zwrotu nakładów inwestycyjnych w takim przypadku nastąpi po trzynastu latach eksploatacji. Analiza kosztów cyklu życia wykazała, że skumulowane oszczędności w ciągu dwudziestoletniego okresu eksploatacji mogą wynieść 106 344 zł. Zaangażowanie przedsiębiorst typu ESCO może zwiększyć zdolność mikrobrowarów do uczestnictwa w projektach typu Spółdzielnie Energetyczna OZE.

Nomenclature and abbreviations

AMS	Advanced Metering System
AC	Alternating Current
BESS	Battery Energy Storage System
BAT)	Best Available Techniques
BREF	Best Available Techniques Reference Document
BMC	Business Model Canvas
CEC	Citizen Energy Communities
CPP	Critical Peak Pricing
DRP	Demand Resource Providers
DR	Demand Response
DSM	Demand-Side Management
DC	Direct Current
DSO	Distribution System Operators
EV	Electric Vehicle
EIA	Energy Information Administration
ESCo	Energy Service Company
EC	European Commission
EU	European Union
HVAC	Heating, Ventilation, and Air Conditioning
IMP	Imported Power from the grid
IBDR	Incentive-Based DR
MPPT	Maximum Power Point Tracking
O&M	Operation and Maintenance
PV	PhotoVoltaic
PVGIS	Photovoltaic Geographical Information System
PBDR	Price-Based DR
PPS	Purchasing Power Standard
RTP	Real Time Pricing
REC	Renewable Energy Community
RES	Renewable Energy Sources
SEDIA	Single Electronic Data Interchange Area
SOFC	Solid Oxide Fuel Cell
SOFC	Solid Oxide Fuel Cell
IEMD	The recast Internal Market for Electricity and Amending Directive
RED II	The recast Renewable Energy Directive
ToU	Time of Use
TSO	Transmission System Operators
VPPA	Virtual Power Purchase Agreement

Contents

1. Introduction

Demand-Side Management (DSM) is a way to empower consumers to participate in the energy transition. The European Union (EU) has introduced a number of regulations to promote its development. For example, the recast Internal Market for Electricity and Amending Directive (IEMD) clarifies technical specifications for prosumers participation in the electricity market, and also states that existing regulatory barriers should be removed [1]; The recast Renewable Energy Directive (RED II) reaffirms the significance of the demand side for advancing consumer-centered renewable energy development [2]; The Energy Efficiency Directive provides methodologies and measures to develop DSM [3]. At the same time, the EU requires member states to transpose the directives into the country and local regulations, which means that concrete policy supports or subsidies can be expected in the near future.

In addition to complying with the policy orientation, DSM can also be considered as a solution to mitigate the continued rise in energy expenditures caused by geopolitical risks. In 2019 and 2020, over one-fifth of Europe's electricity generation comes from natural gas, where around 40% is from Russia [4]. Besides the transition to renewable sources, facilitating DSM is another faster, more economical, and more effective way to lessen the recline on fossil plants by increasing the share of self-consumed electricity in a community and promoting the application of Demand Response (DR). It also has economic appeal for consumers because the electricity bill can be expected cheaper than the conventional ones which include transmission costs.

However, the challenges it faces are also evident, one of which is the limitation of capacity. The energy consumption of a typical household is usually small, and even through aggregators it often takes hundreds of households to meet the lower limit of DR. For non-residential consumers and energy communities, it usually needs a case-by-case analysis, without the possibility of a copy-paste batch promotion. Another obstacle is that there is often an expensive one-time purchase fee in the service package that can be found in the market at present, from the installation of rooftop PhotoVoltaic (PV), batteries, smart meters, and energy management system software. It may bring concerns to potential clients that what if the investment can not be recouped by the electricity bills saved. Therefore, the selection of suitable participants with sufficient energy demand and whether such projects can obtain governmental subsidies on the upfront investment are crucial for the research of DSM.

1.1. Policy background

In the past decades, intergovernmental agencies, academia, and civil society have continuously called on governments to adopt climate-friendly development pathways, which includes setting more ambitious carbon emissions reduction targets and implementing them as soon as possible. However, we have seen that global climate cooperation has suffered successive setbacks in the past few years after the landmark achievements of the Paris Agreement in 2015. For example, in 2017, President Trump announced his withdrawal from this agreement. Then, the Brazilian government delegation as the only country refused to accept Article 6 of the Paris Agreement for two consecutive years from 2018 to 2019 [5], while Article 6 is the core issue in climate cooperation related to the global carbon market mechanism that involves nearly 200 countries. On the contrary, the outbreak of the Coronavirus in 2020 seems to make policymakers aware of the huge disasters it can cause to the society and economy from risks of low probability but high consequences, such as large-scale epidemics or climate crises. It has also injected impetus into countries to find a road to green recovery.

The policy balance is accelerating towards sustainability and innovation. Focusing on green investment is mainly to avoid future asset shelving caused by unsustainable industries and the threat of exacerbating climate change. McKinsey claims that if viewed positively, the COVID-19 pandemic is also unleashing a new area of change for businesses. It has motivated people to formulate future-oriented risk plans or development policies including risk aversion [6]. In other words, the conventional high-carbon industries will face a greater risk of shelving assets. Under this situation, the introduction of green recovery policies has two implications: One is to gradually reduce government subsidies for the black industry; The other is to guide the market to pay attention to this risk and thus attract capital to enter the green field.

Taking the power industry as an example, during the first lockdown affected by the epidemic in Europe, electricity generated by fossil fuels fell by an average of nearly 40% [7]. In contrast, the electricity from Renewable Energy Sources (RES) represented by solar and wind energy increased by around 20% [7], compared to the same period before the pandemic. This demonstrates that renewable energy can be expected to have stronger resilience and higher reliability in the face of risks. Specifically, the short-term impact of the COVID-19 lockdown on energy incorporations is mainly due to the supply chain shortage caused by the shutdown of upstream and downstream companies; Another reason is the decline in market demand, which led to many tenders have been shelved, and the construction progress has been slowed. The delay or withdrawal of some project transactions by financing institutions has further deepened the difficulty of corporate capital turnover. Therefore the support from the authority is essential to help companies tide over difficulties, and it is a wise choice for governments to fund renewable energy industries that are expected to return more social-economic-ecological benefits in the future.

Facts in 2021 have continued to confirm this trend. Global renewable energy growth reached nearly 257 GW in a year, increasing the renewable energy stock by 9.1% while accounting for a recorded 81% of global electricity additions [8]. There are two facts particularly worth noting. Solar power alone accounted for more than half of the new generation from renewables, reaching a record 133 GW in 2021 [8]; Among which the distributed PV capacity additions accounted for around half of the new generation from solar, reaching a record 65 GW in 2021 [9]. IEA has also forecasted that the distributed solar PV capacity can be expected to grow by more than 250%, reaching 530 GW in 2024, compared to 2019 [10]. The increasing performance will depend on the policy scheme in the reality, where the EU's policy support in this regard is better than the global average.

Since the outbreak of the epidemic, the EU leaders and its member states have repeatedly emphasized the importance of green recovery. A €750 billion stimulus package was proposed in 2020, to support countries in recovering from the pandemic and accelerating the green transition. Among the recovery package, there are some specifically for low-carbon transformation, such as the €10 billion Just Transition Fund [11]. Grants related to the development of distributed solar and DSM, such as DR and Renewable Energy Community (REC) projects, are already available on the website of EU Funding & tender opportunities: Single Electronic Data Interchange Area (SEDIA).

1.2. Brewery sustainable development

Breweries belong to the energy-intensive industry, and significant progress has been made in the past few decades in terms of water conservation, energy conservation, circular economy, etc [12]. Energy-intensive means the share of the total production cost allocated to energy at least 3%, while it usually goes from 5% to 20% [13]. In a large brewery, 0.43 kWh of energy can be used to produce one litre of beer [14], and the energy consumption increases as the brewing scale decreases [15]. That is to say, microbreweries can be regarded as the top energy user to produce a unit of beer. Kaleta et al. (2015) introduced that nearly 8% production cost of microbreweries in Poland is allocated to energy-related processes [16], which meets the energy-intensive industry definition. Renewable energy use plays a key role in the brewery sustainability.

Facts & Numbers:

- *Microbrewery definition – yearly production up to* ***1,000*** *hectolitres, according to Brewers of Europe* [83].
- *Microbrewery in Poland has an output around* ***4,542,000*** *hectolitres, according to Brewers of Europe* [84].
  Microbreweries become the target for introduction of DSM.
- ***5.2 - 9%*** *of the production cost is allocated energy process* [14] [66].
- *Around 40% of the energy is used for the electrical processes and 60% used for thermal processes, and most thermal processes in* ***microbreweries are primarily supplied with electricity*** *(such as mashing, boiling, cooling, fermenting)* [52].
- *Commercialization solutions of thermal energy efficiency improvement are available for large breweries, such as services from Steinecker* [59]*. But* ***researches on electricity aspect for microbreweries are limited****, and usually regarding the power factor correction and temperature management, for example a typical study by Hubert et al. (2016)* [85].

A common beer brewing process is shown in ***Figure 1***. From the ingredients down to the distribution chain, breweries are taken actions to decarbonizing their operations. For example, Holland Malt initiated a project to reduce the energy usage in maltings with more than 50%, and plan to built a zero emission malthouse by 2024 [17]; Ibaraki brewery of Asahi Group developed and installed a 200 kW Solid Oxide Fuel Cell (SOFC) in 2020, powered by the byproduct methane gas from brewery's anaerobic wastewater treatment process [18]; AB-InBev proved that all lager and ale profiles, can reduce heat load of brewhouse, by applying the very high gravity brewing and its Simmer & Strip technology, and thus, saving energy expenditures to 10-20% of the total brewing process [19]. This thesis studies the DSM application feasibility in microbreweries, from brewing to fermenting, which can be expected to promote further researches.

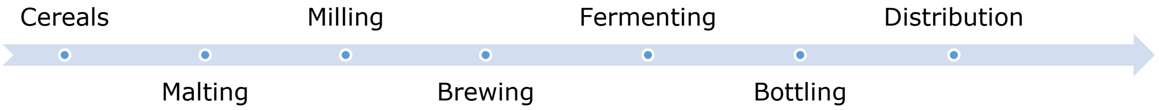


Figure 1 *Brewery production: from ingredients to distribution*
Source: own compiled from [15] [20]

1.3. Structural introduction

The thesis starts giving a general introduction to the topic and main policy background. The introduction is followed by the motivation of the author, following aim and scope of the research (***Chapter 2***). Next is literature reviews which are dedicated for DSM (***Chapter 3.1***) and energy use in the regular brewing process (***Chapter 3.2***). It is followed by giving the methodology and steps of simulation (***Chapter 4***). Finally, results and outcomes under the DR and REC scenarios is presented and a brief discussion on the business opportunity in terms of both sustainability and innovation is included (***Chapter 5***), followed by the conclusions and the future work (***Chapter 6***). These are followed by all references cited in the thesis.

2. Aim and scope of the thesis

This thesis aims to study the role of Small to Medium-sized Enterprises (SMEs) in DSM, and further selects microbreweries in Poland as the focus objective, to define how much energy expenditure can be reduced by adopting DSM. Based on a large number of SMEs and increasing energy prices, it can be expected to become a market opportunity for DSM. Microbreweries belong to one of the fastest-growing industries of SMEs, of which the number in Poland has grown from 50 to 1160, in the decade of 2010 to 2020 [21]. It is also an energy-intensive industry with highly similar production procedures. At the same time, microbreweries are often located in urban communities, which increases the feasibility of participating in DR aggregation, or energy community transactions. This indicates that the development of a technical tool for microbreweries to evaluate the economic performance of DSM may have implications for the whole industry.

In addition, electricity prices based on Purchasing Power Standard[1] (PPS) in Poland are higher than the EU average. According to Eurostat, the electricity price of Poland is observed beyond 25 PPS per 100 kWh in the first half of 2021, ranking among the highest [22]. The reduction of energy costs, therefore, can be expected to drive social participation in DSM. The research questions are described as follows:

1) Does DSM work for microbreweries?
2) Why would microbreweries like to be involved?
3) What devices should be installed, to balance costs and performance?
4) How to increase the benefits for both clients and service providers, and add extra value if possible?

where question 3) is the key issue to be discussed in the thesis by: a) designing a self-consumed Renewable Energy System with PV and battery; b) modelling the energy and economic performance of the proposed system; c) comparing result

---

[1] PPS is an artificial currency unit, which is derived by dividing any economic aggregate of a country in national currency by its respective purchasing power parities [82]. Regarding electricity prices mentioned here, the higher PPS index, the higher proportion of energy bills for households and SMEs in the total expenditure.

differences between scenarios of DR and REC. Question 4) is explained by proposing a business plan in ***Chapter 5.2.2***.

The scope of this thesis is a feasibility study of the application of DSM in microbreweries from brewing to fermenting (see ***Figure 1***), to show the effects on energy and economic performance by participating in DR and REC. The thesis does not involve interaction with distributed grids, smart distribution of Battery Energy Storage System (BESS), and issues such as automatic regulation or response optimization.

The innovation of this thesis topic is that most of the public articles regarding energy analysis of the brewing industry focus on energy efficiency optimization, waste heat recovery, and biomass-based renewable energy utilization. In other words, there are few studies on DSM in breweries. But it doesn't mean there is no reference at all. In fact, relevant studies regarding methodologies, input data consumption, and modelling functions are available in certain articles, which is presented in the next chapter.

3. Literature review

This chapter is an extensive literature review of DSM and energy use in beer brewing processes. The focus of ***Chapter 3.1*** is to introduce the definition, application, challenges and potential solutions of DR and REC projects; ***Chapter 3.2*** introduces the energy demand and balance of each stage in a regular brewing process of the brewery, and focuses on the existing research and deficiencies in the application of DSM in microbreweries.

3.1. Demand-Side Management

Generally speaking, DSM is an operational method to optimize the power system operation and/or reduce the cost of stakeholders, through the management of energy consumption at the demand terminal and by means of behavior shifting and/or energy trading. There are many definitions of DSM. For example, some researchers summarized that DSM refers to all changes that originate from the demand-side of the market to achieve large-scale energy efficiency improvements by new technologies and behaviour changes [23]; The DSM objective is the summation of two parts: to minimize the nodal operational cost, and to minimizes the power losses over distribution line [24]. Enel X, an Energy Service Company (ESCo), defined DSM as a group of actions designed to manage and optimize a site’s energy consumption and to cut costs, from grid charges to general system charges, to modify the overall consumption picture to reduce bills [25]. The US Energy Information Administration (EIA) elaborated DSM as a utility action that reduces or curtails end-use equipment or processes. DSM is often used in order to reduce customer load during peak demand and/or in times of supply constraint [26]. EU has not yet give DSM an official definition, but a certain sub concepts, such as DR and REC, are clarified as single concepts in legislative documents.

DSM has a wide range of participants. Based on the electricity market structure, Behrangrad (2015) identified six DSM stakeholders [27]:

- Demand Resource Providers (DRP), such as aggregator, ESCo
- Consumers
- Energy market operators
- Energy retailers

- Transmission/Distribution System Operators (TSO/DSO)
- Generators

A research from European Commission (EC) pointed out there are other stakeholders in addition to direct participants, such as research institutions, consulting companies and public departments, who are also actively participating in and promoting the development of DSM-related projects [28]. According to the above definition and the scope of this thesis, ESCos and consumers are the mainly subjects in this research.

DSM has a solid foundation and diversified development prospects. Goy & Sancho-Tomás (2019) mentioned in their book that DSM is one of the top three topics regarding smart grid in Europe, accounting for 25% of investment in more than 900 European smart grid projects in 2017 [29]. At the same time, the distinction of peak and off-peak electricity prices in almost all EU countries provides a market basis for residential and commercial consumers to be involved in the DSM, and the relevant Decrees mentioned in ***Chapter 1*** also provide policy supports and are gradually simplifying the cumbersome process of multiple supervision.

Technically, a successful implementation of DSM is based on the deployment of relevant hardware and software, including smart meters, energy management systems and communication systems. The US Department of Energy defined an Advanced Metering System (AMS) in 2016 that integrates the above functions to measure, record and analyze the hourly energy consumption data of the consumer through the client's smart meter. The AMS can also execute other actions through the communication function, such as turning the specified device on or off [30]. Similar systems have been successfully put into commercial use in Europe, such as Tibber [31] and Greenely [32], etc. They can not only fully realize the above functions, but also display real-time data on the user interface, including hourly electricity prices and consumption, etc. to meet EU and local regulatory requirements.

3.1.1. Key definations

Current peer-reviewed researches classify DSM into several different areas: DR, REC, micro-grids, energy efficiency (which is usually included in the preceding options), etc. According to the search results on ScienceDirect, the number of studies related to DR accounted for 46% of the total DSM researches, which is the largest share; followed by REC, accounting for 25%, as shown in ***Figure 2***.

