

## Article

# Local Energy Markets in Action: Smart Integration of National Markets, Distributed Energy Resources, and Incentivisation to Promote Citizen Participation

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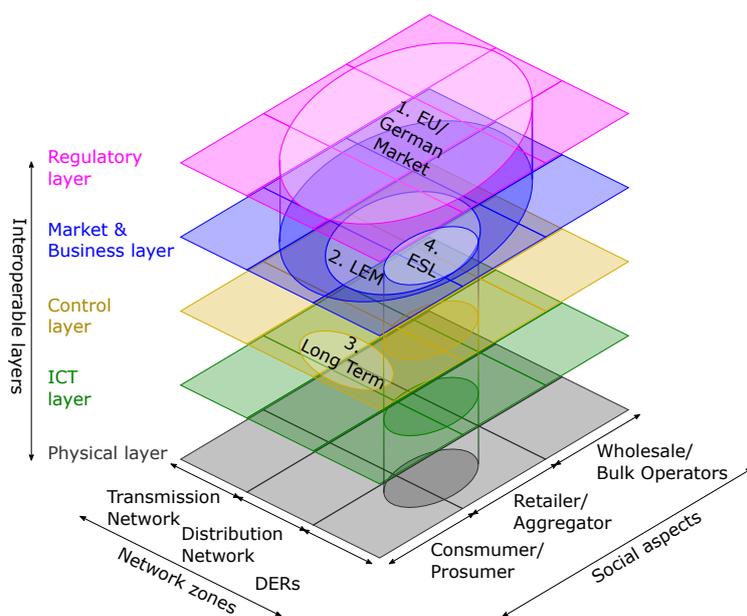
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**Abstract:** Since the Paris Agreement in 2016, the goals of limiting climate change and moving toward climate resilience stand. With a share of about 80 % of global CO<sub>2</sub> emissions, the energy sector is an essential driver for these goals. A shift to low-carbon energy production and a decentralized system for more efficient energy transmission distribution is necessary. In this paper, we present our work on Modeling of Power Exchanges, Algorithms for Local Energy Market (LEM), Competitiveness of Combined Heat and Power Plant (CHP) and Energy Feedback Devices. The study was conducted considering technical, economic, social and regulatory framework. For easy integration into energy simulations or a district energy management system (DEMS), a model for power exchanges was created that allows flexible input or deterministic price patterns. The algorithm handles the clearing of an LEM by a district aggregator using limit orders with the goal of increasing the share of locally consumed electricity using economic incentives. An investigation was conducted into the operation of flexible CHPs in low-carbon power systems to balance the volatility of renewable energy. An energy signal light was developed as an energy feedback device, which is integrated into the DEMS in a living lab and allows individual configuration. In summary, the results presented should be compared with those of other research approaches in the future and require qualitative and quantitative evaluation.

**Keywords:** Local Energy Markets; Energy Feedback; Energy Exchange Market Modelling; EEX & EPEX; Peer-to-Peer Trading; Energy communities; long-term transformation; sustainable supply concept; Participation; Incentivization

## 1. Introduction

Energy related emissions account for almost 80 % of the EU's total greenhouse gas emissions [1]. As one measure to reduce the greenhouse gas emissions the European Commission has therefore decided to foster LEMs [1], because enabling Citizen Energy Communities (CEC) to operate LEMs can result in decarbonising the low-voltage distribution networks [2,3]. Natural persons, local authorities, including municipalities, or small enterprises shall establish CECs which "may engage in generation, including from renewable sources, distribution, supply, consumption, aggregation, energy storage, energy efficiency services or charging services for electric vehicles or provide other energy services to its members or shareholders" [4]. Trivedi et al. [2] have reviewed the concept of community-based microgrids (C-MGs) and how LEM can be decarbonised. They also summarize how CECs can utilize C-MG solutions in order to



**Figure 1.** Overview of concept and chapters in accordance with Santodomingo et al. [5]. 1. A model for EU or German market simulation is presented in Chapter 2. 2. An implementation of a LEM is described in Chapter 3. 3. A concept for long term operation is given in Chapter 4. 4. The concept for Energy Signal Light (ESL) is presented in Chapter 5.

32 set up LEMs. There, functional architectural layers, system integration topologies, inter-  
 33 operability issues, strategies for consumer-centric energy trading under LEM mechanism,  
 34 and socio-economic aspects are considered. Following the concept of the Smart Grid  
 35 Architecture Model (SGAM) [5], Trivedi et al. [2] have developed a generalised  
 36 C-MG structure, which is based on social aspects, network zones and interoperable  
 37 layers. However, C-MGs and LEMs somehow need to be implemented in order to  
 38 allow CECs the participation at the energy market. Abrishambaf et al. [6] figured out,  
 39 that most approaches miss the transfer from model to real world application. This is,  
 40 where the Energetic Neighborhood Quarter (German: Energetisches Nachbarschafts  
 41 Quartier) (ENaQ) project aims to contribute to by demonstrating, how energy can be  
 42 traded amongst inhabitants within a residential district close to Oldenburg, Germany  
 43 called Helleheide. Details on the ENaQ project were described by Wehkamp et al.  
 44 [7], Schmeling et al. [8], Brandt et al. [9].

45 This paper is part of a series of papers describing details of the implementation of  
 46 the ENaQ project. Following the generalised C-MG structure [2](cf. Figure 1), this paper  
 47 explains:

- 48 1. how energy markets are organised all over Europe (cf. Chapter 2) and why a LEM  
 49 shall be implemented,
- 50 2. how a LEM will be implemented in Helleheide during the ENaQ project (cf. Chap-  
 51 ter 3),
- 52 3. how the energy system can be operated in order to perform the transition to a  
 53 completely sustainable supply via dynamic system operation (cf. Chapter 4) and
- 54 4. how the users in this case get informed regarding local availability of renewable  
 55 energy via Energy Signal Light (ESL) (cf. Chapter 5). Other applications as prices  
 56 or CO<sub>2</sub> emissions would be possible.

57 The chapters are consistent within themselves so that the interested reader can focus on  
 58 particular topics.

## 59 2. Power Exchange Markets in Energy Simulations

60 In energy system analyses, the economic efficiency factor of energetic plants is often  
 61 an important object of investigation. Thus, business decisions are made on the basis of de-  
 62 tailed design and operation optimizations of energy-saving plants. These optimizations  
 63 are backed by an objective function that maximizes the economic efficiency [8,10,11].  
 64 In addition to the technical, regulatory and legal framework conditions, modeling of  
 65 the external economic environment, the power exchange markets, is required. The aim  
 66 of this chapter is to explain the power markets and to present an open-source market  
 67 model that can be used in simulations. The market model is based on the respective  
 68 market mechanisms with respect to the temporal resolution of the products and is  
 69 backed by price patterns. The creation of the deterministic price patterns used here was  
 70 presented by Wehkamp et al. [12]. The energy markets are divided into the derivatives  
 71 market (future market), spot market and balancing market (frequency market). Beside  
 72 the regulated energy exchange, there is also the possibility to trade directly. This is  
 73 called Over-The-Counter (OTC) trading. The focus in this chapter is on the European  
 74 Derivatives and Spot Markets for electricity (European Energy Exchange (EEX)) [13,14].  
 75 The balancing markets are not yet part of this work. The information source for the  
 76 mechanisms and products of the exchanges are the websites of the respective exchanges  
 77 and freely available information material. In the following, the individual markets are  
 78 presented in Sections 2.1-2.2, the available data of the markets in Section 2.4, and the  
 79 modeling of the markets for energy simulations in Section 2.5.

### 80 2.1. Future Market

81 On the derivatives market, traders, producers and buyers trade electricity and often  
 82 also fossil fuels and CO<sub>2</sub> certificates for corresponding power plants. On the one hand,  
 83 derivatives markets serve to ensure that sufficient electrical power will be available  
 84 or will be demanded in the future. It functions similar to a capacity market. This is  
 85 achieved because there are up to several years between purchase and delivery. On the  
 86 other hand, the derivatives market serves to hedge prices by allowing energy traders  
 87 to adjust long and short positions to market developments. Behind very few trading  
 88 volumes is an actual physical delivery [13,14] (cf. Table 1). This is well illustrated by  
 89 the fact that the volumes of the national markets are often significantly higher than the  
 90 actual consumption of the countries. For example, the gross electricity consumption of  
 91 Germany in 2020 was 558.8 TWh and the trading volume was 3006.1 TWh [15,16].

Table 1: Historical Trading Volumes on European Electricity Exchange EEX & EPEX in TWh [17–21]

Year	2014	2015	2016	2017	2018	2019	2020
Future EU	1.570	2.537	3.920	2.822	3.347	3.973	4.736
Future US	N/a	N/a	N/a	395	1.039	1.857	1.719
Day-ahead	427	507	468	464	485	502	504
Intraday	47	59	62	71	82	92	111

92 For continuous trading, the pay-as-bid principle applies. This means that the prices  
 93 specified in the offer (bid price) are paid by the demanding parties. This market can be  
 94 understood as purchasing the holding of a power / reservation, not the actual amount  
 95 of energy produced. Physical delivery takes place only if the positions remain open  
 96 until the last possible trading day. The products on the derivatives market have a lower  
 97 resolution than on the spot markets. Here, mainly annual bands for baseload (00h-24h)  
 98 and peakload (08h-20h) are traded.

