Effects of ICT-Enabled Flexible Energy Consumption on the Reduction of CO_2 Emissions in Buildings

Findings and outlook from an explorative case study in Germany

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ABSTRACT

Renewable electricity from wind and solar is on the rise and, consequently, flexible energy consumption and the conversion of electricity into heat or mobility are becoming valid options for integrating fluctuating energy production into the grid. This is a particular challenge for the building sector since it has a high energy demand but often steady and predictable consumption patterns. The authors present results from a case study in Germany in which flexible consumption of energy and the conversion of renewable electricity into heat were tested and evaluated in a smart residential neighborhood. A prerequisite for the study is an interoperable ICT infrastructure that connects smart buildings to flexible energy markets. The case study allows conclusions to be drawn about the technical applicability and economic viability of these solutions as well as about the CO_2 emissions saved as a result of flexible energy consumption. Finally, a brief analysis of a large-scale application of flexibility in the building sector is included.

CCS Concepts

• **Hardware~Power and energy~Energy generation and storage~**Renewable energy**;**

KEYWORDS

ICT-enabled energy consumption, reduction of CO_2 emissions, building sector

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1 INTRODUCTION

European climate policy sets binding climate targets for its member states to reduce greenhouse gas emissions and become carbon neutral by 2050. In the scenarios toward carbon neutrality, the use of renewable energy and energy efficiency in the most important sectors of consumption (residential, transport, industry, etc.) play a major role [10]. But the more imminent emission targets for 2030 are also ambitious. Greenhouse gas (GHG) emissions should be reduced across all sectors by 40% and the share of renewable energies increased to 27% of the total energy supply [9].

The shift towards higher shares of renewable energy not only requires a rollout of these technologies but also a change in the distribution and consumption patterns of the energy. Naturally more volatile than fossil sources, the integration of renewable energy sources, for instance, wind and solar energy, into the electric grid requires storage and flexible consumption (also referred to as flexibility)[1]. Flexibility in a changing energy system has a twofold value. First, it allows us to convert energy in times of high grid loads (e.g. excessive power from wind or solar) into thermal energy or storage. Second, in times of a lower grid load, electricity can be fed back from local production (e.g., combined heat and power (CHP) plant or solar home systems) or storage (e.g., batteries) in buildings to stabilize the grid. Thus, fossil energy consumption can be reduced and CO_2 emissions saved [10].

Residential buildings account for 40% of total energy consumption in the EU, with a high share being used for heating and hot water production [8]. Not only do buildings consume energy but they also provide a high potential for flexibility. However, this potential seems to be difficult to release due to steady and predictable consumption patterns that mainly depend on the building type, the behavior of the residents, weather, season, etc.

ICT and smart building technologies can facilitate flexible consumption by optimizing sources and sinks for heat and electricity and by balancing different options such as own production, storage or the conversion of energy (e.g. electricity into heat) [2], [1]. The present paper will evaluate experiences from a research project and case study that realized flexibility in a residential neighborhood using ICT applications to optimize energy consumption and converting renewable electricity into heat (power-to-heat). The article will outline:

- the ICT infrastructure, technology, and standards necessary for implementation in buildings;
- the interfaces to an energy trading company that optimizes volatile portfolios and offers prices for flexible consumption;

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[1] “Flexibility refers to the ability of elements in the energy system to react actively to an external signal that reflects the variability of power generation and consumption with a change in performance”, see also [16] (p. 11).

- an assessment of the CO_2 reduction potentials from flexible energy in the neighborhood;

and finally, it will also draw conclusions on the broader applicability of the technology.

2 FLEXIBILITY AND ICT-ENABLED ENERGY CONSUMPTION IN THE BUILDING SECTOR

2.1 Flexible energy production and changing consumption patterns

Current scientific literature cites three major reasons for an increasing variability in energy production from renewable sources: Power sources and demand is changing, renewable sources and power supply differ, depending on the weather and seasons (e.g. more solar energy in summer and at daytime, more wind energy in spring and fall) [6]. Time and location of the feed-in of renewable energy into the grid varies and requires accurate weather and climate forecasts (e.g. precise time and location of landfall) [13].