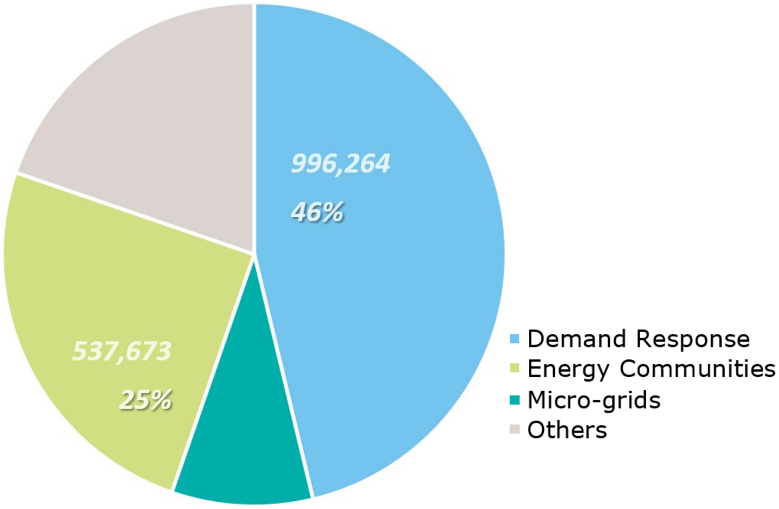


Figure 2 *Number & share of sub-studies under DSM.*
Source: own compiled from [33]

DSM has been an integral part of the load management strategies for many years. Besides DR and REC, it also involves several different technologies and theories, such as smart metering and transaction methods [34]. In fact, DSM appears on the entire chain of the energy system. Jerin et al. (2018) introduced the role of DSM in restoring grid frequency and solving congestion problems [35]; Diekerhof et al. (2018) summarized market economics related DSM issues and introduced relavant optimazation methodologies [36]; Hartnett et al. (2021) described the existing DSM software terminals, including participation steps, transaction rules and design principles [37]; Aliabadi et al. (2021) systematically sorted out the optimization, simulation, and decision-making tools for DSM in the local and intergrated energy systems [38]. Although the content in [34]- [38] is beyond the thesis scope, it is still worth learning the research trends to understand the industry dynamics.

According to the method of determining the research framework and narrowing the research scope in Koirala et al. (2016), ***Figure 3*** shows the representative research trends of specific topics in the field of DSM. The main research trends in DSM (number of publications) are first identified through a keyword analysis in

ScienceDirect for 2010 to 2022. After, search terms such as "demand-side management, demand response" and "demand-side management, energy community" were used to further determine number of sub-topic publications for analysis [33]. Normalized values (0-1) are obtained for each theme by dividing the total number of keywords for each year by the total publications in that year [39].

Figure 3 *Research trends in DSM*
Source: own compiled from [33]

DR and REC are the focuses in this thesis because the indexes of DR are high in both ***Figure 2*** and ***Figure 3***, and it is the only theme in ***Figure 3*** that has accounted for more than half and remains stable over the past decade. Regarding REC, though the proportion of published research is not high, one of the core device in REC projects is community battery, while energy storage has a rising trend in ***Figure 3***. Also, the lack of publications on community governance in the overall DSM research, and the positive energy community policy mentioned in ***Chapter 1*** can make REC be considered a promising theme. The key definitions of DR and REC are introduced below:

1) Demand Response

EU definition: according to the point (20) of Article 2 of IEMD, DR is the change of electricity load by final customers from their normal or current consumption patterns in response to market signals, including in response to time-variable electricity prices or incentive payments, or in response to the acceptance of the final customer's bid to sell demand reduction or increase at a price in an organised market as defined in point (4) of Article 2 of Commission Implementing Regulation (EU) No 1348/2014 (17), whether alone or through aggregation [1].

DR is based on fluctuations in electricity demand in response to changing electricity prices or incentives [27]. It operates by responding to signals from current suppliers or system operators through the intervention of controllers such as ESCos, enabling end consumers to change their power demands on the grid [40]. The main purpose of DR is to reduce energy consumption during peak hours of the day [41].

Specifically, DR projects can be classified into two general categories: Incentive-Based DR (IBDR) and Price-Based DR (PBDR). Kanakadhurga et al. (2022) elaborated an illustration of detailed DR classification, as shown in ***Figure 4***. The IBDR contains two further subcategories: classical projects and market-based projects. Classical represents directly controling or adjusting the use of certain loads; While the other one is more popular and have several mature markets among European countries, for example, Frequency Containment Reserve market, manual Frequency Restoration Reserve market [42], and the Sthlmflex (electricity flexibility) market [43].

The focus of DR in this thesis, however, is on the second option: PBDR. From a system operator’s perspective, PBDR works on the minimization of peak to average ratio by modifying the tariff structure rather than providing incentives to the end users [44]. Time of Use (ToU) has the most concise and clear way of PBDR operation. In a simplest case of ToU, at least two time blocks should be defined as peak and off-peak. End-user rates during peak hours are higher than average rates, whereas rates during off-peak hours are consistently lower than the average [45]. The ToU model is applied to the economic analysis section of this thesis.

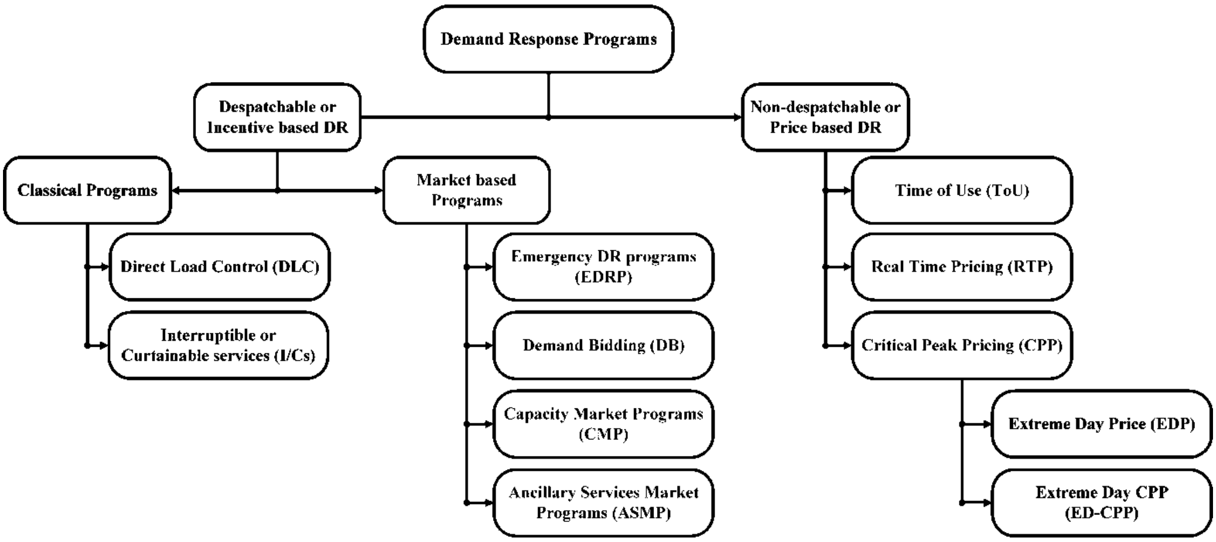


Figure 4 *Classification of DR [44]*

Real Time Pricing (RTP) projects have the same logic with ToU projects. Retailers can pass on fluctuating electricity prices in the day-ahead and intra-day market to end uses. RTP and Critical Peak Pricing (CPP) are out of this thesis scope, thus no further elaboration here, but relavant introduction and application cases can be found in [44], [46] and [47].

2) Renewable Energy Community

EU definition: according to the point (16) of Article 2 of RED II, REC is a legal entity: (a) which, in accordance with the applicable national law, is based on open and voluntary participation, is autonomous, and is effectively controlled by shareholders or members that are located in the proximity of the renewable energy projects that are owned and developed by that legal entity; (b) the shareholders or members of which are natural persons, SMEs or local authorities, including municipalities; (c) the primary purpose of which is to provide environmental, economic or social community benefits for its shareholders or members or for the local areas where it operates, rather than financial profits [2].

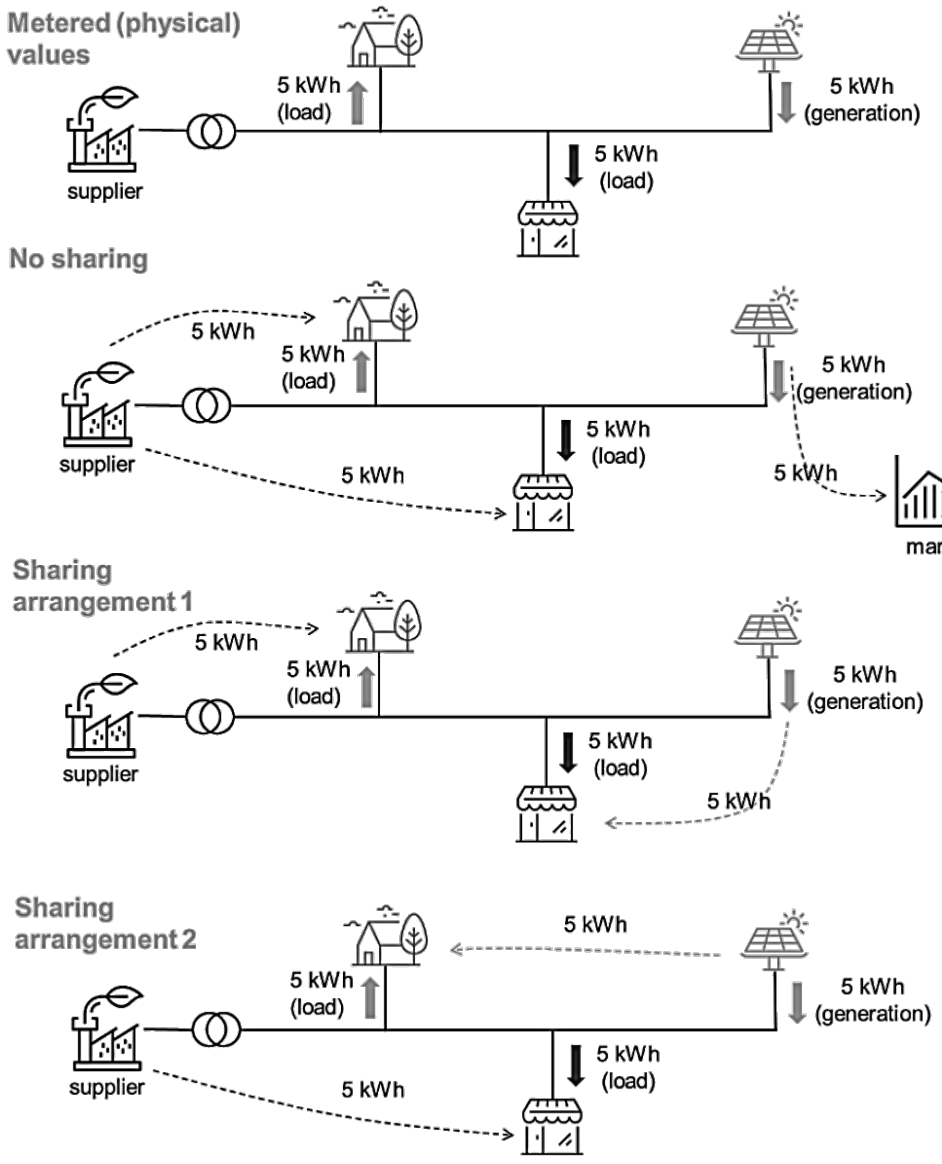


Figure 5 *Illustration of electricity sharing and energy flows [48]*

REC can carry out multiple activities: produce, consume, store, share or sell electricity. ***Figure 5*** shows different energy trading models. Both physical electricity transfers and financial transactions work in a REC. This new form of producing and consuming energy empowers consumers and local actors, giving them the chance to take part in the energy transition. In the short term, access to sharing may change the dispatch of resources and increase the renewables utilization [48]. Distributed generation and self-consumption inside communities bring economic benefits for consumers. End users can obtain fair and easy access to local renewable energy resources and other energy services while benefiting from the investment and reinvesting the benefits. In the long term, incentives from access to sharing frameworks may alter the generation mix of the electricity system [48]. ***Figure 6*** shows a typical REC and the geographical scope of jointly acting renewables self-consumers. In addition, there is another twin concept of REC: Citizen Energy Communities (CEC), which is defined in the IEMD [1]. CEC operates within the electricity sector, including renewable and fossil-fuel energy sources.

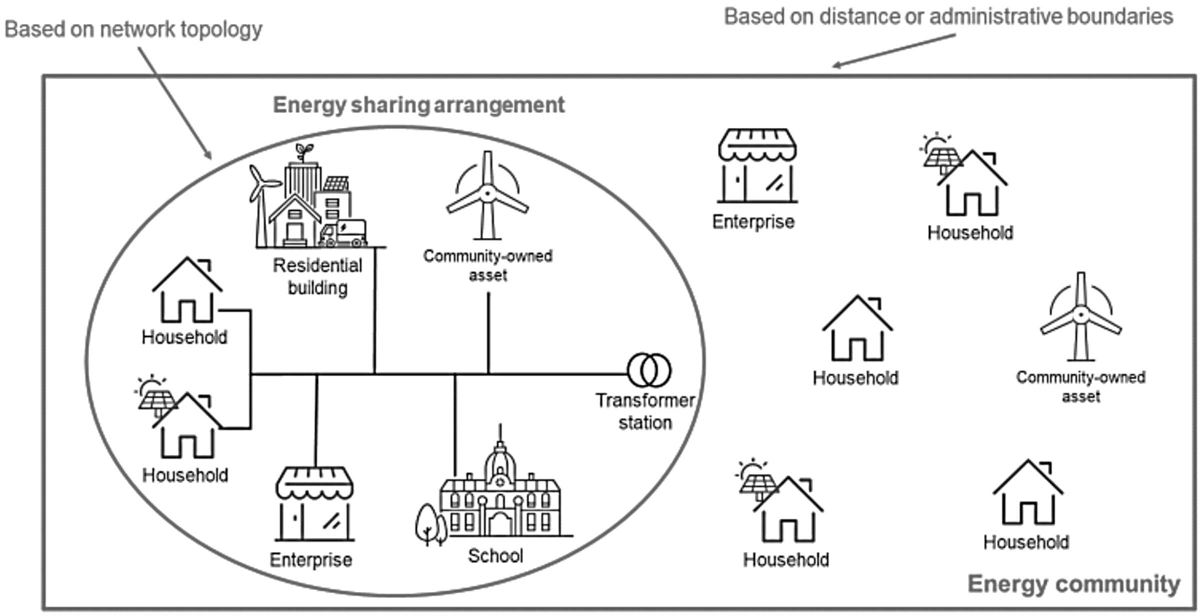


Figure 6 *Example of REC and its geographical scope [48]*

Supportive rules for REC can be found in relevant regulations released by the EU, such as Clean Energy for all Europeans, Fit for 55, IEMD, and the most important one RED II. Based on the instructions given by the EU, the actual regulation may vary in each country according to the local situation. Throughout 2021, most EU member states have introduced or updated applicable legislation on energy communities. Finally, considerable investment is backed up by the increasing interest among European countries in developing the energy sector. The EU-funded projects such as Horizon 2020 and plans at the national level contribute significantly to promoting energy communities.

Nevertheless, challenges exist in developing energy communities. It is hard to collect financial sources from citizens or local authorities before building the community. Furthermore, the lack of a detailed regulatory framework hinders the implementation of business models. Meanwhile, democratic governance over the energy community requires complex managing strategies due to the reliance on volunteer work and the lack of motivation of community members.

3.1.2. Current commercial applications

To conduct DSM, the first action is energy audit. An in-depth analysis of on-site consumption is needed, to identify whether consumption habits can be optimized without resorting to additional instruments. If yes, the action can be behavior change and most likely to install smart controllers for key devices; If it is not sufficient to achieve the desired cost reductions, further evaluation should be conducted on the extra installation of RES (such as rooftop PV, wind, etc.) and/or BESS. ***Figure 7*** shows potential devices, such as PV and BESS, and different types of loads in DSM projects.

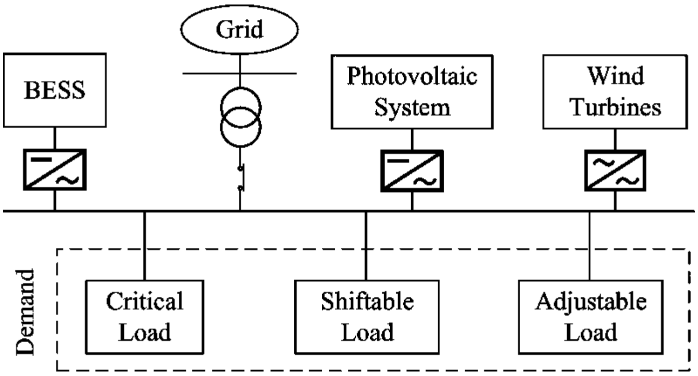


Figure 7 *Typical devices and different loads in DSM [49]*

DSM projects in reality are usually contracted by a third party such as ESCo [50] [51], rather than the end-user themselves, limited by the complex operational steps introduced above as well as the various loads and controlling stratagies shown in ***Figure 8***. Lighting system, Heating, Ventilation and Air Conditioning (HVAC) system and Electric Vehicle (EV) charging system can be regarded as shiftable and/or adjustable loads within a specific time to residential and commercial consumers. While those may become critical loads for industrial consumers. For example, a brewery's lighting system is often a critical load in most relevent studies [52].