### 99 2.2. Spot Market

100 The spot market is used for short-term trading of electricity. It is divided into  
 101 the day-ahead market with minimal hourly and the intraday market with minimal

102 quarter-hourly resolution. On the day-ahead market, the forecast electricity generation is  
103 matched with the forecast electricity consumption. On the day of actual physical delivery,  
104 differences arise between the forecasts. This can be balanced on the intraday market by  
105 the originating traders up to 5 minutes before. The energy system is balanced for the  
106 market participants (traders, suppliers, grid operators, last consumers) in quarter-hourly  
107 resolution [13,14]. In addition to the usual hourly and quarter-hourly contracts, there are  
108 further products over several hours, such as: Middle-Night (01h-04h), Early Afternoon  
109 (13h-16h) and Evening (19h-24h). The Market-Clearing-Price (MCP) is determined by the  
110 intersection of the supply and demand curves on the exchanges. At the European Power  
111 Exchange (EPEX), the uniform-pricing-principle (or merit-order-principle) applies to  
112 auction trading [22]. This means that all parties offering electricity receive the same price  
113 and all parties demanding electricity pay the same price. The spot market consists of day-  
114 ahead and intraday trading. Day-Ahead auction bids (Ask & Bid) can be submitted until  
115 the close of the exchange for delivery on the following day. The time of the market close  
116 depends on the national markets. On the intraday market it is possible to participate in  
117 the auctions and trade on the continuous market. On the continuous market, there are  
118 only very short intervals between trading and physical fulfillment, also called lead time.  
119 The lead time depends on the national market. The lead time is 0 minutes for Finland.  
120 The lead time is 5 minutes for Austria, Belgium, Germany and the Netherlands. The  
121 lead time is 15 minutes for Great Britain. Lead time is 30 minutes for France and Czech  
122 Republic. Lead time is 60 minutes for international Single Intraday Coupling (SIDC)  
123 markets. Intraday auction bids (Ask & Bid) can be submitted from the day before until  
124 the day of delivery. The respective traders are informed about the transactions that have  
125 been concluded.

### 126 2.3. Balancing markets

127 The balancing power markets are not exchanges. They are used for frequency main-  
128 tenance in real time. This means that deviations from the traded electricity quantities are  
129 balanced in real time and up to a duration of one hour. Currently, the mass of turbines  
130 of thermal power plants is used for frequency maintenance. The decline of these large  
131 turbines due to the focus on renewable energies, creates a technical need for alterna-  
132 tive frequency maintenance measures. This includes, for example, the monitoring and  
133 planning of electrical flows as well as the availability of flexibility [13,14]. Electrically  
134 flexible consumers and producers are needed for this purpose. Depending on the speed  
135 at which the power is activated, they are differentiated.

### 136 2.4. Indices Data

137 The EPEX provides additional data on market activity. These are provided to  
138 enable traders to better plan market activity and thus provide an information basis for  
139 decision-making. This data can be used to model the markets. It is possible to precisely  
140 determine the respective supply and demand curves over the entire transaction logs.  
141 This is associated with an increased effort. Alternatively, it is possible to use processed  
142 data directly from the stock exchange. These include various indices: Index Price, ID1-  
143 Price, ID3-Price and WAP. These are explained in the following sections. The indices are  
144 often created for each of the markets (day-ahead, intraday), individual trading types  
145 (auction, continuous), national markets and products (e.g.: 60 minutes, 15 minutes).

#### 146 2.4.1. Day-Ahead

147 The Day-Ahead market consists of an auction-based market. Consequently, there  
148 are only indices for the auctions.

#### 149 Auction Index

The Physical Electricity Index (PHELIX) is available for each market (German/ Austrian,  
German, Swiss, etc.). The calculations for the indices may differ between the markets.

The results are published around 13h00 every day. The index values are given with a precision of two decimals and with the unit [€/MWh]. The PHELIX is calculated using the volume weighted average of the hourly prices:

$$PHELIX = \frac{\sum_n p_n v_n}{\sum_n v_n} \quad (1)$$

150 The prices  $p_n$  are multiplied by their volumes  $v_n$  to weight the prices for this index.  
 151  $n$  the number of time steps to be considered. This index is also available for block  
 152 products: base (0h00 - 24h00) and peak (8h00 - 20h00). They are calculated using the  
 153 arithmetic mean of the market clearing prices [23].

#### 154 2.4.2. Intraday

155 The Intraday market consists of an an auction-based and a continuous market.  
 156 Consequently, there are indices for each market.

#### 157 Auction Index

158 The Auction index is available for several market (Germany, Great Britain, Switzer-  
 159 land). The index has several time resolutions for the given products: 60, 30 and 15  
 160 Minutes. The index price for the baseload is the arithmetic mean of the intraday indices  
 161 between 0h00 and 24:00. The index price for the peakload is the arithmetic mean of the  
 162 intraday indices between 8h00 and 20h00.

#### 163 Continuous Index

164 Some indices are updated close to real-time and some are updated one day after  
 165 trading [23].

166 **IDFull index** The IDFull index has several time resolutions for the given products:  
 167 60, 30 and 15 Minutes. All trades with the same time resolution are included in the  
 168 calculation of the index. Block products are not taken into account. The IDFull index  
 169 is calculated using the volume weighted average price equation (see Equation 1). This  
 170 index is also available for block products: base (0h00 - 24h00) and peak (8h00 - 20h00) as  
 171 separate indexes. If the trading capacity is less than 10 MW, a substitute value calculation  
 172 is performed [23].

173 **ID1-Price** The ID1 index has several time resolutions for the given products: 60,  
 174 30 and 15 Minutes. All trades within a 1-hour timeframe before delivery are included  
 175 in the calculation of the index. The ID1 index is calculated using the volume weighted  
 176 average price equation. If the trading capacity is less then 10 MW, a substitute value  
 177 calculation is performed [23].

178 **ID3-Price** The ID3 index has several time resolutions for the given products: 60,  
 179 30 and 15 Minutes. All trades within a 3 hour timeframe before delivery are included  
 180 in the calculation of the index. The ID3 index is calculated using the volume weighted  
 181 average price equation. If the trading capacity is less then 10 MW, a substitute value  
 182 calculation is performed [23,24].

183 **WAP** The Weighted-Averager-Price (WAP) is given with a precision of 5 decimals.  
 184 The calculation and update of the WAP is given in real time (15 minute update frequency).  
 185 This frequent publishing of this index is to enables market traders to react to sudden  
 186 market developments. At the end of the day, the WAP value is equal to the index  
 187 price [23,25] (cf. Equation 1).

## 188 2.5. Modeling of Energy Exchanges

189 The main objective of the following modelling is investigating which mixture of  
190 markets represents optimal income for power plants. Thus, a model representing one  
191 or several power plants and different simultaneous markets is required. The described  
192 section is implemented upon the model of [8], but is generic in its application.

### 193 2.5.1. Data Sources and Data Preparation

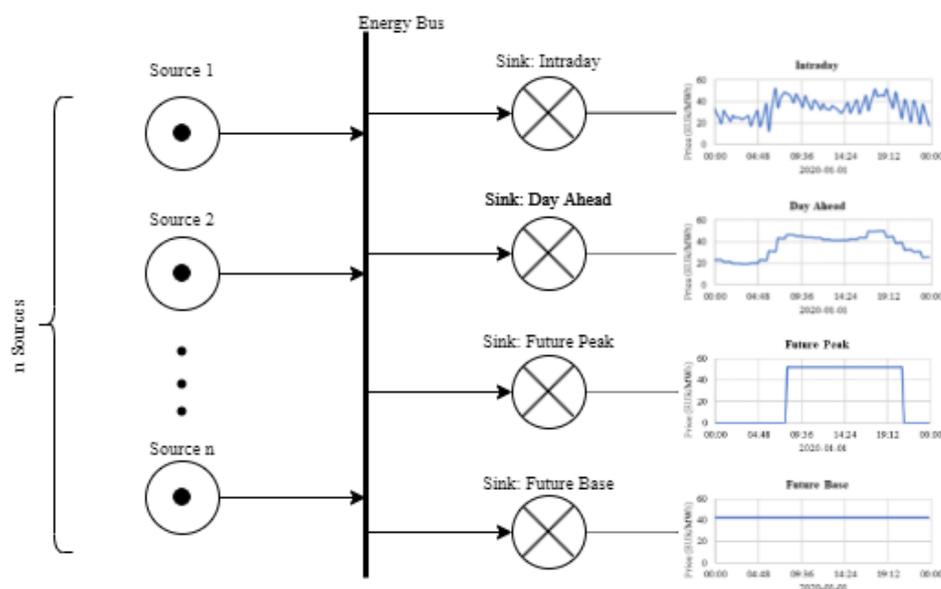
194 The basis of the modelling is the price information available for the Future Base,  
195 Future Peak, Day Ahead, and Intraday Markets. Since the highest resolution of 15 min is  
196 for the Intraday Markets, time-series with this resolution are build for the four above  
197 mentioned markets. Historical data from power exchanges can be used for simulation,  
198 if available. Alternatively, this open-source model includes the price patterns created  
199 by Wehkamp et al. [12], which are based on historical data of electricity markets for  
200 Germany. The information on Future Base and Future Peak was obtained as one price  
201 value for each specific year. For Future Base Market, this value remains constant through  
202 the year, and thus needs no further modification. For Future Peak, a time-series with the  
203 price pattern needs to be build, which fixes the value of electricity at the given value if the  
204 time is inside 08h00 (included) and 21h00 (excluded), and is fixated at EUR/MWh if it  
205 falls outside this boundaries. For Day Ahead markets, the hourly values are resampled in  
206 15 min resolution. For intraday values, these are compiled with their original resolution.  
207 These are latter build in a data structure with quarterly-hour price information for all  
208 the considered markets. The data build starts at 00h00 on January 1st of the given year,  
209 and is build for a complete year.