Even if predictions are accurate, the location of the feed-in and the demand site of energy can be completely contradictory (e.g. high wind generation at coasts vs. consumption in urban areas) [23]. Not only energy production is becoming more volatile, however. While in the past energy and, in particular, electricity consumption in buildings followed relatively predictable standard load profiles, this is now changing for the following reasons:

Consumption patterns in buildings and production change due to new technologies such as efficient appliances and lighting, solar home systems, electric vehicles, or home battery systems. These change consumption patterns and make predictions more difficult (e.g. charging of electric vehicles, own production, and consumption of electricity from solar home systems) [10].

Buildings and their residents convert from being consumers to prosumers[2] of energy. With increasing transparency and technological options, households are able to take over the roles of both producers and consumers of energy and become amenable to more flexible behavior [18].

Finally, the energy market reacts to the changes in production and consumption by offering flexible and load-based prices or similar incentives to meet and control consumption behavior [20].

The aforementioned changes in energy production and consumption present challenges for optimization and distribution at different levels of the energy system (balanced transmission and distribution grid, local bottlenecks, etc.). They also result in questions like whether measures such as grid expansion, (battery) storage systems, demand side management, or flexibility are economically feasible [13]. At present, the demand for flexibility is mostly met by larger power plants (in the MW range). Market access for smaller (individual) flexibilities from the building sector is therefore difficult to realize. However, in particular the building sector with its decentralized structures and existing energy producing units (e.g., CHP plants) or sinks (e.g., warm water buffer tanks) can provide such flexibilities.

These decentralized smaller and medium-sized flexibilities can be of high value for grid operators and markets if made accessible for real-time optimization and grid balancing purposes through ICT applications that connect these units or plants at low costs [15].

2.2 ICT-enabled infrastructures for flexibility from buildings: policies, standards, and technology

Buildings are recognized as a major field of action for carbon neutrality and smart interconnected ICT applications will play an important role in the transition. The European Union addresses this objective in its Energy Performance of Buildings Directive (EPBD), where it emphasizes the necessity of managing the energy demand of buildings and the application of ICT and smart technologies with the aim of securing the efficient operation of buildings [11].

The EPBD states (see Article 8): “System requirements shall be set for new, replacement and upgrading of technical building systems and shall be applied in so far as they are technically, economically and functionally feasible.”[11].

In order to assess intelligent infrastructures in buildings and the energy sector, the European Commission also introduced the Smart Readiness Indicator (SRI) that aims at rating “the capability of buildings (or building units) to adapt their operation to the needs of the occupant, (...) optimizing energy efficiency and overall performance, and to adapt their operation in reaction to signals from the grid (energy flexibility).” [3] Although implementing the SRI is not mandatory for member states, its introduction is a catalyst for creating smart building infrastructures and integrating them into the changing energy system.

From an application perspective, technologies and use cases for flexibility in buildings are currently available. The field of the technical building systems has developed from ICT-based building automation systems (BAS) and building energy management systems (BEMS), toward open and interoperable systems and platforms that have enabled new areas of application such as the optimization of buildings and residential neighborhoods, as well as integrating renewable energies and decentralizing energy pro[duction (e.g., integration of solar panels, heat pumps, or CHP) [2].

What is still underdeveloped, conversely, is the integration of building-based ICT infrastructure into the overlying grid structure. Although, on the European level as well as in

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[2] The term “prosumer” first coined in 1980 by Alvin Toffler [22] means that the role of producers and consumers began to merge in markets of new technologies. Particularly in the digital economy, prosumption became a salient concept for many new business models.

[3] See https://smartreadinessindicator.eu (retrieved January 2020).

individual member states, various approaches for this type of integrated architectures and systems are under development (see, for example, USEF,[4] VHPready,[5] and EEBUS[6]), it still remains to be seen whether one of the initiatives will be established as open architecture or open standard. In addition, two important drivers of the incorporation of buildings into integrated energy systems are financial incentives and environmental effects. The question whether the flexibility or grid-reactive behavior of buildings can be successfully implemented depends partly on the economic incentives for this behavior. It also depends on positive environmental impacts of the applications such as reduced CO_2 emissions.

2.3 Options for flexibility from buildings

Flexibility from buildings can be used for [2]:

- balancing upcoming supply and demand on the market (day-ahead and intraday);
- stabilizing the transmission grid (frequency control) and avoiding network bottlenecks (congestion management); and
- meeting the demand of electricity suppliers[7] (the party responsible for balancing) to supply customers continuously and precisely as required.