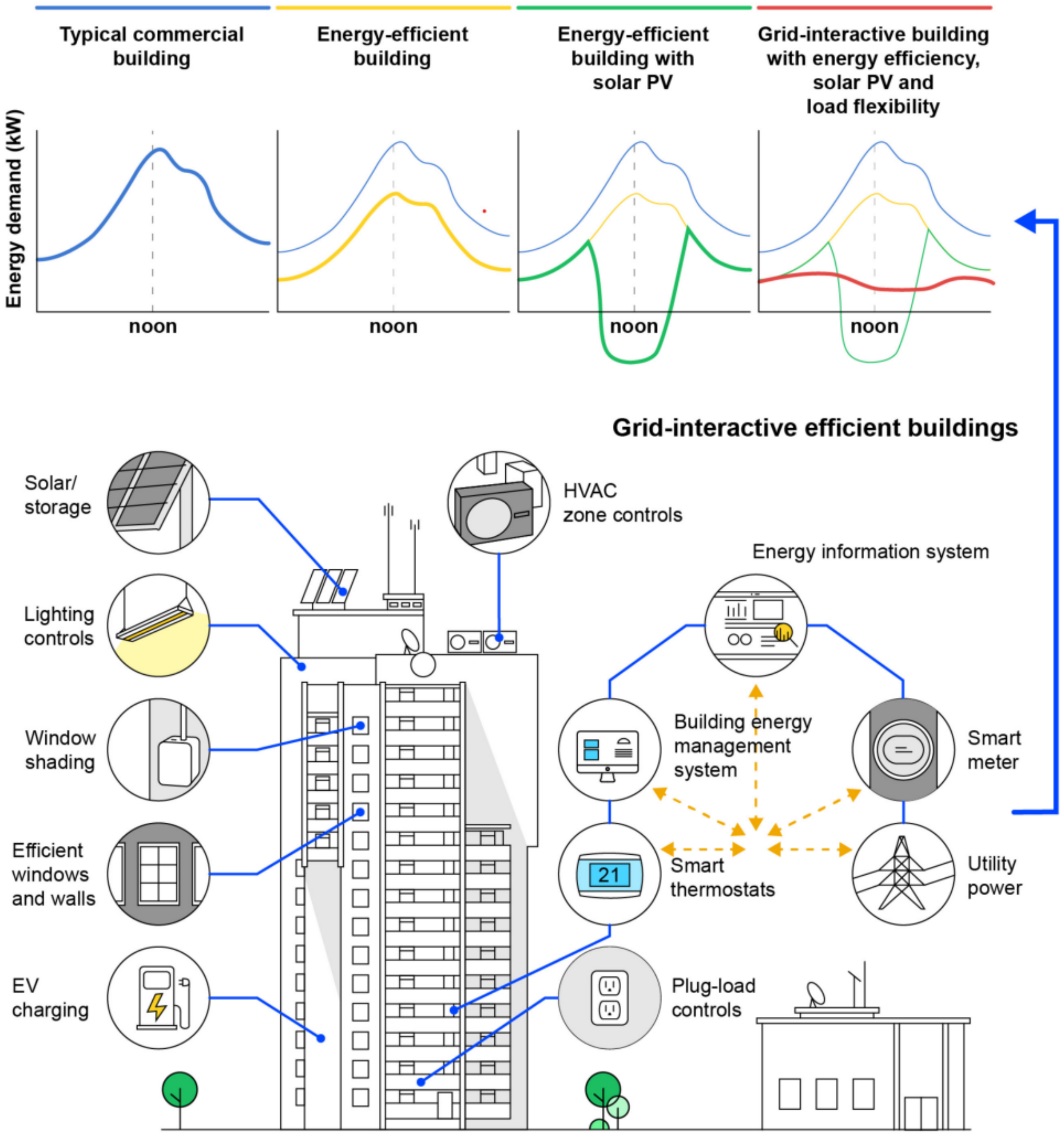


Figure 8 *Illustration of DSM in a building [53]*

Back to the focus of this thesis, SME engagement in DSM has a history of more than 50 years and ESCo has played an active key role on it. According to a guideline of DSM to SMEs by seven European companies and research institutes [54], typical working steps of such projects are introduced, as shown in ***Figure 9***. While the key challenge comes from the lack of a clear, quick and concise method to quantify energy and economics values [29], and a matched business model [55].

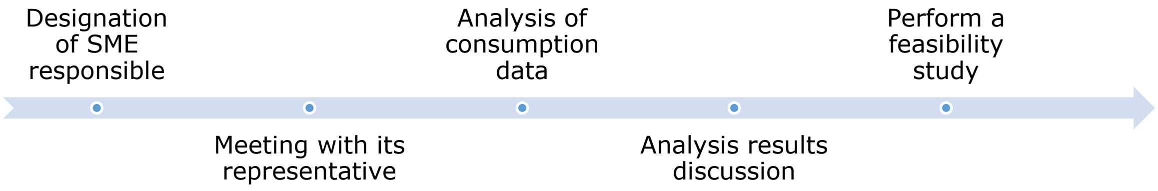


Figure 9 *Steps to perform the feasibility study as a service to SMEs [54]*

3.2. Energy use in the brewing

Several researches applied to the brewery industry focusing on the energy use introduced the energy profile and energy balance of brewing process, as well as the share of electricity bills in the general operational expenditure. As an energy-intensive industry, EC published a Best Available Techniques (BAT) Reference Document (BREF) for it. This BREF document can be considered as a guideline for cuting energy consumption and increasing energy efficiency in various European energy indensive industries including breweries [56]. ***Table 1*** shows the electricity and thermal energy consumption per hectolitre of beer for a European brewery and a Polish microbrewery. Data and articles as of 2015 show that the average energy use of brewing in Poland is higher slightly than the European average [16].

Table 1 *Energy use benchmarks for European and Polish (micro)breweries*

Type of energy		Consumption [kWh/hL]
EU	Electricity	7.5 – 11.5
	Thermal	23.6 – 33
Poland	Electricity	8.5 – 12
	Thermal	27 – 54

Source: own compiled from [16] [56] [57].

Figure 10 shows different types of energy consumed and the proportion of each in the step of milling, brewing, fermenting and bottling. Brewing can be observed as the key contributor to the whole process. The electricity used for brewing mainly comes from the grid, and the cooling comes from electricity; in contrast, the thermal energy have more diverse sources, which includes various RES, such as biogas [58], biomass, heat pump [59], solar (PV thermal systems) [60], geothermal energy [61], and it can also come from district heating systems.

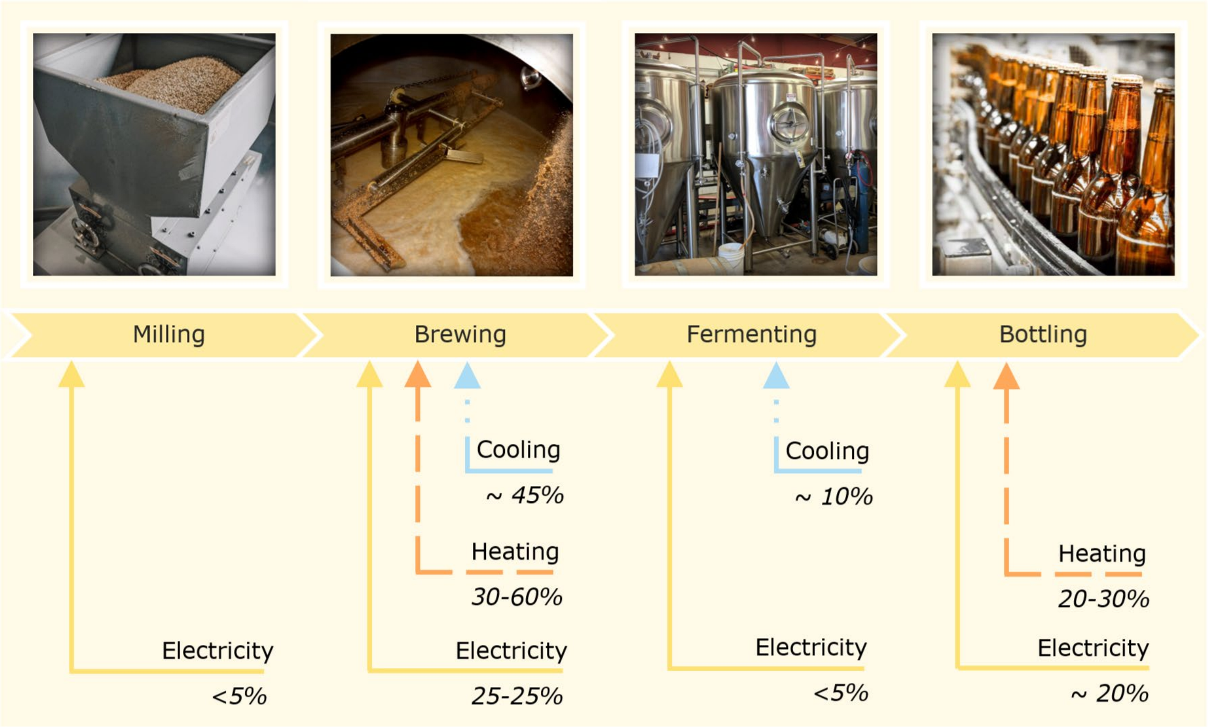


Figure 10 *Schematic diagram of energy flow in the selected production of breweries*
Source: own compiled from [15] [62]

In Poland, electricity for breweries usually comes from the grid, and most thermal processes are powered by natural gas. The cost of thermal energy can be even lower than electricity cost, though heating demand is bigger (see ***Table 1***). This is because the unit price of natural gas is approximately half of the electricity price. For microbreweries, considering that some thermal energy are actually powered by electricity rather than natural gas, electricity bill can account for a larger portion of the overall energy cost, as introduced in ***Chapter 1.2***. In other words, although the thesis is on DSM of electricity, thermal processes still need to be carefully considered for microbreweries.

Furthermore, brewing, as the most energy-intensive section in beer production, deserves further review and analysis. ***Figure 11*** shows the breakdown operations in the brewhouse, which contains boiling, heating, stirring, rotating and cooling. Schleich et al. (2000) described each steps in details: In the mashing process, ingredients such as malt and pre heated water are mixed, and then heated to the target temperature (approximately 75°C). The suspension is filtered in the next stage of purification to separate the wort, from the solid components of grains. It is followed by adding hops, and heating the wort boiling kettle to 100°C for around

90 minutes. Whirlpool is necessary after the boiling, to separate coagulated proteins and other suspended particles. Then, with the heat exchanger, cooling the wort to 4-18°C, depending on what kind of beer is brewed. The above is a typical brewing process. Next, moving to the fermentation and storage. In general, it takes a week to ferment and often another one to two weeks to refrigerate (or called 'cold storage') before bottling [58].

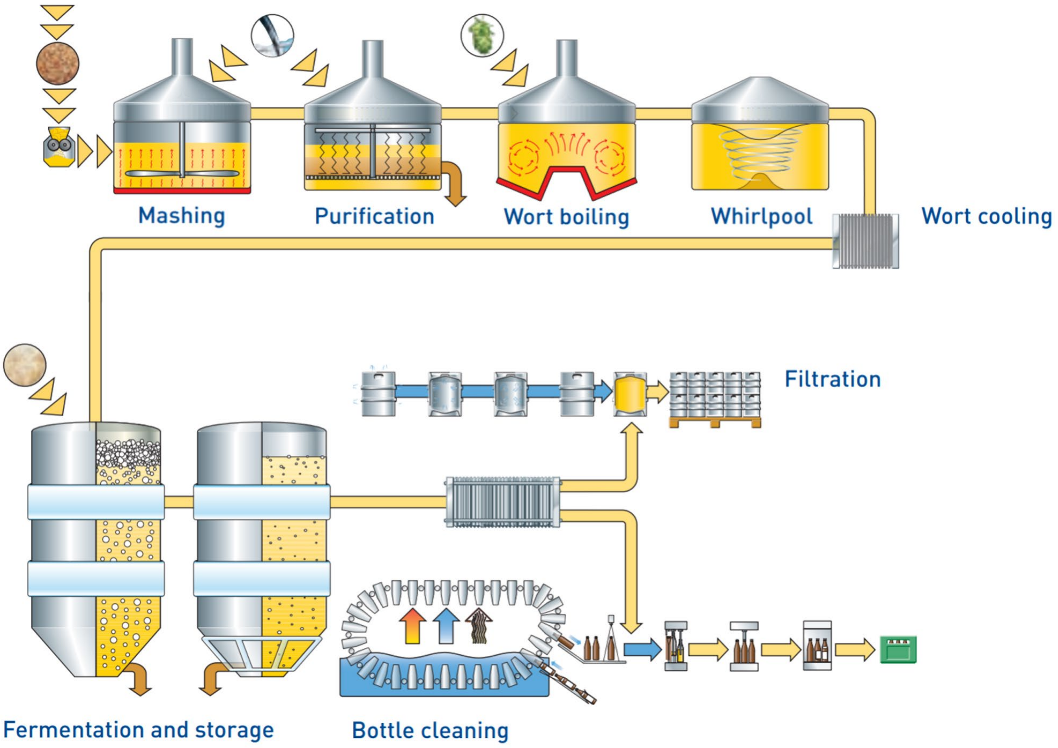


Figure 11 *Overview of the brewing process [63]*

3.2.1. Renewable electricity applications

An increasing number of brewerises have been taking actions towards 100% renewable electricity since 2020. For example, AB-InBev made a 10-year Virtual Power Purchase Agreement (VPPA) with BayWa r.e., a renewable electricity provider, to access 100% renewable electricity for its 14 breweries in 12 European countries. Besides, with the cooperation of BayWa r.e., AB-InBev is planning to build two solar generation projects, one of which named Budweiser Solar Farm. These two solar farms have a total capacity of 250 GWh, which can not only cover the whole energy demand from the breweries, but also provide extra power to nearby households [64]. Another gaint, Heineken, made a 11-year contract with a Spainish ESCo Iberdrola to make its four breweries and offices in Spain fully powered by renewable energy by October 2020 and fully carbon neutral by 2023 [65].

At the research level, several recent researches on small and medium-sized breweries are worth noting. One of the most representative study is from Kusakana (2020), which summarized the available relevant published article sources, developed a case study of a microbrewery with an annual capacity of 41.6 hectolitre in South Africa, and simulated the energy and economics performance for the proposed grid-connected PV and battery system [52]. As shown in ***Figure 12***, the system has a PV-battery system but it is also powered by the grid. There are two DC-DC converter: one is used for the Maximum Power Point Tracking (MPPT), and anther one as the charge controller. The DC-AC inverter is placed in the middle of critical loads and non-critical loads (shiftable and adjustable loads), which means when the RES generation is sufficient, the PV-battery system will cover all critical loads and provide extra power to non-critical loads; while the Imported Power from the grid (P_{IMP}) will only supply to non-critical loads (if needed). Conversely, when the RES is insufficient to fully power critical loads, the grid will fill the gap; in this case, non-critical loads will be fully powered by the grid.

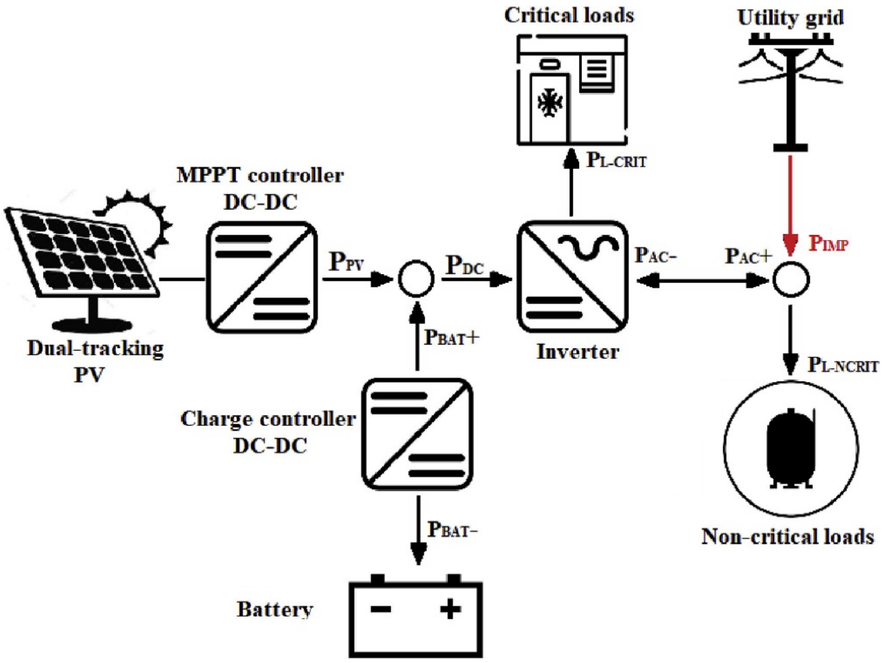


Figure 12 *A grid-connected PV and battery system for microbreweries [52]*

3.2.2. DSM applications

The first step to conduct DSM is to do an energy audit, which is also applicable to microbreweries. Kubule et al. (2016) introduced the energy audit methodology for small breweries [66]. Kusajana (2020) measured the energy use of a typical brewing day in a microbrewery in South Africa, and presented the optimizing energy management results by a simulatiion of participating DR [52]. The unit brewing action usually lasts one working day, that defined as one brewing day.