### 210 2.5.2. Model Building

211 The modelling of a power plant that delivers electricity to one or several of these  
212 markets is built based on an optimization framework which allows estimating which  
213 is the optimal allocation of the produced electricity to maximize income. While this  
214 calculation can be simplified for power plants with constant output, volatile produc-  
215 tion plants require a much more sophisticated calculation. The optimization software  
216 oemof.solph allows modelling different kinds of power sources and optimize the total  
217 income. It provides a set of classes that allow building energy system models, such  
218 as Sinks, Sources, Buses, and Flows. Power plants need to be modelled as Sources,  
219 where the production profile can be given as a fixed value or as a time series (with the  
220 required quarterly hour resolution). For volatile plants, a time-series with the production  
221 is required, which, similar to the market data, needs to start at 00h00 on January 1st of  
222 the given year. Each of the markets can be modelled as a Sink, with the price information  
223 as a fixed value (as in the Future Base Market), or as a time series (as the case with the  
224 other markets). These Sources (representing a power production plant) and the different  
225 Sinks (representing each one a different electricity market) are connected to a Bus via  
226 unidirectional Flows to constrain any reverse power flow. This allows connecting one or  
227 many power plants to one or many electricity markets. Figure 2 illustrates the structure  
228 of the model.

### 229 2.5.3. Market Constraints

230 Since there are contractual obligations related to each market, it is necessary that  
231 these obligations are reflected in the mathematical formulation of the model. These  
232 constraints were aggregated using the pyomo package, which is the basis for the opti-  
233 mization of oemof.solph. For Future Base Market, the same value has to be delivered  
234 during the whole year. This means that all the energy flow values have to be equal  
235 during the year, and thus equal to the first output of the year, which is left unconstrained  
236 and can be modified by the solver. For Future Peak Market, if the value is outside of the  
237 8h00 to 21h00 (excluded) boundaries, it is constrained to 0. If the time stamp is within  
238 the boundaries, the price value must be the same for the whole year, and thus equal to



**Figure 2.** Overview of the model structure representing one or several power plants and different simultaneous markets.

239 the first non-zero output of the year. This first non-zero output is unconstrained and can  
 240 be modified by the solver. For Day Ahead Market, the condition is that all the values  
 241 within the same hour (i.e. from 9h00 to 9h45) have to be the same. This was reached  
 242 by stating that every hour, the first value is unconstrained, and the remaining three are  
 243 equal to the first one. The Intraday values are unconstrained.

## 244 2.6. Conclusion

245 In this chapter, a model of electricity markets used in simulations was presented.  
 246 This model can be used in simulations of power systems on different levels. For the  
 247 simulation of international or national power systems, the market mechanisms of the re-  
 248 spective nations have to be compared with those of the model and, if necessary, adjusted.  
 249 Since the model is based on [EPEX](#), the need for adaptation is presumably small for coun-  
 250 tries where [EPEX](#) is the market regulator. These include: Austria, Belgium, Denmark,  
 251 Germany, Finland, France, Luxembourg, the Netherlands, Norway, Poland, Sweden, the  
 252 United Kingdom and Switzerland. Furthermore, with this model it is possible to equip  
 253 smaller optimization models, such as the [LEM](#) presented in the following Chapter 3,  
 254 with external markets. The advantage of this model is the low computational overhead,  
 255 since the price models are preconfigured and computed as inputs independently of the  
 256 rest of the model. The disadvantage is the need for data on the markets to be modeled  
 257 as well as the verification of market mechanisms for countries other than the [EPEX](#)  
 258 countries. Furthermore, the modeling of future developments is strongly dependent  
 259 on the quality of the input parameters for the price pattern generation. In this respect,  
 260 it must be critically emphasized that the price patterns used by Wehkamp et al. [12]  
 261 have not yet been subjected to any further qualitative or quantitative evaluation. A  
 262 comparison of the often used agent-based market models with the one presented here  
 263 can give beneficial insight into the quality of this model.

## 264 3. Local Energy Market

265 Motivated by climate protection and the phasing out of fossil fuels, the use of  
 266 Distributed Energy Resources (DERs) is increasing more and more, especially at the  
 267 local level, e.g. by installing photovoltaics (PV) on the roofs of private households.  
 268 These households are increasingly acting as prosumers, i.e. they generate electricity  
 269 in this manner and usually consume a large part of it themselves [26]. However, from

270 a technical point of view, complete self-consumption and self-sufficiency are hardly  
271 achievable, so the existing electricity grid is used to compensate by supplying missing  
272 electricity and receiving surplus electricity. Of course, it would be possible to trade  
273 missing and surplus electricity through the national markets presented in Chapter 2.  
274 However, as should become clear during this chapter, these markets are highly complex  
275 as well as difficult and expensive to access, especially given the idea that individual  
276 households should participate in them. Therefore, there are approaches to bundle DERs  
277 in virtual power plants and to trade the capacity portfolio of such plants on national  
278 markets [27]. However, these markets' assumption that energy can flow in any direction  
279 on copper plates is difficult to realise. In reality, the market results and thus the schedules  
280 of the power plants are compared with the limits of the grid and congestion management  
281 has to take place. More expensive power plants must then be used to avoid the grid  
282 bottlenecks. From this point of view, it makes sense to combine consumption with  
283 generation as locally as possible and thus avoid grid bottlenecks from the outset. If this  
284 is to be done efficiently, small-scale markets must be created that offer the possibility  
285 and incentive of local energy use.

286 For districts, as in our case study, this means building a Local Energy Market (LEM),  
287 where prosumers are enabled to trade their energy within the neighborhood. National  
288 markets should then only be used as a back-up for times when the district as a whole  
289 cannot supply itself or produces too much electricity. By bundling neighborhood en-  
290 ergy consumers, it would also be possible to achieve greater market power on national  
291 markets and lower prices for residents overall. In addition, the involvement of resi-  
292 dents in the local energy supply would be conducive to acceptance and participation.  
293 Nevertheless, allowing local energy trading within a district raises regulatory, partici-  
294 patory, organizational and technical questions. In this chapter, a broad overview of the  
295 local energy trading efforts at Energetic Neighborhood Quarter (German: Energetisches  
296 Nachbarschafts Quartier) (ENaQ) is given.

### 297 3.1. Related Work

298 As a definition for LEMs, we follow Weinhardt et al. [28]: "market platforms for  
299 trading locally generated (renewable) energy among residential agents within a geo-  
300 graphic and social community. Supply security is ensured through connections to a  
301 superimposed electricity system (e. g. superimposed grid or adjacent LEMs)". Two parts  
302 of this definition shall be emphasized: firstly, the local market is for a geographically  
303 very limited area, here the Helleheide district, and secondly, the market does not aim for  
304 an self-sufficient island system, but for a market which is also grid-connected.

305 The topic of LEMs has been extensively studied in the literature and there are many  
306 publications on different market mechanisms. An overview of LEMs is given in [29].  
307 The authors distinguish between different market clearing method categories, mainly  
308 describing distributed methods without a central clearing entity, auction based methods,  
309 and multi level optimizations.

310 Another overview of current LEMs can be found in Zang and Kim [30]. Here,  
311 there is a special focus on the use of battery storage in local markets to help flexibility  
312 in trading. Zia et al. [31] discuss and categorise the operation of microgrids in many  
313 different dimensions including the design of LEMs.

314 What many of these publications fail to mention is the actual feasibility of the  
315 approaches, particularly in the social, legal and economic dimensions. The algorithms  
316 are an essential part of the problem, but without a sustainable and feasible business  
317 model, such approaches will not be established. The approach we have chosen is  
318 therefore explicitly holistic and attempts to create an LEM for ENaQ while taking into  
319 account real-world conditions.

### 320 3.2. Starting point in the Helleheide District

321 The establishment of LEMs in residential districts ultimately requires the acceptance  
322 of the residents, who should actively include such systems in their everyday lives. For  
323 this reason, development initially started with citizen participation.