In addition, flexibility can be used to achieve a high self-sufficiency rate and to decrease grid dependency of buildings and residential neighborhoods [17].

Technically flexibility from buildings can be derived from different energy sources or sinks such as:

- power-to-heat (PtH) elements that can convert excessive electricity from the grid or own production into heat (for warm water or heating purposes);
- modulating CHP plants, that can either feed into the grid or lower the production if the grid load is high;
- electric batteries, as fixed installation or from electric vehicles in combination with a charging infrastructure in buildings and neighborhoods;
- finally, the thermal storage capacity of buildings can be used, for example. by slightly overriding the present temperatures by max 1°C and using the buildings as inherent thermal storage [2].

As mentioned in Chapter 2, the usability of theses flexibilities depends largely on smart infrastructures in buildings and their simple integration into ICT infrastructures of the energy system and market.

3 USING FLEXIBILITY FROM BUILDINGS: CASE STUDY RESULTS

The results presented in the following section were derived from a joint research project funded by the German Federal Ministry for Economic Affairs and Energy (see Section 6).

The objective of the project is to evaluate and assess solutions for balancing the generation and consumption of renewable electricity in the power grid. This should be achieved under the constraints of grid stability and an increasing share of renewable energy. A case study within the project implemented an integrated ICT infrastructure and smart building concept in a residential neighborhood in Berlin, Germany. This neighborhood serves as a test site for assessing the technical and economic feasibility, as well as the environmental effects of flexibility from buildings. It will also allow conclusions on the transferability of the results onto similar buildings and neighborhoods and on system-wide effects of these solutions.

3.1 Technical infrastructure for flexibility

The case study was conducted in a residential neighborhood consisting of six multistory residential buildings with 224 apartments. These buildings, owned by a cooperative, were built in the 1950s/1960s and partially refurbished in the 1990s (new windows and insulation). The buildings are supplied with locally produced heat and electricity from a CHP plant (34 kW_{el}/ 78 kW_{th}), operated by a contractor, and additional boilers. Energy (heat and electricity) is distributed via local heating and electric networks.

The buildings are equipped with a smart BEMS that optimizes energy consumption (heat and electricity) in the buildings and households, and allows the optimization of multiple energy sources and sinks. With this system, it is also possible to communicate and interact with standardized bus systems and interfaces from the home automation sector (IP-Bus, EnOcean, wireless M-Bus, etc.) as well as with external platforms (for a detailed description, see [2] and Fig. 1).

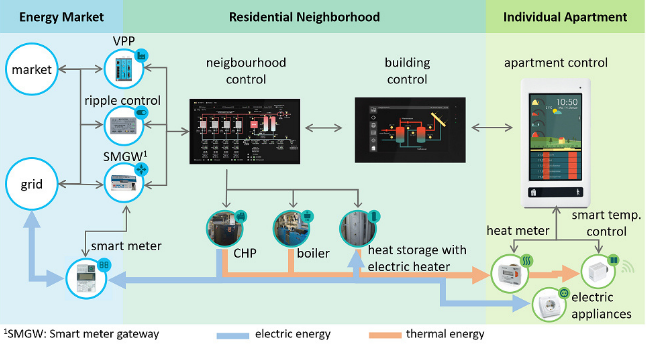

Figure 1: ICT architecture of building energy management and flexibility at building test site in Berlin, Germany (source: DAI-Labor, TU-Berlin, simplifications by the authors)

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[4] USEF is a foundation created by organizations active in the smart energy industry. Its goal is to develop a framework and market model for an integrated smart energy system (www.usef.energy, retrieved January 2020).

[5] VHPready is an open industry standard for the control and integration of decentralized power and heat generation plants, consumers, and energy storage systems into virtual power plants and smart grid applications (www.vhpready.de/en/home/, retrieved January 2020).

[6] EEBUS is an initiative that seeks to introduce a global language for devices in the energy sector to communicate with one another (www.eebus.org/en/vision/language-for-energy/, retrieved January 2020).

[7] Suppliers need to be flexible for short-term adaptation required as a result of unforeseeable fluctuations in electricity generation and consumption [17].

In addition to the existing heating systems, the buildings were equipped with power-to-heat (PtH) elements (6 x 8 kW = 48 kW) in existing warm water buffer systems. This retrofit solution is a simple and inexpensive way to convert excessive renewable energies (e.g., wind) into heat and to couple the electricity sector to the heat sector [2].