In the case from Kusajana, the loads situation were measured and recording manually by a three-pahse energy monitoring device. ***Figure 13*** shows its demand curve, which is quite different with a common one of SMEs or households. This special shape is cause by the unique brewing process of boling and cooling, and the order of each step has to be fixed, which means there are limited room to shift the peak loads. However, with the application of RES, it is possible to lower the grid electricity consumption at peak times, and Kusajana's research demonstrates a potential to cut the operational cost 62% off under a ToU tariff.

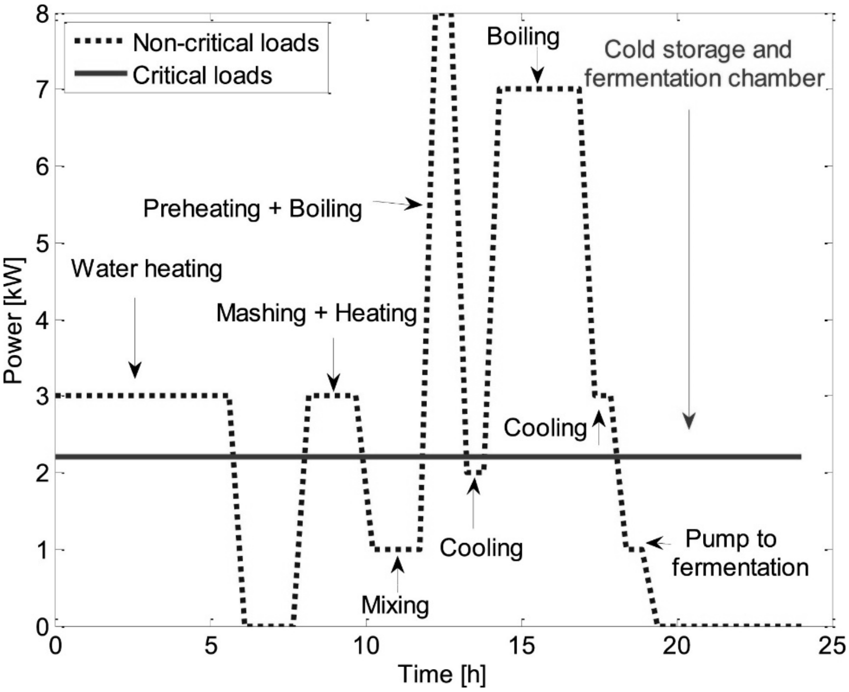


Figure 13 *Demand profile of a typical brewing day of microbreweries [52]*

To further explain ***Figure 13***, it defines the brewing loads as critical, and fermenting loads as non-critical. As the brewing process is always carried out on a regular basis in microbrewies and followed by the fermenting process, the process is actually a cycle of brewing-fermenting-cleaning-brewing. In Kusajana's research, fermenting loads are simplified to run stably throughout the year; while the brewing day is considered to repeat 52 times per year, an average of once a week. Specific to a brewing day, the action starts from preheating water from the ambient tempreture to 85°C, with a during of 5.5 hours. The power of heating element used by Kusajana is 3kW. Turning off the heater for two hours after the preheating step, as it is the peak hour price from 6-8 in South Africa. Then, moving to the regular price between peak and off-peak prices, the 3kW heater is turned on again for another two hours to start the mashing action. In this stage, grains such as malted barley and preheating water are added to the mashing kettle, followed by an one hour's stiring (1kW from 10-11). Next, moving to the purification step, the heater is switched on once again for another hour (3kW from 13-14), accompany with the wort separation (using 1kW pump from 13-14). After that is to boil the wort with a 7kW resistive element system for half and hour, followed by adding hops and boiling the wort mixture to 100°C for two hours (7kW from 15-17). The last two steps happen at the whirlpool (to separate coagulated proteins and other suspended particles) and heat exchanger (cooling element of 2kW) [52] [63]. With the PV-battery system, this microbrewery can be expected to reduce its energy costs without changing or compromising the brewing process and technology, and to minimize the reliance on the grid electricity subjected to the TOU tariff (i.e. being involved in DR).

3.2.3. Critical challenges

Most of current researches are limited to the technic study, but to achieve an energy transition to more distributed and decentralized system, actions from multiple dimensions are required. Geels (2002) defined seven aspects that affect technology-based niches development, which includes markets (user practices), sectoral policy, scientific study background, industrial networks (strategic games), cultural identity, infrastructure, and the last one, technology itself [67]. ***Figure 14*** shows a dynamic multi-level perspective on technological transition and this value chain is ideal for DSM application in microbreweries.

- Challenge one: Lack of research on the integration of market, policy, infrastructure, technology, etc. Recommendation: To develop solutions following the product orientation.

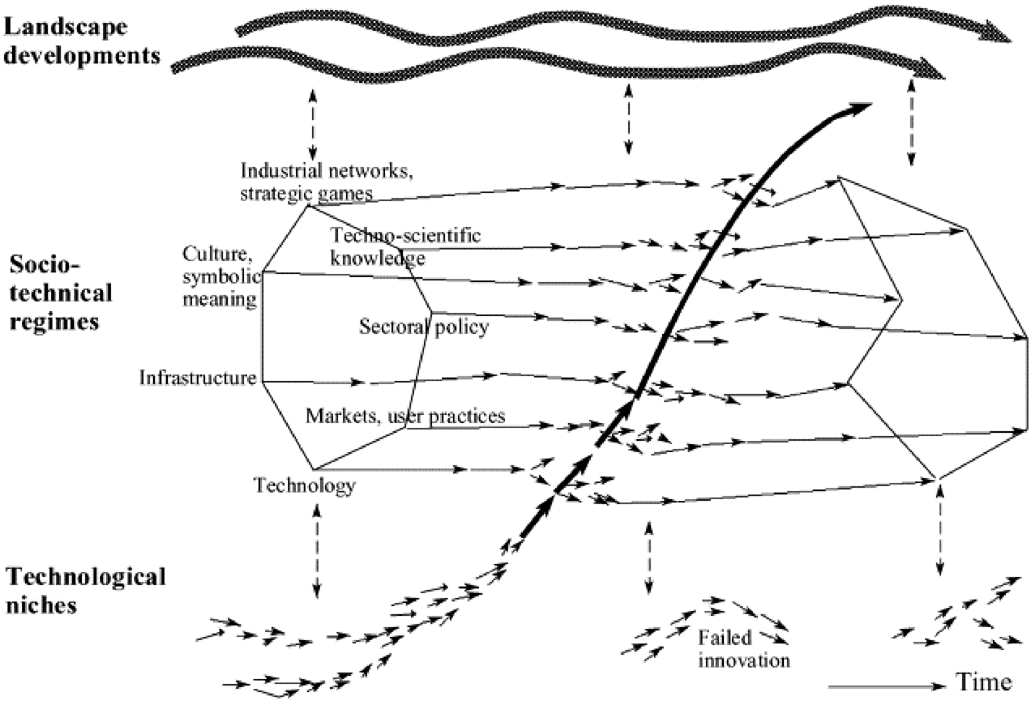


Figure 14 *Technological transitions as evolutionary reconfiguration processes [67]*

- Challenge two: Lack of assessment tool to quickly determine an initial feasibility of DSM applications in microbreweries, especially DR and REC technologies. Recommendation: To develop an "one-click" tool with functions of demand data consumption and economic simulation of participation in DSM.
- Challenge three: Lack of fully exploit the role of batteries in the current studies. For example, Kusajana didn't consider the case of when charging battery from the grid, but only utilizing the surplus energy from PV panels to charge its battery. Recommendation: To consider developing advanced charging and distributing logic for batteries.
- Challenge four: Lack of attractive business models. For example, most of available researches show a payback period of adopting DSM (and installing a new PV-battery system) over 10 years, such as 13.8 years in Kusajana's simulation [52]. This is usually lost potential clients interests on such projects [68]. Recommendation: To look for available public grants or seed fundings to cover some of the very high initial investment, and to consider it as a basis for the proposed business model [69].

4. Methodology

Most of the peak eleltricity demand of a microbrewery in brewing days occues during the day time, which meets the high ToU pricing period in Poland. ToU tariff G12 is adopted in this thesis [70]. According to available data presented on the website of PGE Energia Ciepła S.A. and Tauron Polska Energia, the electricity price is considered as 0.485 PLN/kWh in the peak hours from 7:00 to 22:00, and 0.305 PLN/kWh in the valley hours from 22:00 to 24:00 and 0:00 to 7:00 [71]. Cutting peak loads is one of the best options for Polish microbreweries to be involved in DSM, while PV-battery systems are commonly used for shaving peaks to the valley. Case studies are developed to demonstrate detailed energy and economic analysis. Krakow is selected as the target city, and the average solar radiation of spring and summer in Krakow maintains in a high level of 4.49 kWh/m^2 [72]. In other words, the application of a PV-battery system can be expected to make the microbrewery lower its operational cost of energy use during the high pricing period. The battery is charged mainly by the PV surplus, but can also from the grid during the low pricing period (such as in the midnight), in order to offset the peak of the daytime. It can be expected to improve the utilization of the RES system, and thus to reduce the overall energy expenditure.

The highlight of section is the introduction of operational steps of the proposed simulation tool. Starting with a determine on the scale and location of the microbrewery, followed by a description of the assumption of the input data and parameters, and then an energy system applicable to the microbrewery is introduced. The calculation of shadowing loss of the PV system is in the next, and finally the billings in the two scenarios of DR and REC are forecasted.

Action one – Defining generation potential and consumption curves

The generation potential is calculated using the irradiation values of the beam, diffused, and global irradiation. The values are collected throughout the year for a specific region in Krakow, Poland. The consumption data is assumed according to recent researches shown in ***Chapter 3.2.2***. The generation and consumption curves are graphed and analyzed to get an initial insight and help in visualizing things from a broader perspective.

Action two – Proposing a RES system

A PV-battery system is proposed to achieve DSM. Under the DR model, a simple interaction logic between PV, battery and demands in microbrewery is set as the basic operation method. Under the REC model, an extra allocation of PV generation to other consumers is added, in addition to the basic.

Action three – Calcaulating energy losses

It aims to do the sizing of the panels in a rooftop, give a surface and its inclination and the geographical location of the particular building, taking into consideration possible shadowing between panels and the height of the panels.

Action four – Running to get the result

The billing section considers the ToU tariff G12, with PV, with and without battery, and with and without self-consumption. This step allows calculating the annual savings for the different cases.

4.1. Desription of the proposed energy system

The power produced by a PV system can be calculated by ***Equation 1.***

$$P_{PV} = I_t \times A_{PV} \times N_{PV} \times \eta_{PV} \times (1 - \eta_{loss}) \tag{1}$$

where P_{PV} is the instantaneous power generated; I_t is the solar irradiation; A_{PV} is the panel area; N_{PV} is the panel number; η_{PV} and η_{loss} are the panel efficiency and system losses respectively.

The purpose of the proposed PV-battery system is not to make the microbrewery become an off-grid electricity prosumer, but to reduce the operational energy cost, especially during peak pricing hours from the grid. That is to say, the PV size and battery capacity to be applied actually depond on how much space is available and how many capital funds are there. In other words, these can be regarded as input parameters. According to the common load demand in the recent research shown in ***Chapter 3.2.2***, a 7.2 kW PV system with a 2 kWh battery is considered as the proposed RES system in this thesis.

The PV system is made of 20 monocrystalline panels of 360 Watts each from JA Solar [73]. The height of the panel is 1.134 metres with a width of 2.279 metres. The optimazed inclination is calcaulated to 42 degrees by the EU Photovoltaic Geographical Information System (PVGIS) [74]. With these values, the minimum distance can be determined by ***Equation 2*** as shown in ***Figure 15***, and an extra 5 percent is added to give the recommended distance between panels [75].

$$d = \frac{h}{tan(61-l)} \qquad (\boldsymbol{2})$$

where d is the distance of two neighbouring panels; h is the height of the obstacle; l is the latitude of the location, and in this thesis, the latitude of Krakow is 50.06 degrees.

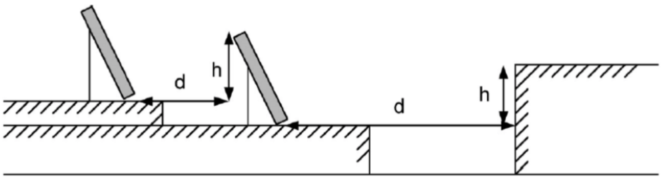


Figure 15 *Calculation of minimum distance between panels*

Table 2 shows the basic parametres of the proposed system.

Table 2 *PV-battery system parametres*

Parametre	Value
PV rating power	7.2 kW
Panel area	2.576 m^2
Number of panels	20
Panel efficiency	0.203
Energy losses	0.2
Battery capacity	2 kWh
Depth of discharge	0.95
(Dis)Charging rate	1.4 kW

Source: own compiled from [52] *and* [73].

4.2. Introduction of functions of the tool

This thesis presents a simulation tool based on Python, which has four main functions as follows:

- Can define the electricity bills for microbrewery under the DR or REC operating model;
- Can easily set the PV and battery capacity;

- Can simulate the energy balance of the proposed system;
- Can allocate the PV generation to each customer by hour (under the REC model).

4.2.1. Simulation steps

PyCharm Edu [76] is used as the programming software to develop the simulation tool. The basic logic is to divide the back-end interface into four areas which are input data, output data, tools to achieve functions such as visualization, etc., and the working panel to simulate generation, consumption, energy losses, etc. To use this tool, simply follow the steps below to create or type in data to the specified location.

Step one – Upload the irradiation data

The current model has applied the hourly irradiation data of Krakow in Poland in the year of 2020, which can be downloaded from [74]. The obtained data should be added to the irradiation file[2], which is then used to calculate the solar generation potential and fed to the battery algorithm.

Step two – Upload the consumption data

Upload the hourly consumption file of the target microbrewery to the folder Customer Consumption[3]. As there is no community consumption data at the moment, assumptions can be made according to the general power consumption of households. Methods as below:

- Open the file named Annual Consumption[4];
- Input an annual demand as you assumed for a neighbouring household;

---

[2] Path: Input_data → irradiation → irradiation_file
  - input slope, azimuth, etc. can be also obtained from [74];
  - the file have to be uploaded in a csv format.

[3] Path: Input_data → customer_consumption

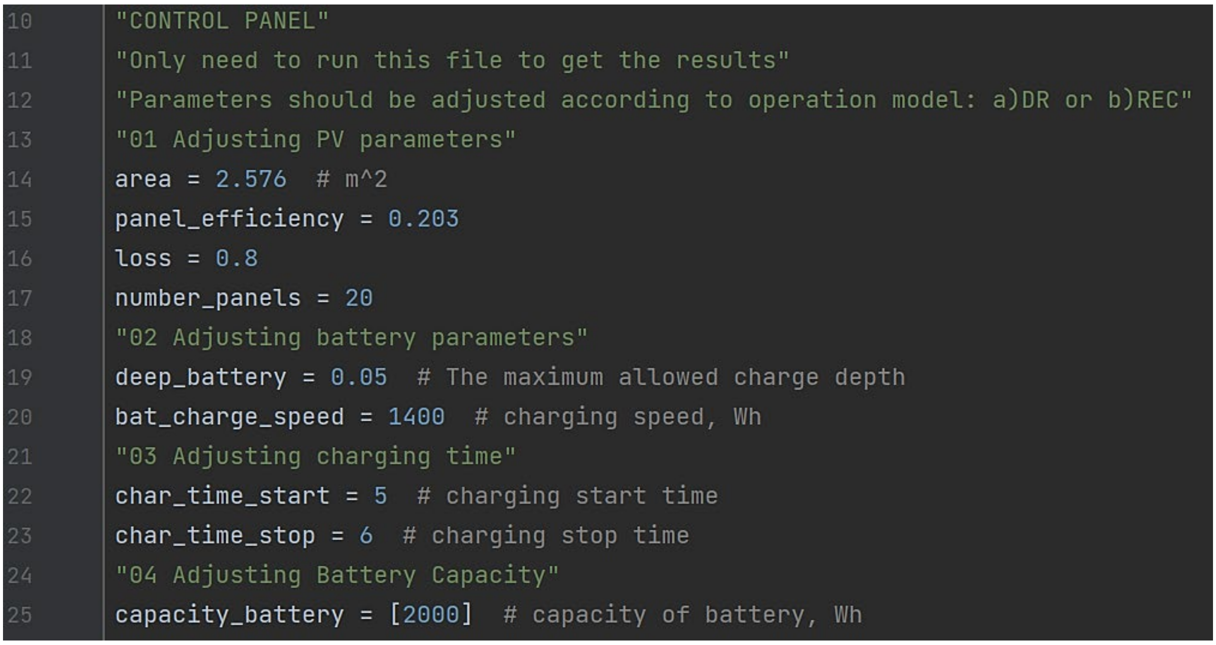
[4] Path: Some_tools → Annual_consumption → Annual_Consumption

- Run in this file and get a new file named Consumption Data as the simulated consumption data which can be used as the household/community consumptions under the REC model.