324 The first question is whether the residents of a district like Helleheide have a general  
325 interest in energy and to what extent they want to become involved in processes and  
326 decisions. For this reason, we conducted a general online survey in 2019, the results of  
327 which are published in detail in [9]. It turned out that over 90 % of those surveyed are  
328 generally prepared to no longer obtain electricity exclusively from conventional energy  
329 suppliers, but would be willing to buy electricity from their immediate neighborhood.  
330 For many, however, the basic prerequisite would be an associated reduction in costs  
331 and/or emissions. 80 % of respondents also said they were interested in innovative  
332 electricity tariffs such as dynamic pricing. In summary, citizens show a high degree of  
333 interest in local energy systems and the courage to try out new things.

334 Building on this initial opinion, the idea of a modified LEM for the district under  
335 study was developed. This would allow residents to buy electricity (proportionally)  
336 directly from the neighborhood and, through this option, reduce both costs by elimi-  
337 nating grid fees and emissions by optimally integrating renewable energy. We began  
338 by evaluating the approaches found in the scientific literature (cf. Section 3.1) for their  
339 feasibility in real projects. We had to modify them to the extent that they could be  
340 implemented in the current German regulatory framework, which will be discussed in  
341 more detail in Section 3.3. This has resulted in two implementable clearing algorithms  
342 published in [32,33]. However, on one hand, these two proposals still contain a lot  
343 of freedom of design and are only prototypes and general feasibility studies. At this  
344 point, it is important to come back to the citizens and to consult with them whether  
345 the concept developed behind closed doors (inward participation process [9]) meets  
346 their expectations and where there is a need for improvement and optimization. On the  
347 other hand, these proposals only prove the applicability in the current legal framework,  
348 but not the possibility of IT-technical implementation. The general methodology as  
349 well as the necessary modifications of the algorithms to a technically feasible solution  
350 will be discussed in more detail in Section 3.5. In the end, however, all four aspects  
351 (participation, technology, business model and legal framework) must always be seen  
352 together and it is essential to constantly mirror the intermediate results especially to the  
353 future users as will be discussed in Section 3.4.

### 354 3.3. Regulatory Framework and Business Models

355 A challenge for LEMs is the regulatory framework, as described in [28]. The legal  
356 framework often differs massively between different nations. For the time being, we  
357 have use the German law as base for the proposed LEM. This should be similar to that of  
358 many other EU countries, but it should be compared in further detail before applying it in  
359 other countries. The proposed approach to allow local energy trading is a novel business  
360 model, the so-called district aggregator. A district aggregator buys all locally generated  
361 electricity and sells it to all local consumers. This way, the regulatory obligations for an  
362 energy supplier are bundled in the aggregator, which makes the trading process simpler  
363 for the participants. In addition, the district aggregator operates a customer system that  
364 waives grid charges and other state levies on locally traded electricity. The regulatory  
365 framework for ENaQ as well as the required business model of the district aggregator  
366 have been described in detail in [9,33].

### 367 3.4. Involving citizens in local energy market design

368 The social approval and acceptance of the decisions associated with the structural  
369 change in the German energy system is an important factor [34]. Human behavior is  
370 not primarily determined by objective scientific facts, but by the subjective perception  
371 of individuals [35]. Voluntariness, controllability, a balanced distribution of risks and

372 benefits as well as trust in risk management are decisive factors influencing how a  
373 technology is perceived and accepted [34]. As explained above the LEMs works only  
374 if the residents actively use it. It is therefore necessary to consult with them in order  
375 to determine if the proposal meets their expectations. Surveys are a well-known form  
376 of consulting with citizens. However, a key aspect of a survey's output being useful  
377 lies in its design. If the questions are not clear or are misunderstood, the results may  
378 lead to incorrect information. Therefore testing the questions and questionnaire is also  
379 an important part of the design. The testing may help reduce technical problems, as  
380 well as misunderstanding of questions, or even improve the order of the questions to  
381 motivate participants to finish the survey. There are different methods for the testing  
382 phase that can be put to use [36,37]. Seeing the complexity of the topic, including new  
383 technology and a complex legal framework, and seeing the work of [34], we decided  
384 for focus groups as method for the pretesting. A focus group would made possible  
385 to understand people's perceptions and understandings in regard to the local energy  
386 trading scheme, which were the main questions in the survey. Therefore two focus  
387 groups took place as pretest, followed by the quantitative online survey.

#### 388 3.4.1. Focus groups

389 Focus groups are a suitable and relatively resource-saving qualitative survey in-  
390 strument to involve a limited number of citizens in a discourse process [38]. As Morgan  
391 [39] expressed, "the hallmark of focus groups is their explicit use of group interaction to  
392 produce data and insights that would be less accessible without the interaction found in  
393 a group." In this case, the focus groups served to pretest, more concretely improve, the  
394 online survey. Due to the COVID-19 pandemic, physical participatory events were not  
395 possible, so the focus groups were held online.

396 In the ENaQ participation process we understand there are different participation  
397 forms, from inward (only project partners) to outward (only external stakeholders)  
398 and hybrid (participants from both), for more details on participation process design  
399 in ENaQ see [9]. For the two focus groups we conducted one was within the inward  
400 participation format and one as outward participation. It is important to mention that  
401 ENaQ has a varied group of partners, as its consortium is multi-sectoral, and therefore  
402 inward participation still allows for a multi-perspective approach. Furthermore, both  
403 focus groups were moderated and accompanied by three further researchers who took  
404 part in taking notes and looking into the non-verbal communication of the group. The  
405 focus groups were also video recorded. The groups' size were decided based on research  
406 that stipulates that smaller groups are more productive and allow for a more equal  
407 participation [40].

408 The first group with only project partners (inward participation) took place with  
409 7 participants, all but two from different institutions and professional background (for  
410 example: IT, construction company, research institution) as well as a balanced number  
411 of women and men. After the first focus group, all input and feedback recollected was  
412 analysed and the survey was improved.

413 At this point a second focus group with people not directly related to the project  
414 (outward participation) took place. In this group we had 5 participants. Here there was  
415 also a mixture of age, sex, qualifications and professional background. The goal was for  
416 the focus group to be as varied as the survey respondents group we wanted to reach.

417 In both focus groups we first introduced the goal of the focus group: survey testing  
418 and improvement. For the focus group two we briefly introduced the project. Then we  
419 gave the participants time to answer the survey live, and took notes on the time it took to  
420 each of them for responding. We asked them to take notes on each item, when necessary,  
421 for example something that was not clear, that was too personal, technical issues, or any  
422 other comment they thought to be important. After each participant was finished, each  
423 of them shared the comments they wrote down, this allowed for an equal participation.

424 Finally we had time for an open discussion about the items which were commented on,  
425 as this was the goal of the focus group, to use the group interaction.

426 The focus groups offered a participation form from an early stage, improving the  
427 survey's design as explained in Section 3.4.2.

#### 428 3.4.2. Survey

429 The intense interaction and constructive feedback in the focus group was very  
430 relevant into the design and improvement of the survey. Through the focus groups we  
431 were able to:

- 432 • timely clarify questions,
- 433 • to eliminate redundancies,
- 434 • to include clarification of concepts or definitions where necessary,
- 435 • to make it more user-friendly,
- 436 • to reorganize questions to make it easier for the respondents to follow.

437 The group interaction was a very relevant aspect of this process, since it opened  
438 conversations and discussions allowing to have feedback from different perspectives,  
439 specially in terms of concepts and definitions it was important to consider how one  
440 word might be understood differently, and how to clarify it in the survey. Another main  
441 discussion point were the questions regarding values, which are used to determine the  
442 respondents' social milieu. In the discussion it was clear that this questions made some  
443 participants feel uncomfortable, and therefore a more clear text explaining the relevance  
444 and use of the questions was included, as well as the option to up out of this question  
445 section. Also a relevant feedback came in terms of technical issues, for example the tools  
446 to respond to the question that were selected.

447 In the end the result was a survey with 6 sections and a total of 40 items, with  
448 an approximately response time of 15 minutes. The survey included questions in  
449 regards to LEMs, as well as a proposal for an online App (cf. [32]) and questions to  
450 evaluate such. Finally demographic questions as well as value questions to determine  
451 the respondents' social milieu were included. The survey as conducted online from  
452 29.03.2021 to 31.08.2021. The results of the survey will be analysed and be part of a  
453 future paper.

#### 454 3.5. Local Market Setup

455 The design of the local market depends on the local situation regarding the number  
456 of participants, the participant structure and the anticipated goals. In ENaQ, we have  
457 around 140 possibly participating households and a very limited number of energy gen-  
458 erating participants of probably below five. Due to regulatory requirements (cf. Section  
459 3.3), a district aggregator is part of the local market as a clearing house.

##### 460 3.5.1. Clearing Algorithm

461 As the basic mechanism for the local market, an auction based clearing method  
462 with limit orders both from the sellers and buyers was chosen. This basic mechanism  
463 allows both the buyers and sellers to actively participate in the market and express their  
464 value for feature of the energy such as local generation and low carbon emissions. The  
465 limit orders also give the participants the possibility to limit the prices they pay for the  
466 electricity, even though this constraint has been softened a bit, as is described in the  
467 following.