3.2 A use case for flexibility from the building sector

Although the case study was part of a project that presumes that flexibility is of value for the changing energy system, it is essential to understand the current and future market requirements for flexibility, to ultimately make use of this. Therefore, various models of flexibility were evaluated under market constraints and in parallel to the development of the technical infrastructure in the buildings. Different use cases were drafted, including details of various project partners and their objectives (technology supplier, a CHP operator, a housing company, and a trader for energy and flexibility).

Finally, from the use cases that were analyzed, a model that aims at integrating flexibility into the market through a virtual power plant (VPP) was selected (see Fig. 2). The model was chosen because it provides for flexibility on existing German markets.

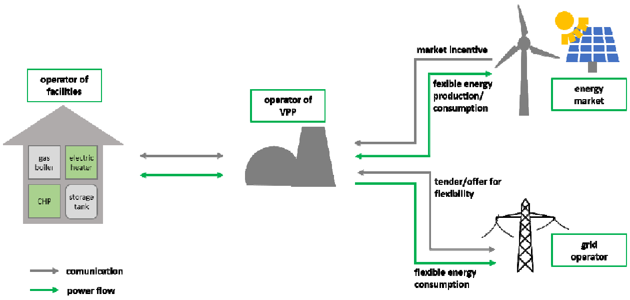

Figure 2: Flexibility model for the building sector through VPP

The mechanism behind the trading scheme is that operators of VPP typically control and optimize various plants for the generation and consumption of electricity. This allows them to react flexibly to fluctuations of electricity production in advance by optimizing schedules. The model aims to provide flexibility to the market by combining functions of a TSO[8]/DSO[9] operational online platform (acquiring flexibility from plant operators) and a coordination platform. Offers for flexibility can be submitted both a day ahead and intraday for individual quarters of an hour (96 values per day). An automated process reduces the specific registration/transaction costs per kilowatt. This is of particular importance for small flexible devices/systems wishing to compete with larger power plants.

3.3 Realization of ICT infrastructure for flexibility

The infrastructure required to provide the flexibility at the building test site is simple (see left half of Fig. 2). A control box (gateway) of the VPP operator was installed in one of the buildings and connected to the operational platform of the BEMS. The BEMS in turn operates and controls the local flexibility options (modular CHP plant and warm water buffer tanks with PtH elements) and optimizes their operation.

4 MODELING OF REDUCTION POTENTIAL OF CO_2 EMISSIONS IN RESIDENTIAL NEIGHBORHOODS BY ADAPTING TO THE SYSTEM-WIDE AVAILABILITY OF RENEWABLE ENERGIES

An important objective of the research project and case study in the neighborhood is to analyze to what extent CO_2 emissions can be reduced by using the buildings and their infrastructure to provide flexibility. This requires adapting the electricity consumption in the buildings with regard to the electricity mix in the energy system. It is precisely the composition of the energy mix that is responsible for the CO_2 emissions.

However, the conventional method of multiplying the energy consumption (kWh) by an average emission factor (gCO_2/kWh) leads to distortions due to the increasingly variable energy mix. For this reason, a dynamic balancing method per 15-min interval was used in the analysis of the emission from the test site.

In addition, the term “electricity supply” is used with reference to the current situation in Germany and its energy mix. Nevertheless, many of the results are transferable to other sites and other countries (see Section 5).

4.1 Background: change in the energy system and dynamic CO_2 factor for electricity

The share of renewable and variable energy production (photovoltaics and wind energy) in the power supply is increasing rapidly and will provide the majority of the electrical energy supply in the future. Since generation and consumption in the electrical energy system must be in balance, stabilization on the consumption side is becoming more important. This involves balancing in seconds and minutes [7], as well as over hours and days (spot market), and even over seasons. The specific CO_2 emissions behind the generation of electricity varies significantly depending on the relevant energy source and mix (see Fig. 3).

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[8] TSO: transmission system operator, the party responsible for the electricity transport grid.

[9] DSO: distribution system operator, the party responsible for operating the distribution grid (sometimes called DNO, distribution network operator).