In this step, all files should be uploaded in the format of CSV, which consists of the hourly data over a year. There will be more than one consumer when in the REC operating model, while the demand file of the target consumer (microbrewery) has to be named as consumption_data0.csv; Other consumers (the community ones) can be named from consumption_data1.csv to consumption_dataX.csv, depending on the scale of the community participants. The DR model is more compact that only the microbrewery is considered and named as consumption_data0.csv.

Step three – Input PV & battery parameters

Find and open the Mainfile[5]. Input or adjust parameters in the control panel, as shown in ***Figure 16***.



```
"CONTROL PANEL"
"Only need to run this file to get the results"
"Parameters should be adjusted according to operation model: a)DR or b)REC"
"01 Adjusting PV parameters"
area = 2.576  # m^2
panel_efficiency = 0.203
loss = 0.8
number_panels = 20
"02 Adjusting battery parameters"
deep_battery = 0.05  # The maximum allowed charge depth
bat_charge_speed = 1400  # charging speed, Wh
"03 Adjusting charging time"
char_time_start = 5  # charging start time
char_time_stop = 6  # charging stop time
"04 Adjusting Battery Capacity"
capacity_battery = [2000]  # capacity of battery, Wh
```

Figure 16 *Control panel in the Mainfile*

---

[5] Path: Working_file.py → Mainfile.py

Step four – Run the Mainfile

Keep the MainFile.py open, and run it. The results can be found in the folder of Output Data[6].

4.2.2. Visualization

This tool has a function of visualizing the simulation results. To find those outputs, go to the folder Visualization[7], and the default visualization is for the microbrewery (consumption_data0.csv). To further visualize results for community consumers, go to visualization.py, and change the file name. Note that the file name here corresponds to the name of output files in the folder Output Data. Run this file after adjusting, the program will then generate updated figures to the folder Visualization.

4.2.3. Billings

This tool has an easy-to-understand billing system. After having the grid energy consumption, multiply the obtained output data by the G12 tariff for the corresponding hour to get the billings over the year. Considering the initial investment of devices including PV panels and the battery, a Lifecycle Cost (LCC) analysis can be performed for economic viability, which can be calculated by ***Equation*** **3**.

$$LCC = C_{I,i} + C_{R,i} + C_{OM,i} + C_{EC,i} \tag{3}$$

where LCC is the target value of the total cost for its whole lifecycle, and for each component i, $C_{I,i}$ is the initial cost; $C_{R,i}$ is the replacement cost; $C_{OM,i}$ is the Operation and Maintenance (O&M) cost; and $C_{EC,i}$ is the electricity consumption cost.

---

[6] Path: Output_data → EnergyFlux_data

- It is recommended to open PV.py, Energy_flux.py, and visualization.py before running MainFile.py.

[7] Path: Some_tools → Visualization

5. Result

Simulations are performed to assess the feasibility of the proposed DSM model to reduce the operational energy cost purchased from the grid. All possible scenarios have been discussed by hour throughout a year, which includes the following aspects:

- The brewing energy demand is powered by the PV-grid system;
- The brewing energy demand is powered by the PV-battery system, in addition to the electricity from the grid;
- The microbrewery participates in DR only;
- The microbrewery participates in REC.

By comparing the results of total energy consumption and economic performance under different scenarios, the feasibility of DSM application in a microbrewery in Krakow, Poland is evaluated. Since the PV generation capacity fluctuates greatly due to seasonal effects, quarterly energy consumption is further compared and discussed in this chapter.

5.1. Case study one: Demand Response

A PV-battery system is applied in this section. The electricity supply mainly comes from the proposed RES system during the daytime, and from the grid at night. This section has compared energy performance in the situation of with and without a 2kW battery in the PV system. In the PV-battery situation, the charging is not only from the PV surplus during the daytime, but also by the grid in the off-peak pricing period (22:00-24:00, 0:00-7:00) at night. The time slot 5:00-6:00 in the low pricing area is set as a charging time from the grid in the case study.

5.1.1. Energy analysis

The microbrewery is considered to consume 10.98 MWh per year, which is 30.08 kWh per day on average. ***Figure 17*** shows the simulation results of average daily consumption in a year. By comparing the scenarios with and without battery, it can be found that the grid energy consumption during peak pricing periods (7:00-22:00) can be significantly reduced, with an in-advanced charging from the grid (5:00-6:00), shown as the circled areas in ***Figure 17***. After entering 7:00, the grid power consumption of the PV-battery system is about half of that without a battery. And the grid consumption of the PV-battery system between 7:00 and 19:00 is consistently lower than that of the without battery system. After 19:00, the PV no longer generates electricity, but the battery can continue to supply power for approximately 1.5 hours in this case, which further reduces the power purchase of the grid during the peak period. Specific to the numbers, the simulation result shows that the average grid consumption of the PV-only system is 24.53 kWh in a day, 18.45% lower compared with no PV scenario; in the case of the PV-battery system, there is an additional 20.98% down compared with the current savings. The orange rectangle area in ***Figure 18*** shows the grid

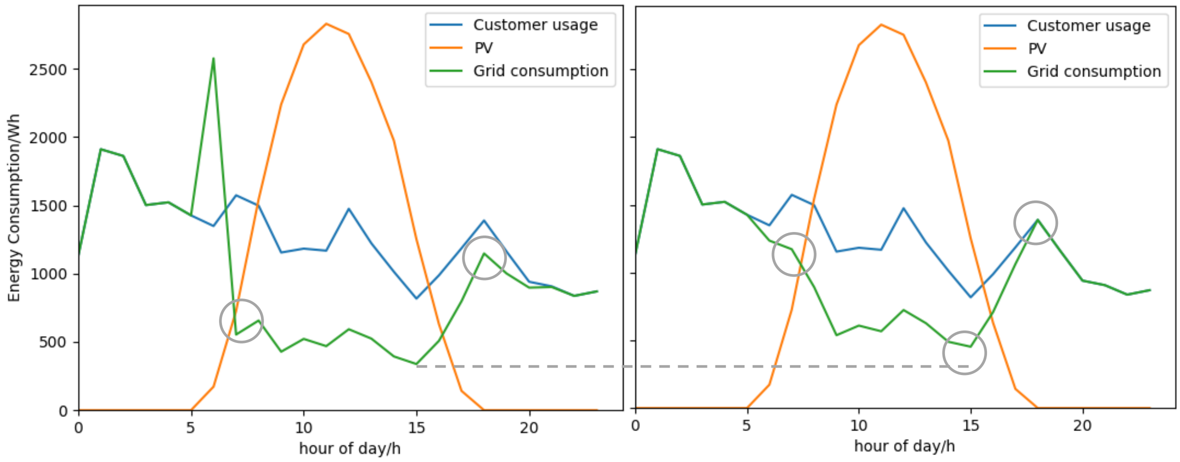


Figure 17 *Average consumptions over a day*
a) with battery on the left; and b) without battery on the right

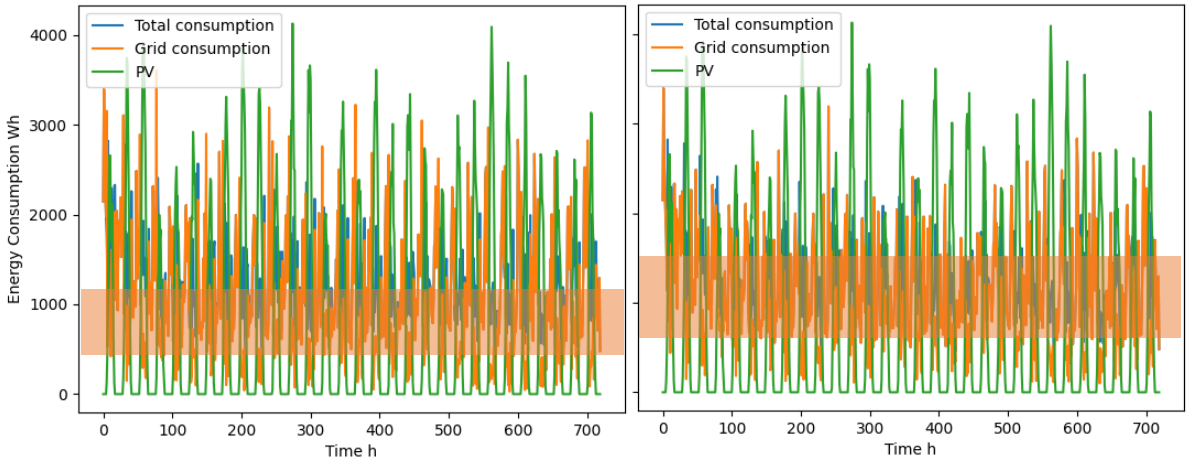


Figure 18 *Average consumptions over a month*
a) with battery on the left; and b) without battery on the right

consumption during peak hours over a month, which once again demonstrates that the utilization of battery leads to a greater potential of DSM.

However, compared to battery, the role and contribution of PV to DR is much more fundamental and considerable, which can be observed by the comparison by quarter. ***Figure 19*** shows daily consumptions in Q1 when the solar irradiation is lower than the average level. Although the effect of battery in Q1 is still noticeable,

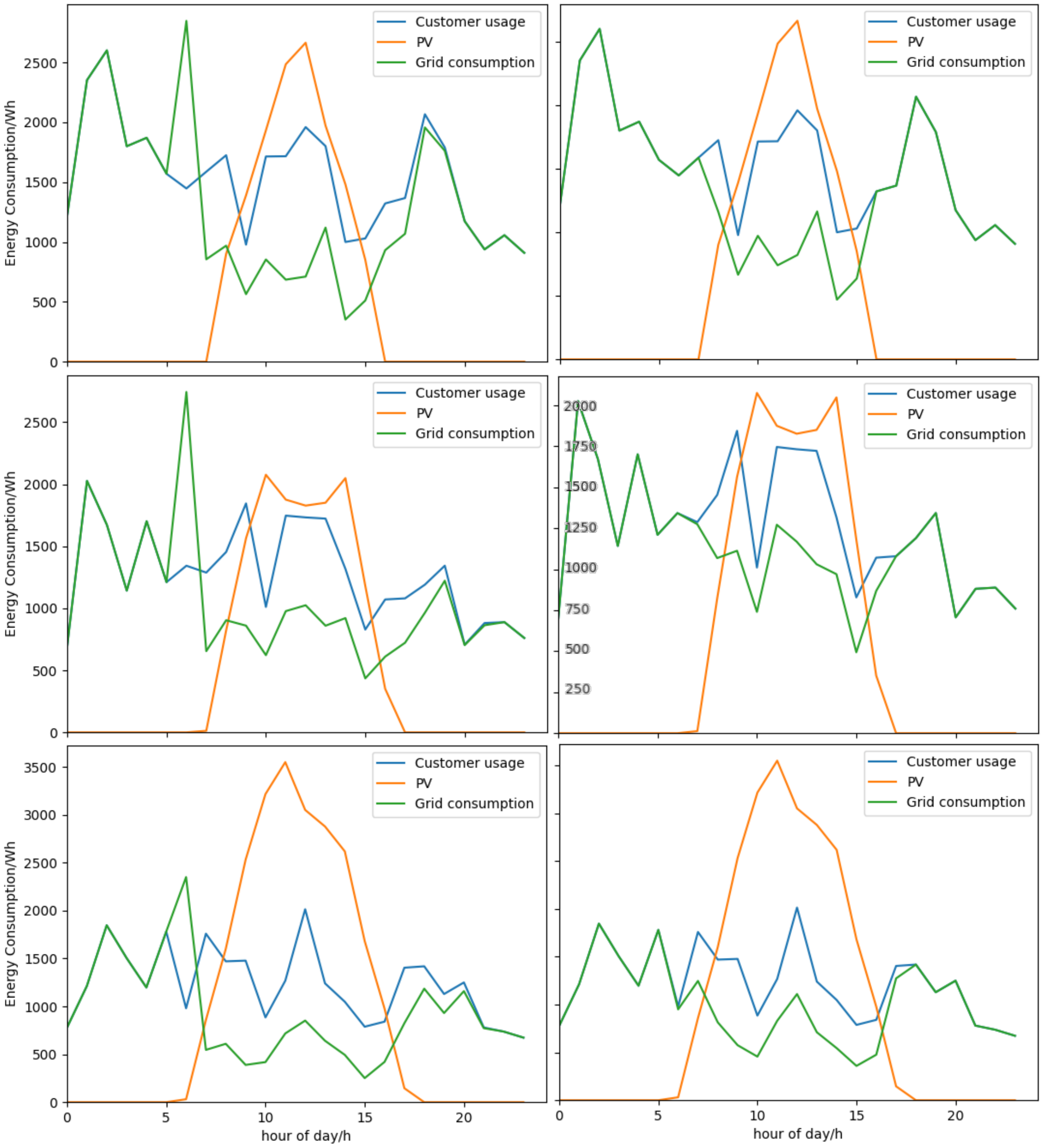


Figure 19 *Average consumptions in Q1*
a) with battery on the left; and b) without battery on the right

the overall grid electricity purchase in this quarter is well below the annual average due to the lower PV generation capacity.

From Q2, the trend of grid consumption has been reversed. A swift improvement of solar conditions leads to a more sufficient PV generation, which can not only cover most of the demand during the daytime, but the surplus can also contribute more to battery charging. ***Figure 20*** and ***Figure 21*** show that the grid consumption

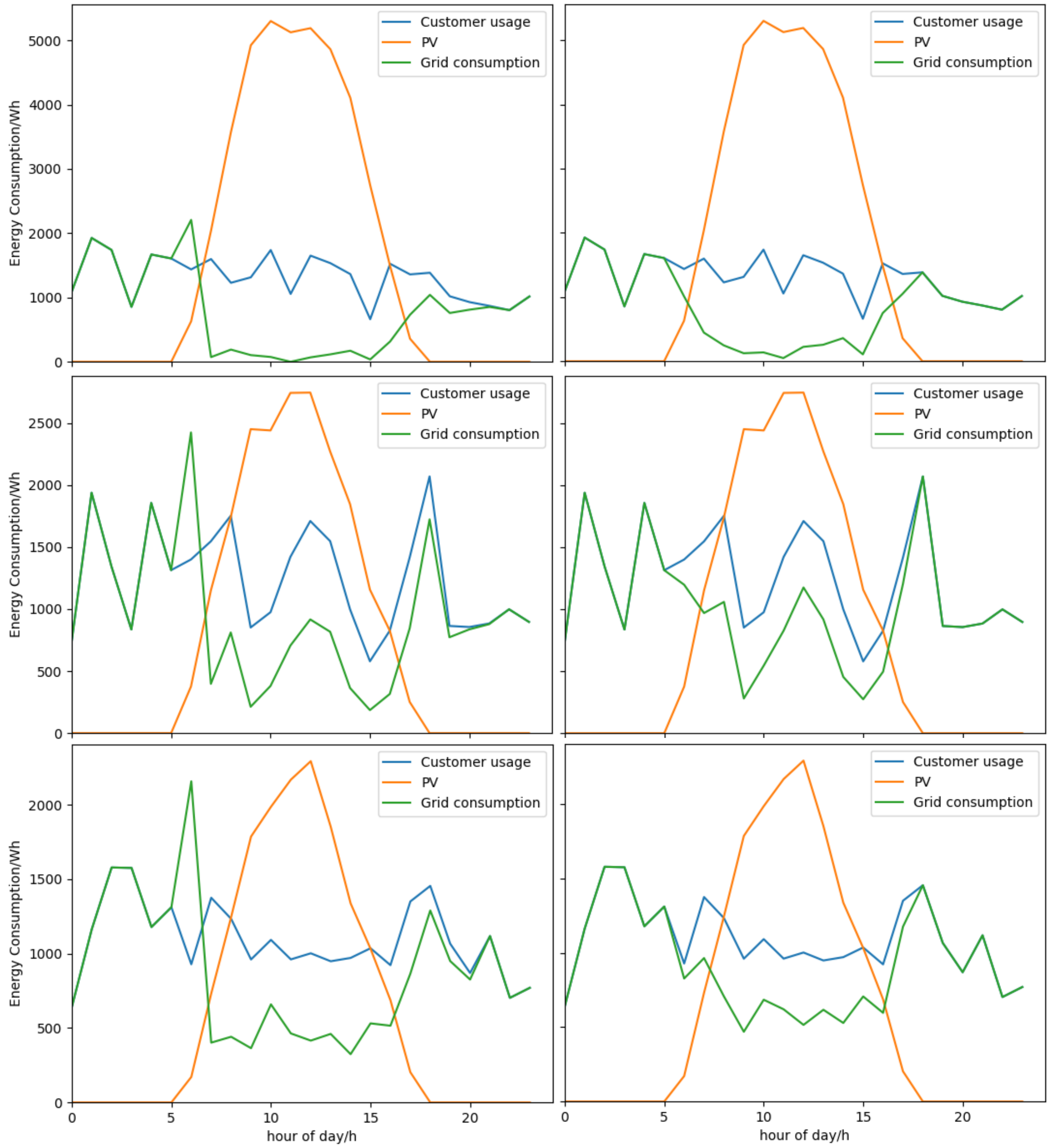


Figure 20 *Average consumptions in Q2*
a) with battery on the left; and b) without battery on the right

is close to zero in the 4th, 7th, and 8th month, while a near-zero electricity bill during peak hours can be considered as an indicator for the reasonable design of DR projects. In addition, the battery performance in Q2 and Q3 is more adequate, which is reflected in the relatively smoother grid consumption curve, the lower grid access capacity at 7:00 when the peak tariff starts, and the battery has a longer run time.