468 The mechanism is depicted in Figure 3 and consists of four parts. The sellers  
469 table with the limit orders is shown on the left and the buyers table on the right. The  
470 matching is depicted by the connecting lines between the orders in the tables. The  
471 pricing algorithm calculates the price of each sell. The calculation is written next to the  
472 respective matching line.

473 In our market framework, parts of the clearing algorithm are interchangeable. The  
474 matching algorithm can be changed, for example by changing the sorting of the bid-

475 tables. The pricing algorithm can be changed so that the price calculation and with that  
476 also the incentives for the buyers and sellers change. In the following, the standard  
477 components as we intent them in a first version are presented.

478 On the sellers side, the bids are ordered ascending by the limit (`min_price`), on the  
479 buyers side descending by the limit (`max_price`). Additionally, each buyer and seller  
480 states the amount of energy that needs to be bought or sold.

481 The matching algorithm iterates through all buyers and sellers from the top to  
482 bottom and matches them accordingly. This process is done once per cleared order book,  
483 so for example once every 15 minutes. Due to the sorting, the algorithm starts with the  
484 lowest sell price and the highest buy price and iterates down to the highest sell price and  
485 lowest buy price. This can be seen in Figure 3. A buyer can buy from multiple sellers  
486 and a seller can sell to multiple buyers. The matching algorithm has an effect on the  
487 market behavior. For a market where local energy is scarce, buyers with high limits have  
488 a higher chance to get delivered with local energy. This may be beneficial to get lower  
489 prices compared to the energy from the grid and may also be an ideological incentive to  
490 support the local generation or to get green energy.

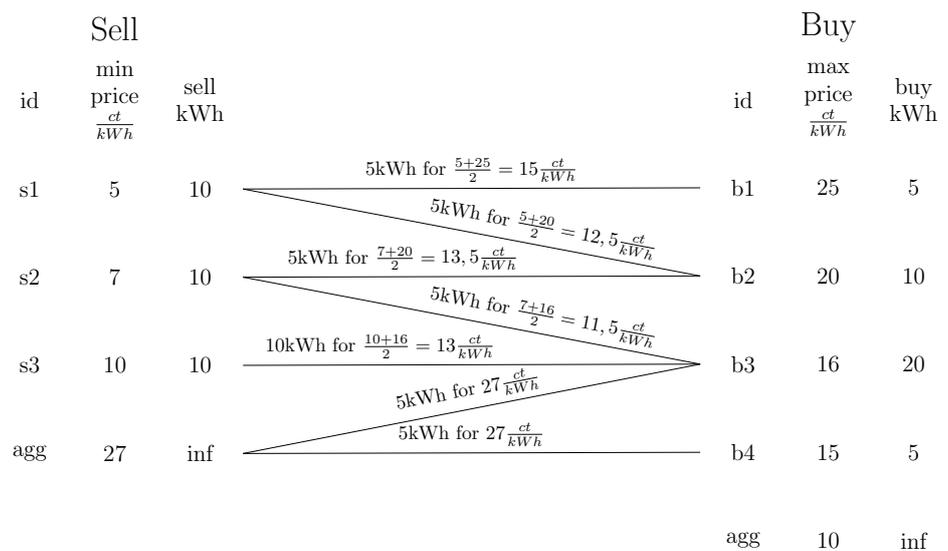
491 The pricing algorithm calculates the price for each transaction. In the current  
492 version, the price for a matching buyer-seller-pair is the mean from the two limits.  
493 This has some incentivizing side-effects: a seller which offers for a lower price may  
494 be matched to the buyer with the highest price, leading to a higher price for the seller.  
495 The buyer on the other hand has the incentive to bid a higher price to be matched  
496 to the cheapest seller, resulting in a lower price for the buyer. The external markets,  
497 here represented by the aggregator *agg*, are an exception in the price calculation. If the  
498 external market is involved, the price from the external market (seller or buyer) is used  
499 and no average is calculated. This can be seen in the lower two transactions where the  
500 price is 27 cents per kWh. The additional service that the external market is offering to  
501 justify the fixed price is the theoretically unlimited amount of energy that they can buy  
502 or sell. The price offered here can also be the margin for the aggregator running the local  
503 energy grid: the aggregator buys and sells the surplus or missing energy at the national  
504 energy market, possibly to a better price than offered in the local market. The pricing  
505 algorithm is a possible candidate to change the incentive of the market, wherefore it is  
506 interchangeable in our market framework implementation. For example, it would be  
507 possible to always use the price from the seller, not the average price from the bids from  
508 the seller and buyer of a match.

### 509 3.5.2. Including Controllable Devices

510 The basic market schema presented above has some limitations. Mainly, controllable  
511 devices such as Energy Storage Systems (ESSs) are not taken into account. Those have  
512 the intention to only charge if there is surplus electricity from the local generation. In  
513 the current market design, they could not limit their supply to the local generation or  
514 their sells to local consumers. We address these issues with an extended version of the  
515 local market, which is depicted in Figure 4.

516 The first addition is the *optional* field. The field is used by controllable devices which  
517 can buy or sell a certain amount of energy, but which also can decide freely if they will  
518 do that. This is opposed by household consumers, which cannot simply control their  
519 consumption, or solar systems, which cannot control their generation. This is also the  
520 reason for the split of the auction into a planning (*ex ante*) and a billing step (*ex post*).

521 The planning step is done before the actual consumption and generation happens,  
522 for example just before a new 15-minute window. In this step, the bids with the limits  
523 are made by the participants. The prices cannot be changed afterwards. Additionally,  
524 the forecasted energy amounts are added in this step. The forecasts have to be delivered  
525 by the market participants themselves, e.g. through forecasting algorithms that take  
526 historical data and weather forecasts into account. Nevertheless, with this two step  
527 approach, it is acknowledged that the consumption and generation cannot be predicted



**Figure 3.** Clearing mechanism for limit orders. The matching is done from top to bottom. Starting with the first buyer *b1*, the demand of 5 kWh is met by the first seller *s1*, which then has 5 kWh left to sell. This one is used for the demand of the second buyer *b2* and so on.

528 with a 100% accuracy. The optional consumers and generators, here *battery 1*, add  
 529 themselves to the market with the maximum amount of energy they want to buy or sell.  
 530 Then, the market clearing algorithm is run on the available orders with the forecasted  
 531 data. The result in this example is that the battery currently cannot sell anything into the  
 532 local market, but it can buy 5 kWh. It would have bought at maximum 10 kWh, but only  
 533 5 kWh where available locally. Therefore, the battery will only consume these 5 kWh in  
 534 the time slot where this market clearing run is for. In case that a battery with buys and  
 535 sells energy, the amounts are balanced.

536 The billing step is done after the respective time slot, hence, after the actual genera-  
 537 tion and consumption has happened. As can be seen in Figure 4, the actual generation  
 538 and consumption differs from the plan. Now, the clearing algorithm is run again and the  
 539 actual deliveries are calculated. The battery has planned to consume 5 kWh, which is not  
 540 changeable during the time period. Unfortunately, the locally available surplus energy  
 541 has been less than expected, wherefore the battery consumes 1 kWh from the grid. It can  
 542 be seen here that a good forecast helps for a better management of the devices and that  
 543 the planning step is helpful to have an estimate about the next time slot.

### 544 3.5.3. Discussion

545 The presented market design based on limit orders has the goal to integrate con-  
 546 trollable energy devices such as batteries, non-controllable generation such as PV, non-  
 547 controllable consumption from private households, and the energy grid. The planning  
 548 step in the two step approach makes it possible to plan the next time slot for control-  
 549 lable devices, while the billing step takes into account that the actual generation and  
 550 consumption can differ from the plan.

551 The deviation from the plan is expected to be lower when the forecast is shorter,  
 552 i. e., when the time slot for which the market is cleared is smaller. Hence, it could be  
 553 useful to reduce the time slot size from, for example, 15 min to 1 min. Nevertheless,  
 554 the downsides are a higher communication overhead and shorter times for the energy  
 555 systems. For example, a CHP would preferably run for a longer period of time instead  
 556 of being turned on and off every few minutes or even seconds. The effects of different  
 557 sizes for the time slot needs to be analyzed.