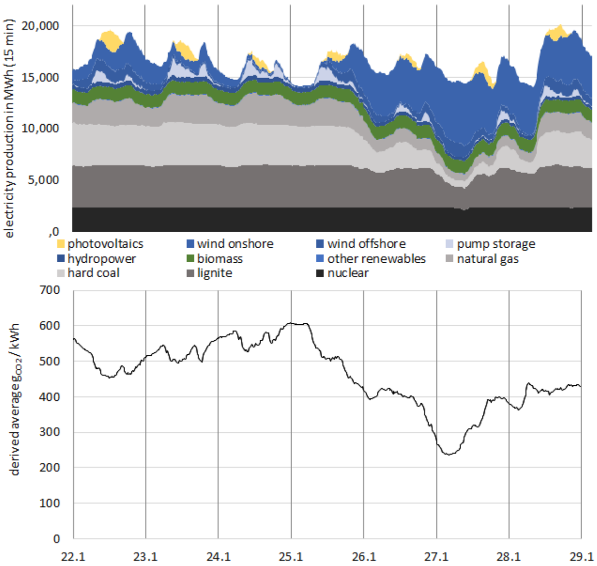

Figure 3: Energy production mix during a week in January 2019 (top) and average CO₂ emissions in gram per kilowatt hour produced in the same week (bottom)

The first graph in Figure 3 shows the generation mix of electricity in Germany over a week in January 2019, with data from [3]. The second graph shows the average CO₂ emission per kilowatt hour resulting from the electricity consumption. These values represent a dynamic CO₂ coefficient calculated by the following equation:

$$avg_{emssions} = \frac{\sum_k^i (prod\_energy_k * spec\_emissions_k)}{\sum_k^i Energy_k}$$

This is done by summing up the emissions of all production types with a specific emission factor ($spec\_emissions_k$) from [14], each multiplied by the energy produced. The sum is divided by the total amount of energy produced within that 15-minute time frame. As shown in the bottom graph of Figure 3, the specific CO₂ emissions in the electricity sector fluctuate greatly over time. In phases of high renewable production, wind farms are often closed down because of insufficient consumption and grid bottlenecks. Since these effects will continue to increase with the ongoing expansion of renewable-based energy production, there is a motivation to shift load to times when a surplus of renewable energies is available.

Therefore, the dynamic CO₂ factor is used to calculate the emissions in the energy system depending on the electricity consumption. Also, the value of electricity production of a combined heat and power plant (CHP) can be characterized more accurately using this dynamic factor.

4.2 Model based calculation of CO₂-reduction potentials in a residential neighborhood

To determine whether the CO₂ footprint of the residential neighborhood can be reduced by intelligent temporal shifting of electricity consumption and generation, the following three steps were conducted (see Fig. 4):

1. In a first step, all energy sources and sinks in the neighborhood and its buildings were described.
2. The different sectors and modes of energy consumption were shifted or converted in the buildings and its applications were described and restrictions defined.
3. The CO₂ footprint of the applications was calculated as a reference for comparison without optimization retrospectively for the entire year 2019.
4. Calculation of the reduced CO2 emissions as a result of the shifted load and production times of electricity within the limits defined in step 2 for the year 2019. Comparison of the results.

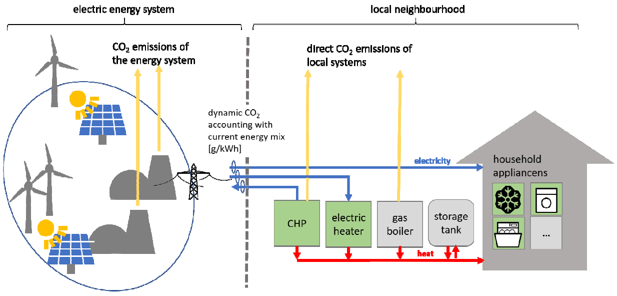

Figure 4: Scope of the analysis with the flexible applications observed highlighted in green

The calculation of the CO₂ footprint of the neighborhood was carried out for the local systems as well as for the exchange with the energy system. The corresponding emissions were calculated on the basis of time-dynamic CO₂ factors using data on power generation in the German energy system from 2019 [3]. The optimization was conducted on the basis of the CO₂ emissions and not the electricity price in the energy market. At present, there is already a slight dependency of the energy price on CO₂ emissions (see Fig. 5). This dependency can be expected to further increase due to a rising CO₂ emission price.