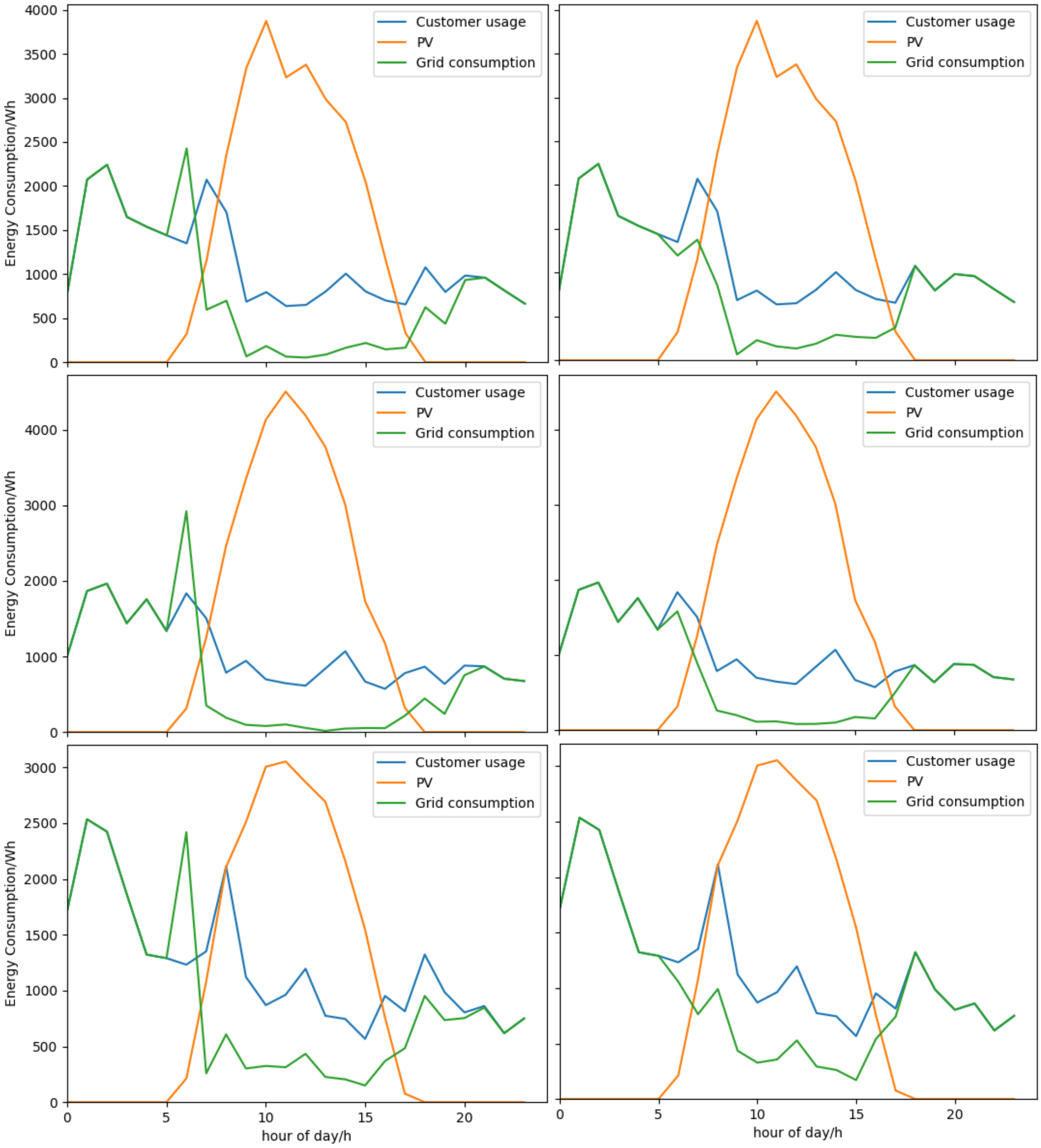


Figure 21 *Average consumptions in Q3*
a) with battery on the left; and b) without battery on the right

The situation in Q4 is similar to Q1. The 11th month has the lowest PV generation over the year, see ***Figure 22***. In other words, the proposed system has the minimum DR capacity in the last three months of the year. This is because, on the one hand, the energy demand in winter is greater, and it takes more electricity to heat raw materials such as water from a lower ambient temperature to the same specified temperature. On the other hand, the suboptimal solar irradiation amplifies the impact of the previous problem.

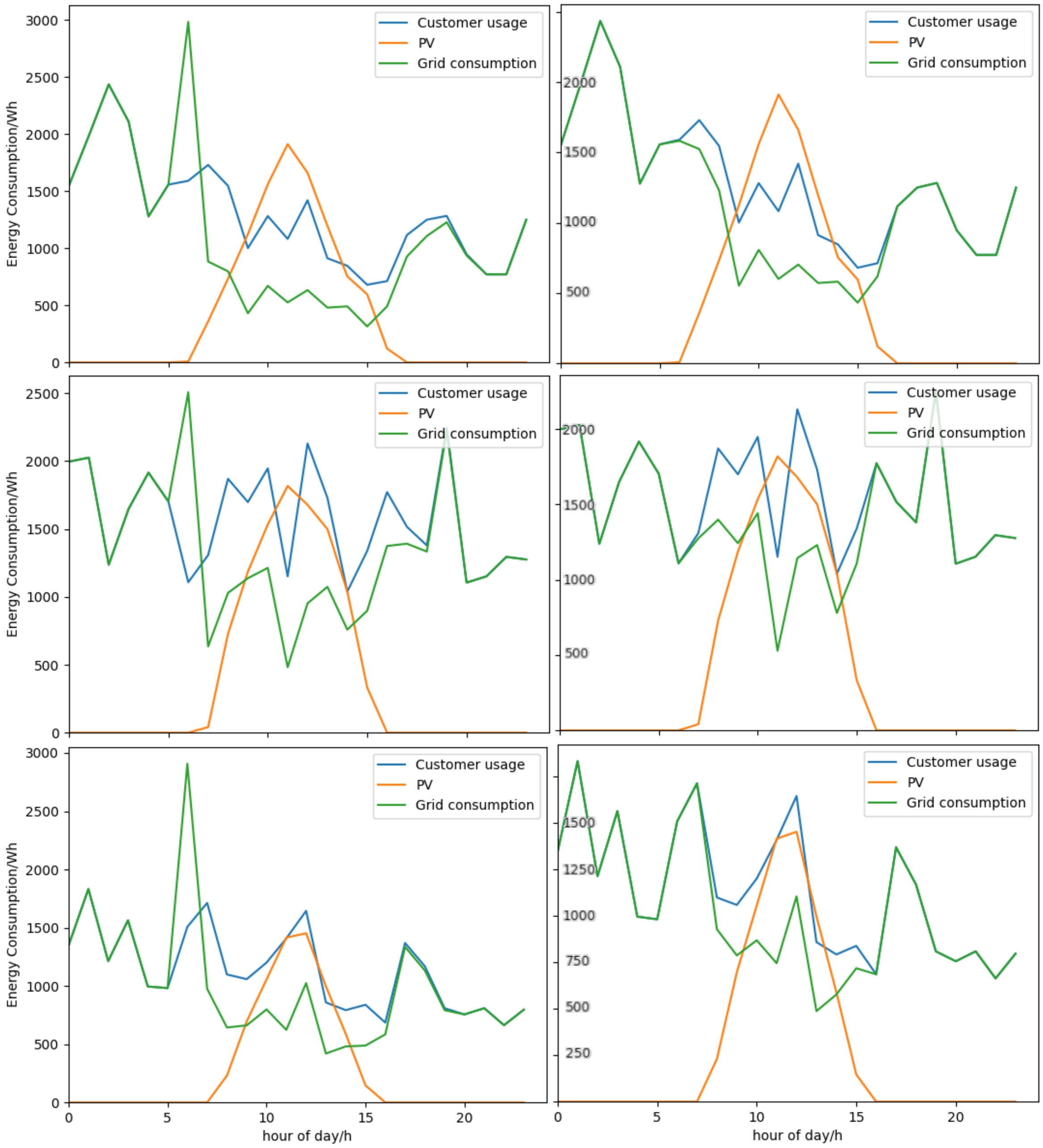


***Figure 22** Average consumptions in Q4*
a) with battery on the left; and b) without battery on the right

5.1.2. Economic analysis

The annual electricity expenditure to the grid is 4519.01 PLN for a microbrewery in Krakow with a daily energy demand of around 30 kWh. With the proposed 7.2 kW PV system, the operational cost can be expected to reduce by 21% to 3570.24 PLN. If a 2 kW battery is further adopted, an additional 26.73% can be saved compared with the existing savings. ***Figure 23*** shows the average monthly bills under different scenarios, in which the 4th month has the largest saving potential, while the 12th month has the least.

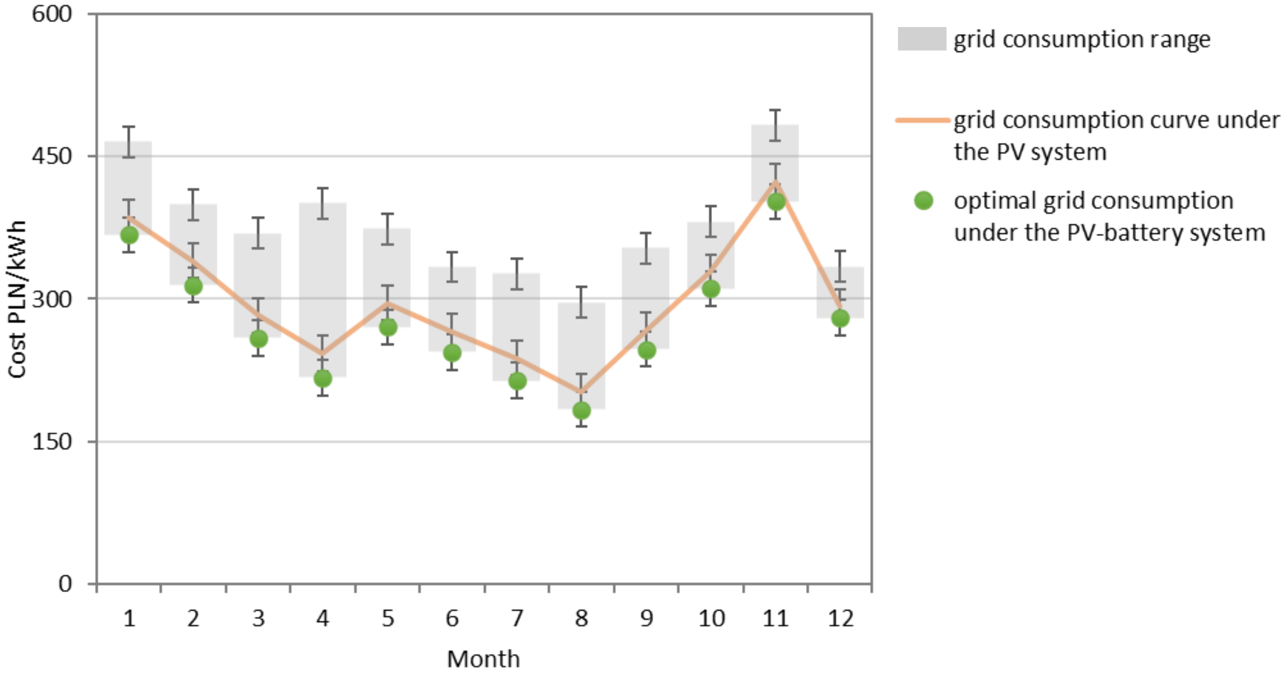


Figure 23 *Monthly electricity bills*

To develop an LCC analysis, the up-front investment of the devices should be taken into account, which the data is shown in ***Table 3***. There are several loan and financing plans available from Polish energy retailers and banks, such as Tauron Polska Energia, who provides a 10-year loan for such PV installations with an

Table 3 *Bill of quantity for the PV-battery system*

Component	Price/ PLN	Life/ years
PV system (20 panels with 360 W)	18640	20
Battery (2 kWh)	2000	5
Inverter, connector, cable, etc.	15000	20
Total capital	35640	

Source: own compiled from [52] *and* [77] interest rate of 5.64% *[78]*. In addition, Tauron provides a 5% off for the prosumers who sign an energy contract with it *[78]*. Both of that have been considered in the LCC analysis of this case study. ***Table 4*** shows the amortized cost of the initial investment. Note that the battery needs to be replaced every five years, and this part of the cost is not amortized. The recycling value of the discarded battery is not considered in this case study.

Table 4 *Amortized cost scheme*

Year	PV system/ PLN	PV-battery/ PLN
1	3364	5364
2	3553	3553
3	3754	3754
4	3965	3965
5	4189	4189
6	4425	6425
7	4675	4675
8	4939	4939
9	5217	5217
10	5512	5512
11	0	2000
12	0	0
13	0	0
14	0	0
15	0	0
16	0	2000
17	0	0
18	0	0
19	0	0
20	0	0

Source: own compiled from [78]

The grid tariff is considered to go up by 10% annually [71]; O&M fees in the year are defined as 1% of the total expenditure of the past year; A 5% inflation rate is applied to the LCC analysis [52]. ***Figure 24*** shows the comparison of grid energy cost among a) no RES; b) PV system; and c) PV-battery system for an operational lifetime of 20 years. The break-even point can happen after the 13th year when the cumulative bill reaches 179000 PLN. The most significant gap occurs in the 10th year, which is 18413 PLN. But soon after that, it can be expected to pay back and turn into earning money. A total amount of 106334 PLN can be saved with the PV-battery system in the year 20, compared with business as usual.