### Step 1 (ex ante, planning): fix bids and energy amount for controllable devices

Sell					Buy				
id	min price [ $\frac{ct}{kWh}$ ]	sell plan [kWh]	sell real [kWh]	optional	id	min price [ $\frac{ct}{kWh}$ ]	sell plan [kWh]	sell real [kWh]	optional
s1	5	10	?	No	b1	25	5	?	No
s2	7	10	?	No	b2	20	10	?	No
s3	10	10	?	No	b3	16	20	?	No
battery 1	15	$max = 10$	$? \rightarrow plan = 0$	Yes	battery 1	10	$max = 10$	$? \rightarrow plan = 5$	Yes
agg	27	inf	?	Yes	agg	10	inf	?	Yes

Annotations for Step 1:

- 5kWh for  $\frac{5+25}{2} = 15 \frac{ct}{kWh}$  (between s1 and b1)
- 5kWh for  $\frac{5+20}{2} = 12,5 \frac{ct}{kWh}$  (between s1 and b2)
- 5kWh for  $\frac{7+20}{2} = 13,5 \frac{ct}{kWh}$  (between s2 and b2)
- 5kWh for  $\frac{7+16}{2} = 11,5 \frac{ct}{kWh}$  (between s2 and b3)
- 5kWh for  $\frac{10+16}{2} = 13 \frac{ct}{kWh}$  (between s3 and b3)
- 5kWh for  $\frac{10+10}{2} = 10 \frac{ct}{kWh}$  (between s3 and battery 1)

### Step 2 (ex post, billing): bill actual consumption

Sell					Buy				
id	min price [ $\frac{ct}{kWh}$ ]	sell plan [kWh]	sell real [kWh]	optional	id	min price [ $\frac{ct}{kWh}$ ]	sell plan [kWh]	sell real [kWh]	optional
s1	5	10	10	No	b1	25	5	10	No
s2	7	10	7	No	b2	20	10	5	No
s3	10	10	10	No	b3	16	20	8	No
battery 1	15	$max = 10$	$plan = 0$	Yes	battery 1	10	$max = 10$	$plan = 5$	Yes
agg	27	inf	1	Yes	agg	10	inf	0	Yes

Annotations for Step 2:

- 10kWh for  $\frac{5+25}{2} = 15 \frac{ct}{kWh}$  (between s1 and b1)
- 5kWh for  $\frac{7+20}{2} = 13,5 \frac{ct}{kWh}$  (between s2 and b2)
- 2kWh for  $\frac{7+16}{2} = 11,5 \frac{ct}{kWh}$  (between s2 and b3)
- 6kWh for  $\frac{10+16}{2} = 13 \frac{ct}{kWh}$  (between s3 and b3)
- 4kWh for  $\frac{10+10}{2} = 10 \frac{ct}{kWh}$  (between s3 and battery 1)
- 1kWh for 15ct (between battery 1 and agg)

**Figure 4.** Clearing mechanism for limit orders with controllable systems and possibility for divergent consumption and generation.

558 The described pricing algorithm matches the highest buyers bid with the lowest  
559 sellers price and takes the average of the two prices. This has the effect that the buyers  
560 have the incentive to bid higher prices to be matched with a cheaper seller and the  
561 sellers have the incentive to bid lower prices to be matched with a more paying buyer.  
562 Nevertheless, the market consequences of this pricing algorithm have not been investi-  
563 gated further, i. e., simulations and real world tests are an open issue for further research.  
564 Similarly, some shortcoming would need to be investigated, e.g., how to handle the case  
565 that the same battery wins bids both in the selling and buying market.

### 566 3.6. Conclusion

567 In this chapter, we have presented a realistic and comprehensive approach to estab-  
568 lishing LEMs under the current German framework for a residential district. Motivated  
569 by the efficient use of DERs, the higher market power on national markets and the par-  
570 ticipation of residents, we presented our design process with the participation of citizens  
571 including preliminary results. Building on that we presented a market mechanism based  
572 on limit orders. It shall enable LEMs to integrate local consumers, local DERs such as  
573 PV, local ESSs and the grid in the market. The market implementation allows to change  
574 the matching and pricing algorithm. The effects of the algorithms have to be researched  
575 with simulations and real-world tests.

## 576 4. Long-term competitiveness of combined heat and power

577 In an integrated energy supply system, heat generation devices play a big role in  
578 the electricity supply. This can be on both, the supply or the demand side, depending  
579 on whether a CHP or a Heat Pump (HP) is used. Thus, it is advised to spend special  
580 attention to these participants of the energy market.

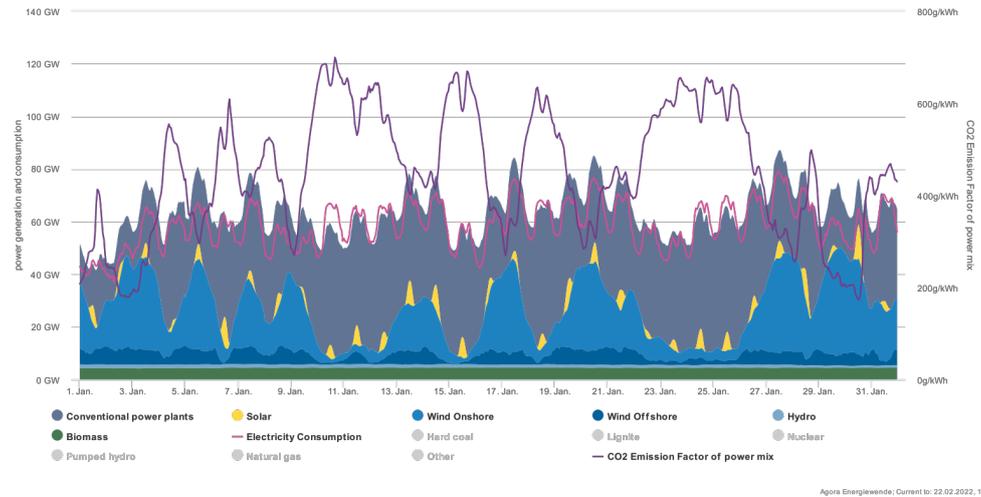
581 Especially heating systems are replaced infrequently. In Germany, about 40 % of the  
582 heating system were installed more than 20 years ago [41]. According to the applicable  
583 norm [42], boilers, HP, or CHPs have depreciation periods of 15 to 20 years. Thus, not  
584 only current conditions play a role but foreseeable changes should be considered.

585 Energy costs are highly influenced by political decisions. On the one hand, the  
586 energy sector is highly subsidised [43]. On the other hand acquisition, distribution and  
587 margin only account for a fraction of the energy prices for households. I.e. in Germany,  
588 half of the price for natural gas is related to these market-related factors (25 % taxes, 25 %  
589 fees), while it's only 22 % for electricity (23 % taxes, 30 % fees, 25 % surcharges) [44]. So,  
590 in this chapter the focus is on the mid to long term competitiveness in terms of CO<sub>2</sub>  
591 emissions.

592 Coupling of the electricity and the heating sector, does not only allow for decar-  
593 bonising space heating but does also provide flexible demand to match renewable  
594 production of electricity [46–48]. To fully use this potential, an energy system has to  
595 either use renewable electricity when it is available or alternatively produce electricity  
596 that complements the production of (other) renewable sources. Figure 5 displays real-  
597 world data for electricity demand and production for January 2020, as well as resulting  
598 specific emissions. Within that time frame, the CO<sub>2</sub> intensity of grid emission varied  
599 between about 200 g/kWh and 700 g/kWh. Concluding, it is not sufficient to assume  
600 a gradually decreasing emission factor for electricity; instead time-varying emission  
601 factors are needed.

### 602 4.1. Grid emission model

603 A modelling approach for this kind of data combines information about of power  
604 plants with historic weather data. The software DeFLex [49,50] offers such kind of  
605 models of the German energy supply. By scaling the installed capacities of the power  
606 plants, time series for both, market clearance prices and specific emissions, are be created  
607 for various scenarios. For the sake of simplicity, in this paper the focus is on scaling the  
608 installation of wind power plants.



**Figure 5.** Example time series for electricity production and demand as well as resulting emissions attributed to grid electricity [45].

609 There are some simplifying assumptions made for the model, i.e. times for ramp-  
 610 ing up or down thermal plants are neglected, meaning negative electricity prices are  
 611 abundant and zero emissions are reached if the supply of renewable sources is sufficient.  
 612 While this does not correctly reproduce all details of the quantities of interest, the errors  
 613 of the DeFLex models are mostly systematic [51]. As this means all time series are  
 614 effected in the same way, we consider it capable to investigate trends and long-term  
 615 changes. The present study focuses on the addition of wind power to the national grid.  
 616 We consider two scenarios, both differ in the installed capacity of onshore wind farms.  
 617 This choice has been made as we assume the impact greater when compared to PV,  
 618 because heat demand is typically higher when sun is shining less. The value of 55 GW  
 619 refers to the capacity currently installed [52], while 105 GW are a projected for 2030 [53]  
 620 or 2035 [54].