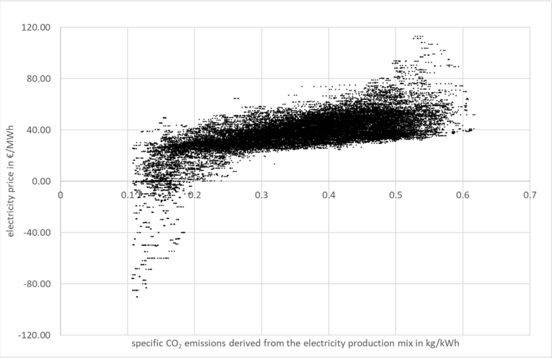

Figure 5: The correlation of electricity price on the energy exchange and the corresponding specific CO2 emissions

4.2.1 Description of flexibility sectors in the residential neighborhood (Step 1)

4.2.1.1 Household consumption.

Characteristic consumption profiles (e.g. washing, cooking, refrigeration, etc.) were created for all relevant areas of application in households. These correspond proportionately to the average annual consumption of the applications and are based on typical usage times. The individual loads are distributed over the day on the basis of assumptions resulting in the typical load profile for households in Germany. A standard load profile from [21] and the share of individual appliances of [4] were used together with further assumptions as a basis, to model the intraday load distribution of specific household appliances (see. Fig. 6).

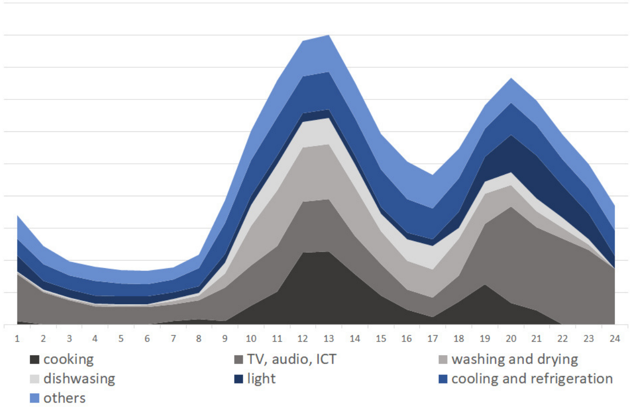

Figure 6: Electrical load distribution per household application distributed over a winter day

4.2.1.2 Charging points for electric vehicles

In addition to those for household appliances, synthetic load profiles for charging points of electric vehicles were created. The usage of electric vehicles was simulated in a TRNSYS[10] model. This model is based on average transport needs in Germany (kilometers per day and kilometers per trip based on [19]) and usage distribution over the daytime, taking typical usage patterns into account. Electric load profiles for eight charging points, each with a power of 11 kW were created, considering the calendar days of 2019.

4.2.1.3 Combined heat and power plant and electric heating elements

The electric production profile for the CHP plant (34 $\mathrm{kW_{el}}$) was simulated using a building model of the neighborhood (described in Section 3). This model considers hourly weather data for Berlin from 2019 [5]. The basic usage of the CHP is optimized purely on the thermal side so as to supply as much heat demand as possible. Only during the hours with higher thermal load is the gas furnace automatically switched on.

For the electric heating elements (48 $\mathrm{kW_{el}}$) in the warm water buffer tanks, it was estimated that they remain switched off due to current high specific end-user price for electricity in Germany.

4.2.2 Definition of restrictions for load shifting (Step 2)

4.2.2.1 Household consumption

For household appliances, only the electricity consumption of washing and drying, dish washing, and refrigeration were considered as shiftable and promising for demand side management [12]. Based on these assumptions, washing and drying can be delayed and automatically set for specific windows during the daytime (the washing machine should not spin-dry at midnight). Similar restrictions were made for dishwashers.

The electricity consumption of refrigeration (fridge and deep freezer) can mainly be shifted by automatically cooling to a lower temperature than necessary and using the surplus cold as a buffer.

In total, for the neighborhood observed, the maximum additional load through load shift per 15 minutes was limited to 80 kW to avoid local network overloads.[11] The absolute amount of energy consumed per year does not change through the load shift; only the energy from one 15-minute time frame was added to another within the restrictions described.

4.2.2.2 Charging points for electric vehicles

Electric vehicles can only be charged when they are parked at a charging station. Flexibility results mainly from the fact that vehicles are connected to the charging point for longer than the actual charging period. This applies in particular at night. At the same time, shifting is only possible within the limits of the number and power value of specific charging point (in this case 8

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[10] TRNSYS is a simulation software developed by the University of Wisconsin. It is primarily used in the fields of renewable energy engineering and building simulation (see http://www.trnsys.com).