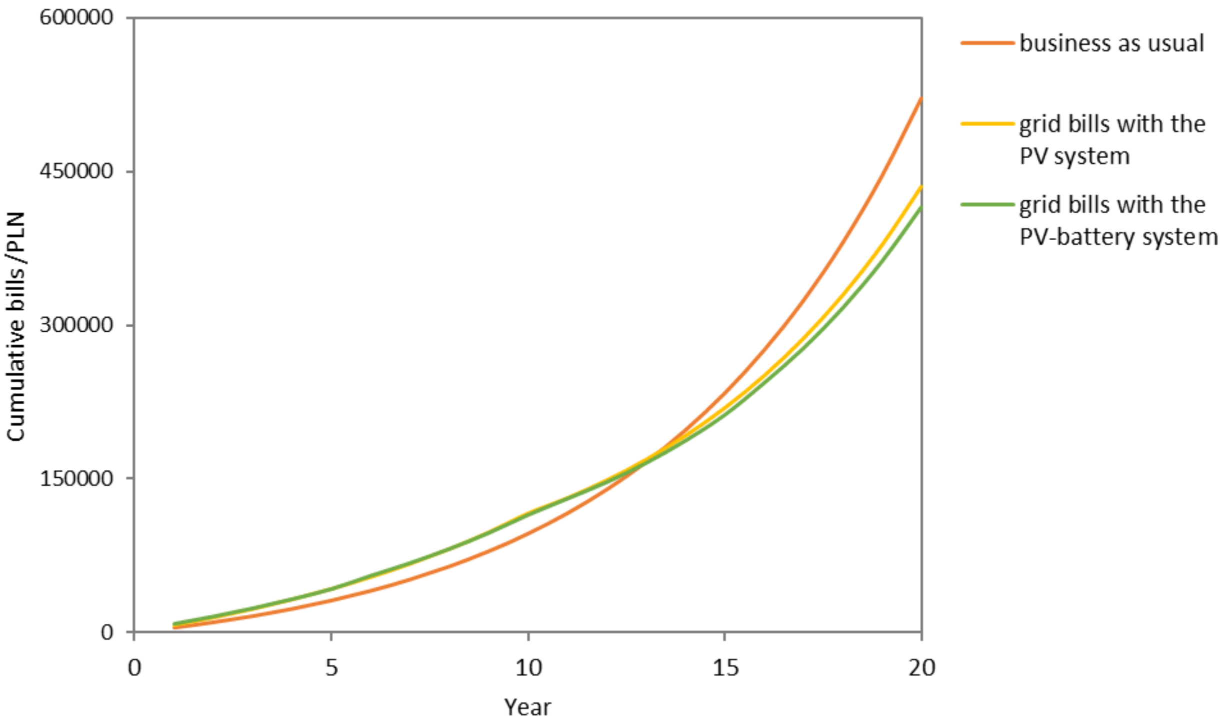


Figure 24 *LCC comparison for the three supply options*

5.2. Case study two: Renewable Energy Community

There are two possibilities for the role of microbreweries in an energy community which are prosumers and consumers. As a prosumer in the REC, when installing the same PV-battery system as that presented in ***Chapter 5.1***, there is no additional value added since the self-generated energy is basically all consumed by the microbrewery itself. In other words, there will be no extra electricity to share within the REC. Therefore, this case study focuses on the situation of being a non-producer consumer, that is, participating in the REC by purchasing an equal share of power from the community RES via an ESCo. Another difference is that only a certain part of the community battery can be used, while the charging and discharging logic is not as flexible as that in Case One. A same 2 kW capacity for the microbrewery is only a fraction of the community battery and cannot achieve the timed charging function from the grid. ***Figure 25*** shows the charging logic of the community battery.

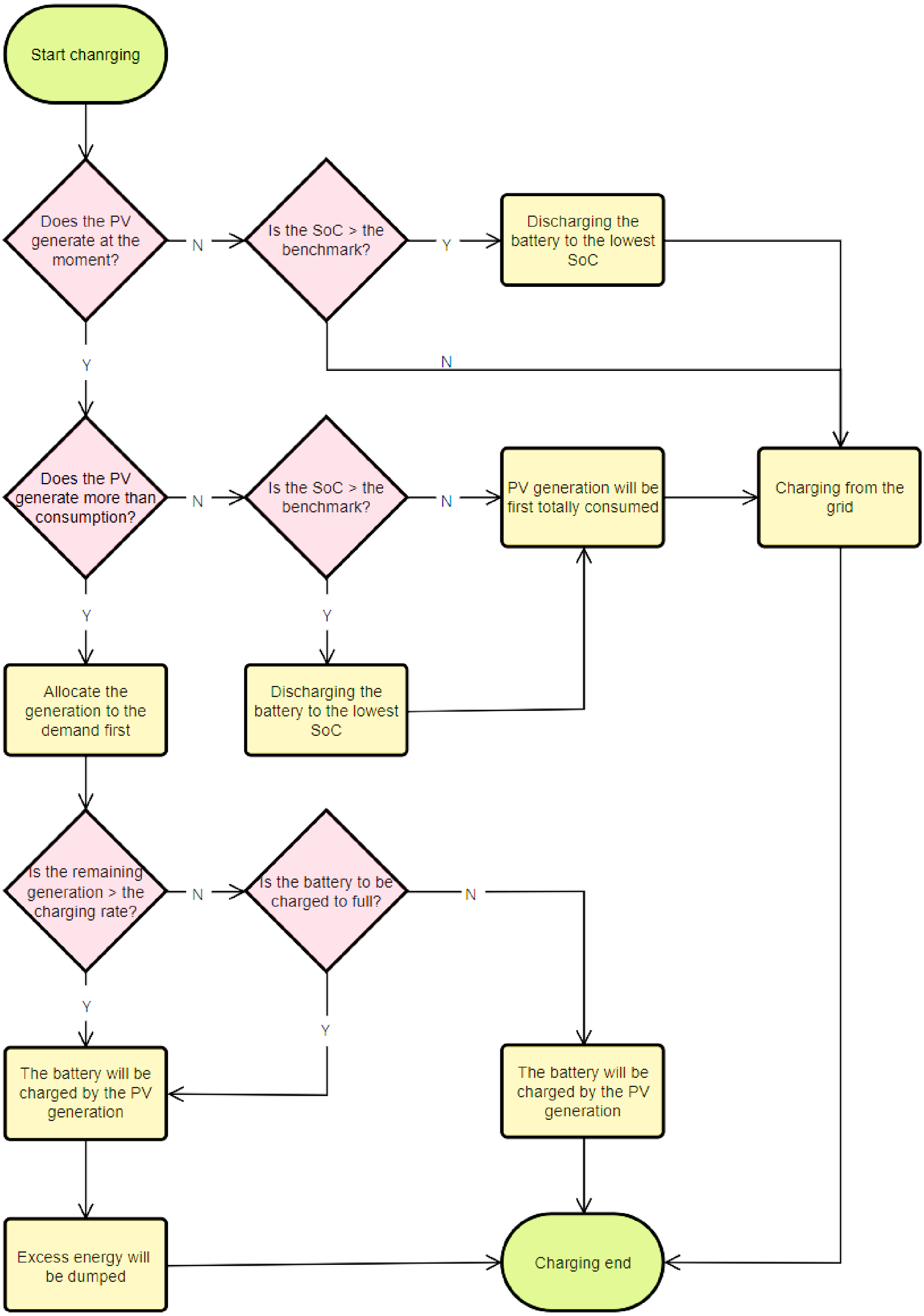


Figure 25 *Community battery charging algorithm*

5.2.1. Energy analysis

With the same 7.2 kW PV and 2 kWh battery allocated to the microbrewery from the REC, the simulation results are very close to DR results, as shown in ***Figure 26***. However, as introduced in ***Chapter 3.1.1***, there are usually geographical restrictions for REC, which requires the microbrewery has to be in the scope of an existing REC project. In addition, a service fee is often required to pay to the ESCo. For business consumers, the cost is approximately 550 PLN per month [79]. In contrast, it is less feasible for microbreweries to choose being involved in REC.

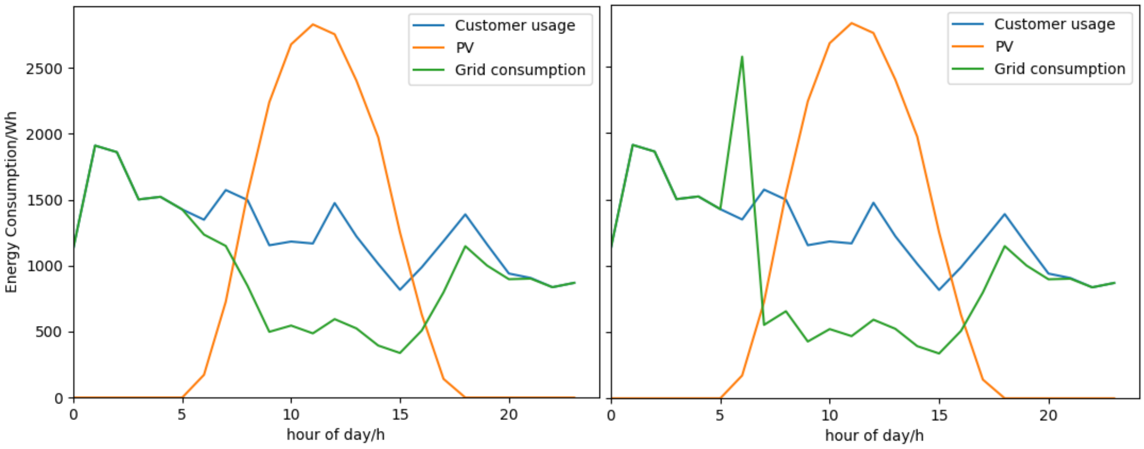


Figure 26 *Comparison of the daily consumptions in REC/DR scenario*
a) REC scenario on the left; and b) DR scenario on the right

5.2.2. Business plan for ESCo

Although the result shows that REC looks not attractive to microbreweries, it is an opportunity for ESCo who is planning to develop new business. Most of current REC projects in Europe were granted by EU or local governments, see ***Chapter 1.1***. With these grants or subsidies, part of the up-front investment and operating expenses can be offset, and all players in such REC projects can be expected to achieve economic benefits. ***Figure 27*** shows a general Business Model Canvas (BMC) for REC from an ESCo perspective. One core clients is the microbrewery. Because microbreweries are usually located in communities or some commercial parks, where nearby households and other SMEs can also be potential consumers of REC.

Key Partners	Key Activities	Value Propositions	Customer Relationship	Customer Segment
Financing supportor (e.g. gov. or banks) Municipality Hardware and software provider (e.g. smart metres) Energy suppliers Installators	Feasibility assessment Signing the contract Installation DSM O&M Communication	Financial compensation (e.g. energy savings) Enhanced DSM capacity Portfolio diversification Additional renewable energy services Access to local energy market Positive environmental impact Enterprise reputation	Win-win: promote profit for both sides (ESCo and microbrewery) Community cohesion Long-term contracts	Microbreweries Households nearby Other SMEs DSOs Aggregators
	Key Resources		**Channels**	
	This feasibility assessment tool Policy and regulation knowledge Technical team Selling skills		Orientation visit Industrial conferences and events Network Ads Social media	

Cost Structure	Revenue Streams
R&D: assessment tool development, controller software development, etc. Networking cost: customer acquisition O&M activities Staff salaries Fixed costs to the system operators Variable costs for electreicity purchase	Feasibility assessment service Contract fee in a monthly base Sale of surplus to community consumers Sale of extra surplus to aggregators Grants and subsidies from governments

Figure 27 *Business Model Canvas for REC from an ESCo perspective*

A key question to answer regarding value proposition is what value to deliver to the customer. For example, community cohesion is one of the most important issues for microbreweries, as the community market is relied on to sell their beer. By adopting REC projects, the ESCo can help boost activity and strengthen relationships in the community, which meets microbreweries expectations. Taking such an empathic approach is critical, and proper solutions to those identified problems should be designed.

Interviews have confirmed this trend. Dr. Liliane Ablertner, who is the Co-founder and CEO of an ESCo named Exnaton AG in Switzerland, pointed out that *”A successful project needs people that participate and like engaging with the energy community. You need a tech that doesn’t crash. If you have that, it is successful* *in itself, but not yet a successful company. It needs to be a product, and it will be, if you find the business model. For that, you have to find the right setting, calculate the unit economics, a different regulation, which market are you attacking first*" [80]. The industry is also confident in its development, as Dr. Boris Sucic stated "*We want to be part of the transition, not just part, we want to be leaders in some sectors. That is one of the biggest motivations. To show the good examples that we are doing here, and what can be replicated in other countries*" [81].

6. Summary and conclusions

DSM is an effective way for microbreweries to improve their competitiveness. On the one hand, it can reduce energy costs without compromising the quality of the brewing process. On the other hand, it can facilitate the establishment of a climate-friendly brand reputation and strengthen their relations with community-based customers. This thesis lists the energy use at each stage of beer production and reviews the development of DSM technologies represented by the DR and REC. Generally, there is a lack of techonomic assessment of DSM in microbreweries in the available literature.

In this thesis, a microbrewery in Krakow with an annual demand of 10.98 MWh has been set as the modelling object. The model applies a 7.2 kW PV system and a 2 kWh battery, with the ToU grid tariff G12. Developed with Python programming, this simulation tool is designed to quantify energy and economic performance in DR and REC scenarios to assess the application feasibility. Results have shown that a considerable energy expenditure saving can be achieved when using the proposed system compared with the scenario where the grid is used as the sole energy supply option.

- A potential grid consumption saving of 18.45% is possible when the model is applied to the PV system. An additional 20.98% down compared with the current reduction can be expected for the PV-battery system.
- In the case of DR, the PV system can potentially save 21% energy cost. An additional 26.73% down compared with the existing reduction can be expected for the PV-battery system.
- A near-zero ToU bill during the G12 peak pricing period is possible in the 4th, 7th and 8th month over a year.
- For an operational lifetime of 20 years, the break-even point of the DR project can happen after the 13th year, when the cumulative bill reaches 179000 PLN. The PV-battery system can potentially save 106334 PLN on the LCC, compared with business as usual.

The results have also revealed that though REC has less econimoic attractive and lower feasibility to microbreweries, it is a blue ocean for ESCo who is exploing to develop new business.

6.1. Future work

The satisfactory results obtained in this thesis demonstrate the potential techonomic benefits of DSM application in the microbreweries. There are both technical and commercial aspects of future work.

6.1.1. Technical tool development

- Optimization of the current modelling
    - The size of the flexible loads that can be provided by microbreweries
    - Mutiple ToU tariff comparison
    - The activation probability, and the potential benefits in comparison with: a) only powered by the grid; b) PV for self-consumption; c) trading in the community
    - Advanced controlling logic on battery systems
- Review of regulatory and policy frameworks
    - Self-consumption, demand response, energy communities, etc.
- Development of on-site studies on energy performance in microbreweries
- Market research of the existing optimal software of Demand-Side Management (for SMEs)

6.1.2. Business plan development

- Optimization of the Business Model Canvas
- Definition of market opportunities for microbreweries to a 100% renewable electricity transition
- Stakeholder analysis
    - TSO, DSO, energy retailers, ESCo, investors, prosumers, consumers
- Identify the [return on investment, extra value and benefits] and [go-to-market strategy]
- Identify potential funding options for the development of a pilot project
- Identify the most influential indicators:
    - Sensitivity analysis to determine potential revenue for stakeholders

References

[1] European Commission, "Directive (EU) 2019/944 of the European Parliament and of the Council of 5 June 2019 on common rules for the internal market for electricity and amending Directive 2012/27/EU," 5 June 2019. [Online]. Available: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32019L0944. [Accessed 21 June 2022].

[2] European Commission, "Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources," 11 December 2018. [Online]. Available: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv:OJ.L_.2018.328.01.0082.01.ENG&toc=OJ:L:2018:328:TOC. [Accessed 21 June 2022].

[3] European Commission, "Proposal for a DIRECTIVE OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on energy efficiency (recast)," 14 July 2021. [Online]. Available: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52021PC0558. [Accessed 21 June 2022].

[4] Eurostat, "Extra-EU imports of natural gas by partner, 2019 and 2020," 9 June 2021. [Online]. Available: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=File:Extra-EU_imports_of_natural_gas_by_partner,_2019_and_2020.png#file. [Accessed 21 June 2022].

[5] E. Mendonça , "Bolsonaro's Brazil unlikely to achieve Paris Agreement goals: experts," 22 September 2019. [Online]. Available: https://news.mongabay.com/2019/09/bolsonaros-brazil-unlikely-to-achieve-paris-agreement-goals-experts/. [Accessed 21 June 2022].

[6] McKinsey, "COVID-19: Implications for business," 13 April 2022. [Online]. Available: https://www.mckinsey.com/business-functions/risk/our-insights/covid-19-implications-for-business#. [Accessed 21 June 2022].

[7] I. Tiseo, "Change in electricity output in Europe during COVID-19 lockdown by fuel type 2020," 12 May 2020. [Online]. Available: https://www.statista.com/statistics/1114557/europe-electricity-generation-reductions-due-to-covid-19/. [Accessed 21 June 2022].

[8] IRENA, "Renewable Capacity Statistics 2022," The International Renewable Energy Agency, Abu Dhabi, 2022.

[9] IEA, "Unlocking the Potential of Distributed Energy Resources: Power system opportunities and best practices," International Energy Agency, Paris, 2022.

[10] IEA, "Renewables 2019: Distributed Solar PV," International Energy Agency, Paris, 2019.

[11] EU, "EU's next long term budget & NextGenerationEU Key Facts and Figures," 10 November 2020. [Online]. Available: https://ec.europa.eu/info/sites/default/files/about_the_european_commission/eu_budget/mff_factsheet_agreement_en_web_20.11.pdf. [Accessed 21 June 2022].

[12] Brewers Forums, "Brewers Forum & 38th EBC Congress," 2022. [Online]. Available: https://brewersforum.eu/. [Accessed 24 June 2022].

[13] C. Stenqvist and L. J. Nilsson, "Energy efficiency in energy-intensive industries-an evaluation of the Swedish voluntary agreement PFE," *Energy Efficiency,* vol. 5, no. 2, pp. 225-241, 2012.

[14] J. Conduah, K. Kusakana and P. Hohne, "Energy Efficiency Improvements in a Microbrewery in South Africa," in *Open Innovations*, 2019.

[15] C. Galitsky, N. Martin, E. Worrell and B. Lehman, "Energy Efficiency Improvement and Cost Saving Opportunities for Breweries: An ENERGY STAR(R) Guide for Energy and Plant Managers," 1 September 2003. [Online]. Available: https://doi.org/10.2172/819468. [Accessed 24 June 2022].