#### 621 4.2. Ecologic competitiveness of operation

In the following, we investigate the long-term competitiveness of CHPs in systems where also a HP is available. For the latter, the Emission Factor (EF) depends on the (time-dependent) Coefficient Of Performance (COP) and the EF of the grid electricity

$$EF_{th,HP}(t) = EF_{el}(t) / COP(t). \quad (2)$$

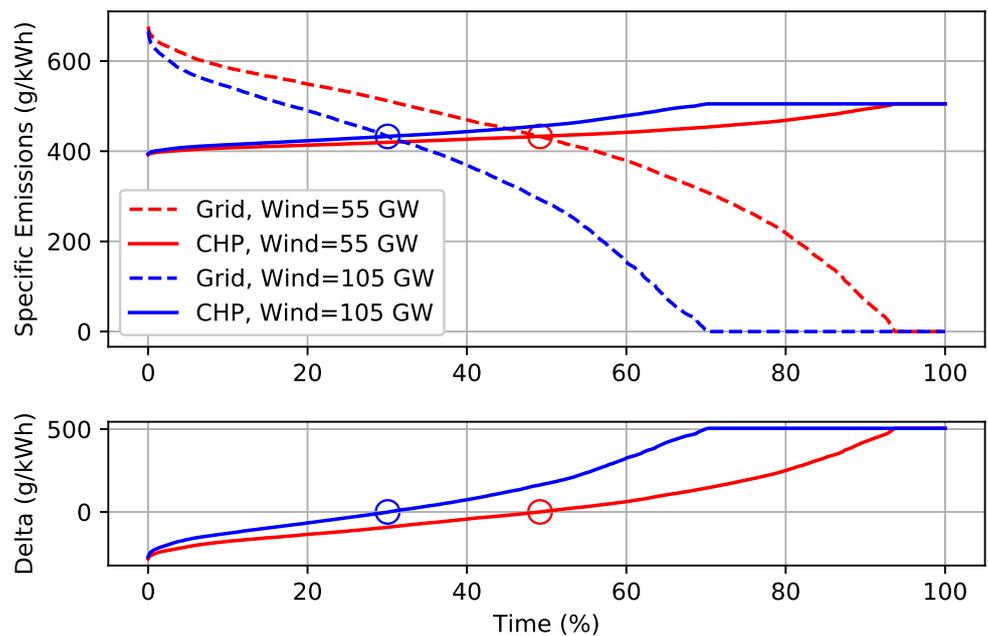
For the CHP, there are various methods that can be used to attribute emissions and costs to the produced electricity and heat [55]. As the breakdown is actually less important than the total, we subtract avoided emissions in the heat sector

$$EF_{el,CHP}(t) = EF_{fuel} / \eta_{el} - \eta_{th} \times EF_{th,HP}(t), \quad (3)$$

where  $\eta_{el}$  and  $\eta_{th}$  denote the electrical and thermal efficiencies, respectively. Note that this way the calculation of total emissions just for the electricity sector is offset. In particular, the resulting emissions can be negative. Thus, the heat sector has to be considered to get meaningful absolute values. Combining Eqs. (2) and (3), yields

$$EF_{el,CHP}(t) = \frac{EF_{fuel}}{\eta_{el}} - \eta_{th} \times \frac{EF_{el}(t)}{COP(t)}. \quad (4)$$

622 The simulation should be understood as a prove of concept and therefore rough  
 623 estimations for efficiencies and COP are taken. The COP is assumed to be constant at  
 624 3. This corresponds to a ground-source heat pump that provides a flow temperature of

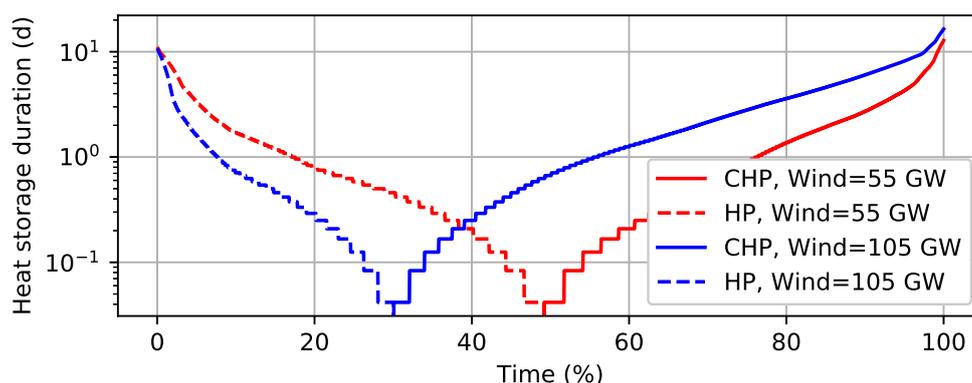


**Figure 6.** Duration curves (100 % corresponds to one year) of the emission factors of electricity from both, CHP and grid, for two scenarios of nation-wide installed wind capacity (upper panel) and difference of the two duration curves (lower panel).

625 about 50 °C, making it a conservative estimate. For the **CHP**, we set  $\eta_{el} = 0.4$ ,  $\eta_{th} = 0.5$ ,  
 626 and  $EF_{fuel} = 202$  g/kWh. The latter is assuming natural gas.

627 Figure 6 shows duration curves for the specific emissions of the grid electricity and  
 628 the **CHP** calculated according to Eq. (4) for the two scenarios for the installed wind farm  
 629 capacities. It can be seen that under current conditions (55 GW), the **CHP** is competitive  
 630 approximately half of the time (the delta is less then zero in the lower panel in Figure 6).  
 631 For the almost doubled capacity (105 GW), this time reduces to approximately 30 %.

632 If there is no option to store electricity or to reduce demand and to reduce global  
 633 emissions that way, it is beneficial if a **CHP** can produce electricity when it is competitive.  
 634 While these points in time where the **CHP** is competitive should become fewer with an  
 635 increasing share of renewable energies, they do not stop to exist and operation strategies  
 636 need to be developed in order to reduce emissions. At other times, heat has to be either  
 637 produced using alternative techniques or provided by a storage. To estimate required  
 638 capacity of a complementing heat storage, the duration of non-competitive times is  
 639 relevant. A possible measure is the time since the last hour the **CHP** was competitive.  
 640 Although one hour might not be enough to fill a storage, this quantity can provide an  
 641 estimate – especially as the typical period is longer than this minimal time. It is displayed  
 642 in Figure 7. It can be seen that under current conditions of installed wind capacities  
 643 (55 GW) a storage period of one day is sufficient to cover approximate 75 % of the time.  
 644 For the 105 GW scenario, the one-day storage can increase the time possibly covered by  
 645 **CHP** heat increases from 30 % to 45 %. At other times, a different heat source has to be  
 646 available if the operation of the **CHP** should not increase the local specific emissions  
 647 of the electricity. To supply all heat by the **CHP**, significantly more then a week has to  
 648 be buffered, rarely. On the other hand, one day of storage capacity combined with a  
 649 **HP** is sufficient to perform load shifting so that electricity is only consumed when grid  
 650 electricity has less specific emissions than the electricity provided by the **CHP** in 82 % of  
 651 time. For the increasing availability of wind power, this value increases to 92 %.



**Figure 7.** Duration curves of the time since the last moment the **CHP** was competitive. (Steps are due to hourly time resolution.)

#### 652 4.3. Conclusion

653 It was shown that **CHPs** can find points in time for the production of electricity  
 654 when they have emissions competitive to the upstream network, provided that there  
 655 is demand for heat. In this scenario that uses a flow temperature of 50 °C which is not  
 656 optimal for heat pumps, running an existing **CHP** is an ecologic option about half of the  
 657 time when compared to the current German electricity mix. However, this result also  
 658 implies that a **HP** is the better option if a single heat source is desired. The usage of this  
 659 competitive time can be significantly expanded by a heat storage. In the investigated  
 660 scenario, competitiveness increases to 75 % of the time and remains at 45 % of the time  
 661 even if the capacity of installed wind turbines in Germany is doubled.

662 As the **CHP** has to be complemented by a second heat source to limit the size  
 663 of the required heat storage, they also have to compete with this second heat source.  
 664 So, the question remains for how long **CHPs** can remain profitable. Provided that the  
 665 **CHP** is already in place, as long as the revenues from selling electricity cover fuel and  
 666 maintenance costs. In a **LEM** this is easier to achieve.

667 It is ecological beneficial to operate **CHPs** as long as there is residual electric load.  
 668 In this sense, load shifting is a favorable, yet more challenging solution. Traditionally,  
 669 for residential demand the focus is on automated control of smart devices. Especially in  
 670 a local energy community, empowering informed individual behavior can be considered  
 671 as an additional option.

#### 672 5. Using Electricity Smartly with the Energy Signal Light

673 This chapter describes the idea and our prototype of an Energy Signal Light (**ESL**).  
 674 The purpose of the Energy Signal Light is to indicate to the neighborhood resident when  
 675 it is beneficial to use electrical energy. For example, it is favorable during the periods  
 676 when a lot of renewable electricity is produced in the neighborhood.

677 The Energy Signal Light is an energy feedback system. With energy feedback,  
 678 information about personal energy consumption and potentially other energy data  
 679 is provided to the residential consumer to effect a change in the consumer behavior.  
 680 Energy feedback can increase the awareness of energy consumption and can lead to  
 681 changes in consumption behavior [56]. Vine et al. [57] states that energy savings of 5 %  
 682 to 20 % can be achieved by visualizing energy consumption using smart meters and  
 683 digital displays. Many previous studies in the field of energy feedback investigated  
 684 the effect on energy savings, especially the electrical one [57–59]. In extension, the goal  
 685 of the Energy Signal Light is to optimize the time of personal energy consumption  
 686 with the help of load shifting. This way of conscious and well-timed consumption is  
 687 intended to counteract the weakness of some renewable energy sources, such as solar-  
 688 or wind power, namely weather-related fluctuation. The conventional solution would

689 be electricity storage, which has disadvantages of requiring energy and materials to  
690 produce, operate and recycle, besides having high investment and operational costs at  
691 the moment. Load shifting with the help of the Energy Signal Light comes to assistance  
692 in this regard. By load shifting, part of the electrical energy can be used directly without  
693 conversion losses of the electrical storage. Due to the adapted and increased direct  
694 consumption of electrical energy at times of high feed-in of renewable energy, smaller  
695 amounts of energy need to be stored. Lower stored energy amounts allow the electrical  
696 storage to be dimensioned smaller, thus saving resources and energy. The Energy  
697 Signal Light is a lamp that can turn green or red. At optimal consumption times,  
698 the Energy Signal Light turns green, signaling to residents the timing of conscious  
699 and smart energy consumption; for example, favorable time to switch on the washing  
700 machine or dishwasher or charge the battery of the e-bike during these times. In this  
701 way, every resident with a conscious electricity behavior can physically increase their  
702 renewable energy share of electricity consumption and actively support the energy  
703 transition. The idea of the Energy Signal Light has already been tested in field trials  
704 in the Franklin district in Mannheim (Germany) [60,61]. A similar, but purely digital  
705 approach to load shifting by using forecasts for today and tomorrow is taken by the  
706 Peakpick homepage [62].