[16] P. Kaleta and T. Wałek, "Benefits of MCHP XRGI use in the brewing industry," *Systems Supporting Production Engineering,* pp. 51-57, 28 June 2015.

[17] Holland Malt, "Sustainability and great taste," Holland Malt, 2022. [Online]. Available: https://hollandmalt.com/sustainability/. [Accessed 24 June 2022].

[18] Asahi, "Environment: Response to Climate Change," Asahi, 2022. [Online]. Available: https://www.asahibeer.co.jp/sustainability/environment/climatechange/index.html. [Accessed 24 June 2022].

[19] AB-InBev, "Sustainability: Climate Action," AB-InBev, 2022. [Online]. Available: https://ab-inbev.eu/core-value/sustainability/. [Accessed 24 June 2022].

[20] Brewers of Europe, "Beer: Heritage and craft," The Brewers of Europe, 2022. [Online]. Available: https://brewersofeurope.org/site/beer/index.php?doc_id=472. [Accessed 24 June 2022].

[21] J. Conway, "European beer microbreweries by country 2020," 4 Feburary 2022. [Online]. Available:

https://www.statista.com/statistics/444691/european-beer-microbreweries-by-country/. [Accessed 21 June 2022].

[22] Eurostat, "Electricity price statistics," April 2022. [Online]. Available: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Electricity_price_statistics#Electricity_prices_for_household_consumers. [Accessed 21 June 2022].

[23] S. Adams, D. Kuch, L. Diamond, P. Fröhlich, I. M. Henriksen, C. Katzeff, M. Ryghaug and S. Yilmaz, "Social license to automate: A critical review of emerging approaches to electricity demand management," *Energy Research & Social Science,* vol. 80, no. 2214-6296, p. 102210, 2021.

[24] Y. Wang and H. Nazaripouya, "Chapter 13 - Demand-Side Management in Micro-Grids and Distribution Systems: Handling System Uncertainties and Scalabilities," in *Classical and Recent Aspects of Power System Optimization*, Academic Press, 2018, pp. 361-387.

[25] Enel X, "What is Demand Side Management?," 2022. [Online]. Available: https://corporate.enelx.com/en/question-and-answers/what-is-demand-side-management. [Accessed 21 June 2022].

[26] US Energy Information Administration, "Glossary - D," 2022. [Online]. Available: https://www.eia.gov/tools/glossary/index.php?id=D. [Accessed 21 June 2022].

[27] M. Behrangrad, "A review of demand side management business models in the electricity market," *Renewable and Sustainable Energy Reviews,* vol. 47, no. 1364-0321, pp. 270-283, 2015.

[28] A. Mengolini, J. Vasiljevska, C. F. Covrig, F. Gangale and G. Fulli, "Smart grid projects outlook 2017: Facts, figures and trends in Europe," Joint Research Centre of European Commission, 2017.

[29] S. Goy and A. Sancho-Tomás, "4 - Load management in buildings," in *Urban Energy Systems for Low-Carbon Cities*, Academic Press, 2019, pp. 137-179.

[30] SmartGrid.gov, "Advanced Metering Infrastructure and Customer Systems: Results from the smart grid investment grant program," US Department of Energy, 2016.

[31] Tibber, "Join the electric revolution: Tibber Impact Report 2021," 2022. [Online]. Available: https://downloads.ctfassets.net/zq85bj8o2ot3/6v7Ztrg4mgcpmljNyMKj1y/85153b720077da74ac1b5c2b3977b333/Tibber_Impact_Report_2021.pdf. [Accessed 21 June 2022].

[32] Greenely, "Save energy, Save money: Smart app," 2022. [Online]. Available: https://greenely.com/en/free-app/. [Accessed 21 June 2022].

[33] "ScienceDirect," 2022. [Online]. Available: https://www.sciencedirect.com/. [Accessed 8 March 2022].

[34] D. Milborrow, "Wind Energy Economics," *Comprehensive Renewable Energy (Second Edition),* vol. 2, no. 9780128197349, pp. 463-496, 2022.

[35] A. R. A. Jerin, N. Prabaharan, N. M. Kumar, K. Palanisamy, S. Umashankar and P. Siano, "Smart grid and power quality issues," *Hybrid-Renewable Energy Systems in Microgrids,* vol. 10, no. 9780081024935, pp. 195-202, 2018.

[36] M. Diekerhof, A. Monti and S. Schwarz, "Demand-Side Management—Recent Aspects and Challenges of Optimization for an Efficient and Robust Demand-Side Management," in *Classical and Recent Aspects of Power System Optimization*, Academic Press, 2018, pp. 331-360.

[37] S. Hartnett, J. Morris and I. Vlachos, "EW Flex: A decentralized flexibility marketplace fostering TSO-DSO cooperation," in *Mathematical Modelling of Contemporary Electricity Markets*, Academic Press, 2021, pp. 279-286.

[38] D. E. Aliabadi, E. Çelebi, M. Elhüseyni and G. Şahin, "Modeling, simulation, and decision support," in *Local Electricity Markets*, Academic Press, 2021, pp. 177-197.

[39] B. P. Koirala, E. Koliou, J. Friege, R. A. Hakvoort i P. M. Herder, „Energetic communities for community energy: A review of key issues and trends shaping integrated community energy systems," *Renewable and Sustainable Energy Reviews,* tom 56, nr 1364-0321, pp. 722-744, 2016.

[40] A. Gillich, A. Ford, C. Zagoni, G. Oakes and M. Hewitt, "A smarter way to electrify heat – the balanced energy network approach to demand side response in the UK," in *ECEEE Summer Study Proceedings on energy efficiency: Consumption, efficiency and limits*, 2017.

[41] J. Rodríguez-Molina, M. Martínez-Núñez, J.-F. Martínez and W. Pérez-Aguiar, "Business Models in the Smart Grid: Challenges, Opportunities and Proposals for Prosumer Profitability," *Energies,* vol. 7, no. 1996-1073, pp. 6142-6171, 2014.

[42] J. Aengenvoort, E. D. Keyser and P. Kreutzkamp, "Opening the aFRR Market in Belgium – A unique and innovative 2 step auction model," Next Kraftwerke, 10 March 2021. [Online]. Available: https://www.next-kraftwerke.com/energy-blog/opening-afrr-market-belgium#:~:text=To%20increase%20competition%2C%20Elia%20and%20the%20Belgian%20regulator,also%20consumption%20assets%20%E2%8

0%93referred%20to%20as%20demand%20response.. [Accessed 21 June 2022].

[43] Svenska kraftnät, "sthlmflex," Svenska kraftnät, 3 November 2021. [Online]. Available: https://www.svk.se/sthlmflex. [Accessed 21 June 2022].

[44] D. Kanakadhurga and N. Prabaharan, "Demand side management in microgrid: A critical review of key issues and recent trends," *Renewable and Sustainable Energy Reviews,* vol. 156, no. 1364-0321, p. 111915, 2022.

[45] C. Li, X. Yu, W. Yu, G. Chen and J. Wang, "Efficient Computation for Sparse Load Shifting in Demand Side Management," *IEEE Transactions on Smart Grid,* vol. 8, no. 1949-3053, pp. 250-261, 2017.

[46] F. Luo, G. Ranzi, S. Wang and Z. Y. Dong, "Hierarchical Energy Management System for Home Microgrids," *IEEE Transactions on Smart Grid,* vol. 10, no. 1949-3053, pp. 5536-5546, 2018.

[47] Q. Zhang, X. Wang and M. Fu, "Optimal implementation strategies for critical peak pricing," in *2009 6th International Conference on the European Energy Market*, Leuven, 2009.

[48] Directorate-General for Energy (European Commission); Tractebel Impact, "Energy communities in the clean energy package: Best practices and recommendations for implementation," 29 March 2021. [Online]. Available: https://data.europa.eu/doi/10.2833/51076. [Accessed 21 June 2022].

[49] M. Farrokhifar, H. Bahmani, B. Faridpak, A. Safari, D. Pozo and M. Aiello, "Model predictive control for demand side management in buildings: A survey," *Sustainable Cities and Society,* vol. 75, no. 2210-6707, p. 103381, 2021.

[50] M. H. Didden and W. D. D'haeseleer, "Demand Side Management in a competitive European market: Who should be responsible for its implementation?," *Energy Policy,* vol. 31, no. 13, pp. 1307-1314, 2003.

[51] S. Breukers, E. Heiskanen, B. Brohmann, R. Mourik and C. Feenstra, "Connecting research to practice to improve energy demand-side management (DSM)," *Energy,* vol. 36, no. 4, pp. 2176-2185, 2011.

[52] K. Kusakana, "Optimal energy management of a grid-connected dual-tracking photovoltaic system with battery storage: Case of a microbrewery under demand response," *Energy,* vol. 212, no. 0360-5442, p. 118782, 2020.

[53] IEA, „Unlocking the Potential of Distributed Energy Resources: Power system opportunities and best practices," International Energy Agency, Paris, 2022.

[54] S3C, "Guideline: Introducing Demand Side Management to SMES," 2015. [Online]. Available: https://www.smartgrid-engagement-toolkit.eu/fileadmin/s3ctoolkit/user/guidelines/GUIDELINE_INTRODUCING_DEMAND_SIDE_MANAGEMENT_TO_SMES.pdf. [Accessed 21 June 2022].

[55] M. Y. Recalde, "Which aspects may prevent the development of energy service companies? The impact of barriers and country-specific conditions in different regions," in *Energy Services Fundamentals and Financing*, Academic Press, 2021, pp. 293-315.

[56] European Commission, "Reference Document on Best Available Techniques for Energy Efficiency," September 2021. [Online]. Available: https://eippcb.jrc.ec.europa.eu/sites/default/files/2021-09/ENE_Adopted_02-2009corrected20210914.pdf. [Accessed 24 June 2022].

[57] European Commission, "Decision (EU) 2019/2031 on establishing best available techniques (BAT) conclusions for the food, drink and milk industries, under Directive 2010/75/EU of the European Parliament and of the Council," 12 April 2019. [Online]. Available: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv%3AOJ.L_.2019.313.01.0060.01.ENG&toc=OJ%3AL%3A2019%3A313%3ATOC. [Accessed 24 June 2022].

[58] J. Schleich, U. Bode, K. Ostertag and R. Peter, "Reducing Barriers to Energy Efficiency in the German Brewing Sector," Fraunhofer Institute for Systems and Innovation Research, Karlsruhe, 2000.

[59] Steinecker, "The brewing power station," 2022. [Online]. Available: https://www.steinecker.com/media/downloads/brewnomic_en.pdf. [Accessed 24 June 2022].

[60] A. Pino, F. J. P. Lucena and J. G. Macho, "Economic Analysis for Solar Energy Integration in a Microbrewery," in *2019 International Conference on Smart Energy Systems and Technologies (SEST)*, Porto, 2019.

[61] B. Muster-Slawitsch, W. Weiss, H. Schnitzer and C. Brunner, "The green brewery concept – Energy efficiency and the use of renewable energy sources in breweries," *Applied Thermal Engineering,* vol. 31, no. 13, pp. 2123-2134, 2011.

[62] Clarke Energy , "Brewing industry," Clarke Energy , 2022. [Online]. Available: https://www.clarke-energy.com/us/applications/brewing-industry-chp/. [Accessed 24 June 2022].

[63] JUMO, "Brewery Technology," 17 June 2015. [Online]. Available: https://www.jumo.net/attachments/JUMO/attachmentdownload?id=7126. [Accessed 24 June 2022].

[64] AB-InBev, "AB INBEV AND BAYWA R.E. ANNOUNCE BIGGEST EVER PAN-EUROPEAN CORPORATE SOLAR POWER DEAL TO BREW BUDWEISER WITH 100% RENEWABLE ELECTRICITY," Brewers of Europe, 1 January 2020. [Online]. Available: https://brewing4.eu/sustainability-initiatives/ab-inbev-and-baywa-r-e-announce-biggest-ever-pan-european-corporate-solar-power-deal-to-brew-budweiser-with-100-renewable-electricity/. [Accessed 24 June 2022].

[65] Heineken Spain, "BREWED BY THE SUN," Brewers of Europe, 2 January 2020. [Online]. Available: https://brewing4.eu/sustainability-initiatives/brewed-by-the-sun/. [Accessed 24 June 2022].

[66] A. Kubule, L. Zogla, J. Ikaunieks and M. Rosa, "Highlights on energy efficiency improvements: a case of a small brewery," *Journal of Cleaner Production,* vol. 138, no. 2, pp. 275-286, 2016.

[67] F. W. Geels, "Technological transitions as evolutionary reconfiguration processes: a multi-level perspective and a case-study," *Research Policy,* vol. 31, no. 8-9, pp. 1257-1274, 2002.

[68] J. R. Thakur, Interviewee, *Researcher at KTH Royal Institute of Technology.* [Interview]. 31 March 2022.

[69] F. Melchioretto, Interviewee, *SDG Localization Expert at UN-Habitat.* [Interview]. 27 June 2022.

[70] Enerad.pl, "Taryfa G12 – Dla kogo? Jakie godziny?," Enerad.pl, 2022. [Online]. Available: https://enerad.pl/prad/taryfy/taryfa-g12/#:~:text=Taryfa%20G12%20godziny%20PGE%20Obr%C3%B3t%20Godziny%3A%206%3A00%20%E2%80%93,22%3A00%20do%206%3A00%20i%20mi%C4%99dzy%2013%3A00%20%E2%80%93%2015%3A00.. [Accessed 27 June 2022].

[71] PGE, "OŚWIADCZENIE O PRZYJĘCIU OFERTY," 31 March 2022. [Online]. Available: https://www.bing.com/search?q=PEG+O%C5%9AWIADCZENIE+O+PRZYJ%C4%98CIU+OFERTY&cvid=5f3d622ecfab4bba994fb2f93123054d&aqs=edge..69i57.3581j0j4&FORM=ANAB01&PC=U531. [Accessed 27 June 2022].

[72] Z. Caputa, "Incoming solar radiation in the Southern Part of the Kraków-Częstochowa Upland in 2008–2014," *Prace Geograficzne ,* vol. 25, no. 147, pp. 129-138, 2015.

[73] JA Solar, "410W MBB Half-Cell Module Mono JAM72S10 390-410/MR," JA Solar, 2022. [Online]. Available: https://autosolar.es/pdf/Panel-JaSolar-400w-JAM72S10.pdf. [Accessed 27 June 2022].

[74] European Commission, "PHOTOVOLTAIC GEOGRAPHICAL INFORMATION SYSTEM," EC, 2022. [Online]. Available: https://re.jrc.ec.europa.eu/pvg_tools/es/#PVP. [Accessed 27 June 2022].

[75] Monsolar.com, "SEPARATION CALCULATOR BETWEEN SOLAR PANELS TO AVOID SHADOWS," Monsolar.com, 2022. [Online]. Available: https://www.monsolar.com/separacion-paneles-solares. [Accessed 27 June 2022].

[76] JetBrains, "PyCharm Edu," JetBrains, 2022. [Online]. Available: https://www.jetbrains.com/pycharm-edu/. [Accessed 27 June 2022].

[77] AutoSolar, "Panel JA Solar 380W Monocristalino PERC," AutoSolar, 2022. [Online]. Available: https://autosolar.es/paneles-de-conexion-a-red/panel-ja-solar-380w-monocristalino-perc. [Accessed 27 June 2022].

[78] Tauron Polska Energia, "Fotowoltaika," Tauron, 2022. [Online]. Available: https://www.tauron.pl/dla-domu/urzadzenia/fotowoltaika. [Accessed 27 June 2022].

[79] L. P. Caballero, Interviewee, *Energy and Environmental Engineer at R2M Solution.* [Interview]. 17 March 2022.

[80] L. Ableitner, Interviewee, *Co-founder & CEO at Exnaton AG.* [Interview]. 22 April 2022.

[81] B. Sučić, Interviewee, *Expert at Energy Efficiency Centre of Jozef Stefan Institute.* [Interview]. 25 April 2022.

[82] Eurostat, "Purchasing power standard (PPS)," 11 December 2014. [Online]. Available: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Glossary:Purchasing_power_standard_(PPS). [Accessed 21 June 2022].

[83] Brewers of Europe, "European beer trends: Statistics report 2021 Edition," 2021. [Online]. Available: https://brewersofeurope.org/uploads/mycms-files/documents/publications/2021/european-beer-statistics-2020.pdf. [Accessed 24 June 2022].

[84] Brewers of Europe, "Key figures 2019: Poland," 2020. [Online]. Available: https://brewersofeurope.org/uploads/mycms-files/documents/publications/2020/country-profiles/Poland.pdf. [Accessed 24 June 2022].

[85] S. Hubert, T. Helmers, F. Groß and A. Delgado, “Data driven stochastic modelling and simulation of cooling demand within breweries,” *Journal of Food Engineering,* vol. 176, no. 0260-8774, pp. 97-109, 2016.