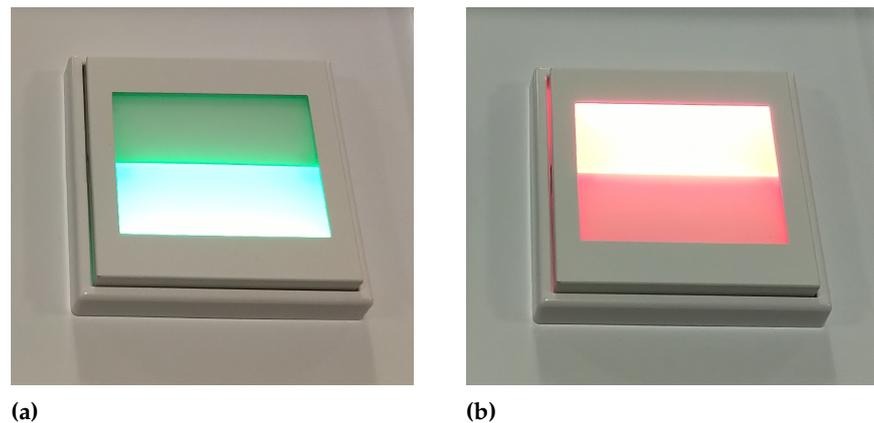
707 We conducted an online survey to gather opinions on the Energy Signal Light.  
708 For this purpose, we used a questionnaire with 26 questions on attitudes towards  
709 energy issues, the Energy Signal Light, another demonstrator of the project, as well  
710 as demographic and other information of the participants. The 250 respondents were  
711 not familiar with the Energy Signal Light before the survey. The survey concluded the  
712 following:

- 713 • 86 % of respondents do not yet use systems to control their energy consumption,  
714 such as electricity meters, smart plugs, smart sockets, or apps.
- 715 • 75 % of respondents can imagine using an Energy Signal Light in their everyday  
716 life to optimize their energy consumption.
- 717 • 30 % of respondents feel the hallway is an ideal location for the energy light, while  
718 26 % of respondents have no preference about location.
- 719 • 76 % of respondents consider a local, green surplus power for display option as  
720 helpful. Low-carbon electricity was considered helpful by 65 %, low-cost electricity  
721 by 64 %, and a comprehensive algorithm by 64 % of respondents.
- 722 • 73 % of respondents would like to decide for themselves which of the display op-  
723 tions is shown to them.

724  
725 These lights are to be installed in every residential unit in the ENaQ neighborhood  
726 called Helleheide. Our current Energy Signal Light demonstrator consists of four com-  
727 ponents: a lamp, a frame, a power supply, and a remotely controllable power switch  
728 (namely, the Shelly 2.5<sup>1</sup>). The demonstrator has the dimensions of a conventional light  
729 switch and fits together with the communication device into a flush-mounting box. To  
730 switch states (turning the light red or green), the Energy Signal Light relies on external  
731 information from the DEMS, which publishes any changes using a message broker. The  
732 two main goals of the DEMS are to monitor and intelligently control all energy compo-  
733 nents in the neighborhood. The controllable power switch of the Energy Signal Light  
734 gets the required information from the message broker and switches the corresponding  
735 lamps on and off.

736 Similar to the use in apartments in multi-party buildings, it would also be possible  
737 to install the Energy Signal Lamp in a single-family house with its PV system. In this  
738 case, the energy light could turn green when the PV system produces more electricity  
739 than is consumed in the house. This display option would help the homeowner increase  
740 the self-consumption of own PV generation and thus reduce electricity costs.

<sup>1</sup> <https://shelly.cloud/products/shelly-25-smart-home-automation-relay/>



**Figure 8.** Demonstrator of an Energy Signal Light: (a) Energy Signal Light is green. (b) Energy Signal Light glows red.

741 Besides the good conscience of making something count for the energy transition  
742 and the environment, a dynamic electricity tariff can be an additional motivation for the  
743 user [9,63]. With a dynamic tariff, the electricity price fluctuates, for example, depending  
744 on the stock exchange price or during peak hours of high consumption. Since the stock  
745 exchange price is often low at times of high regenerative generation, the resident can  
746 save electricity costs by conscious consumption behavior and load shifting, in case of  
747 electrical tariff with flexible prices.

## 748 6. Conclusions and Outlook

749 Concluding all over, we have presented a European/German market model where  
750 LEMs under the current German framework for a residential Neighborhood are linked  
751 to. Operating a CHP system with sufficient storage allows operation of CHPs at reduced  
752 emissions, even when wind power increased in the upstream network. Finally we intro-  
753 duced the concept of Energy Signal Lights, which are used as an energy feedback system  
754 for residential consumers. More detailed conclusions can be found in the appropriate  
755 chapters.

756 As the ENaQ project proceeds, the concepts will be implemented and tested during  
757 operation of the Helleheide district. In the future, the results presented need to be com-  
758 pared with those of other research approaches and require qualitative and quantitative  
759 evaluation.

760 The presented electricity market model, based on EPEX, is a tool which requires  
761 low computing capacities. The method created for it is subject to the requirement of  
762 deterministic generation and the basis of historical data. This limitation suggests an  
763 effect on the quality. Quantitative and qualitative investigation in comparison with  
764 alternative approaches is needed to evaluate this conjecture.

765 The European Union intends to promote the participation of the citizens on energy  
766 markets and decentralised energy production. Seen from the current point of view, it is  
767 not clear if LEMs will be implemented all over Europe. Therefore LEMs need to be seen  
768 as one possible embodiment of the European Unions goals. Therefore, the proposed  
769 approaches of this paper need to be seen under that perspective as well. Furthermore,  
770 as mentioned before, the results of the survey will be analysed and introduced in a  
771 future research paper, in order to better understand the citizen's interest in their own  
772 participation in energy markets.

773 With increased availability of renewable sources, the role of a integrated heat supply  
774 in the LEMs will probably shift from generation (CHP) to consumption (HP) of electricity.  
775 Sufficient heat storage capacity, however, facilitates timed operation, and thus increases  
776 the heat demand that can still be covered by a CHP in an ecologically favorable way.

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777 Upcoming research should also investigate to which extent the shift will be accelerated  
778 by renewable energy storage such as batteries or power to gas.

779 In the near future, the previous Energy Signal Light demonstrator is to be further  
780 developed and improved in three points: First, the Energy Signal Light should commu-  
781 nicate via the Long Range Wide Area Network (shortly LoRaWAN) of the neighborhood  
782 to be independent of the Wi-Fi of the residents. Second, the design and usability shall be  
783 evaluated and improved in a co-design workshop and study with citizens. Third, each  
784 resident should have an opportunity to choose which display option their Energy Signal  
785 Light will show. Nevertheless, there are still some research questions which need to be  
786 explored such as: How strong is the effect of the Energy Signal Light on the residents'  
787 behavior? Which display option has the strongest effect? Is additional information such  
788 as a forecast for the next day useful?

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## 810 Abbreviations

811 The following abbreviations are used in this manuscript:

812

813	<b>C-MG</b>	community-based microgrid
814	<b>CEC</b>	Citizen Energy Communities
815	<b>CHP</b>	Combined Heat and Power Plant
816	<b>COP</b>	Coefficient Of Performance
817	<b>DEMS</b>	district energy management system
818	<b>DER</b>	Distributed Energy Resource
819	<b>EEX</b>	European Energy Exchange
820	<b>EF</b>	Emission Factor
821	<b>ENaQ</b>	Energetic Neighborhood Quarter (German: <u>E</u> nergetisches <u>N</u> achbarschafts <u>Q</u> uartier)
822	<b>EPEX</b>	European Power Exchange
823	<b>ESL</b>	Energy Signal Light
824	<b>ESS</b>	Energy Storage System
825	<b>HP</b>	Heat Pump
826	<b>LEM</b>	Local Energy Market
827	<b>MCP</b>	Market-Clearing-Price
828	<b>OTC</b>	Over-The-Counter
829	<b>PHELIX</b>	Physical Electricity Index
830	<b>PV</b>	photovoltaics
831	<b>SGAM</b>	Smart Grid Architecture Model
832	<b>SIDC</b>	Single Intraday Coupling
833	<b>WAP</b>	Weighted-Averager-Price

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