[11] It is assumed that, for the neighborhood observed, an additional 80 kW can always be realized through the physical capacities of the power lines installed.

x 11kW). While the vehicles are connected, charging can be postponed for up to five hours on the condition that at the end it is at least 95% charged.

Combined heat and power plant and electric heating elements

The CHP in the residential neighborhood complements the heat supply of electric heater elements well. The production of electricity in the local CHP (based on natural gas) only makes sense if the electricity produced would otherwise have a high CO_2 footprint in the system. If a high proportion of renewable energies is available, electricity production with the CHP is not reasonable. This means in turn that part of the heat production is no longer necessary. At the same time, electric heating elements powered with electricity from renewable sources is becoming reasonable because they reduce CO_2 emissions. In such a case, the “missing” heat from the CHP can be substituted by electric heating elements.

There are relatively few restrictions on the heat side but the production of heat should roughly correspond to the heat load of the neighborhood, although there are short-term storage effects due to the thermal inertia of the heating system and the buffer tanks. In TRNSYS, the shift of the CHP profile and the electric heater elements is carried out in such a way that thermal restrictions (temperatures and load coverage) are always met. In the event of insufficient heat coverage, the gas heating is automatically used and in the event of excess heat coverage, the CHP/electric heater elements are switched off.

For the heat supply of the building, the system with the lowest specific emissions (gCO_2/kWh_{heat}) is selected for every 15-minute interval as the primary heat source. If the preferred heat source is not sufficiently covering the load, the storage tank will compensate for short-term fluctuations and the gas furnace will compensate for larger deficits. Thus, heat production can be shifted not only to different 15-minute intervals but also to a different heat source (no subsequent compensation required).

For all energy-consuming appliances (household plus vehicle charging), the maximum additional load (accumulated at neighborhood level) that is shifted to another time frame is set at 80 kW because of grid restrictions. An overview of restrictions is presented in Table 1.

Table 1: Overview of the restrictions for the flexible appliances

Flexibility type	***Time restrictions (past(-); future(+)***	***Power restrictions** (limit for shifting)*
Charging points for electric vehicles	+5h while connected (the car needs to be charged)	80 kW in total
Washing and drying	+3h	Not late at night, 80 kW in total
Dishwashing	+3h	80 kW in total
Cooling and refrigeration	-1h…+0.25h	80 kW in total
Combined heat and power (CHP)	Within the restrictions unlimited	Heat supply must always be ensured; no overproduction, 48 kW in total
Electric heating		

4.2.3 *Calculation of CO_2 emissions (Step 3)*

The CO_2 emissions were calculated retrospectively for 2019 without optimization and serve as a base case (see Fig. 7). The total CO_2 emissions (direct local and indirect) for household applications (blue) as well as heat supply and mobility applications (grey) amounts to approximately 643 t for the test site (neighborhood with 224 apartments), calculated with dynamic CO_2 factors.

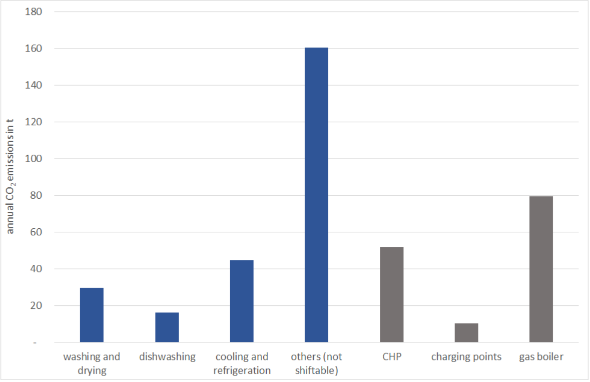

Figure 7: Annual CO_2 emissions for household appliances, heat supply, and electric charging points

4.2.4 *Shifting load and production times of electricity (Step 4)*

Within the limits defined in Step 2, the following shift in load and production times with their corresponding CO_2 emissions were calculated:

4.2.4.1 *Household consumption*

With regard to energy consumption in household appliances, the time shift in energy consumption only leads to minor CO_2

savings (see Fig. 8). This is partly because time restrictions for the devices are relatively strict, and also because the total CO_2 emissions are not particularly high even without optimization.

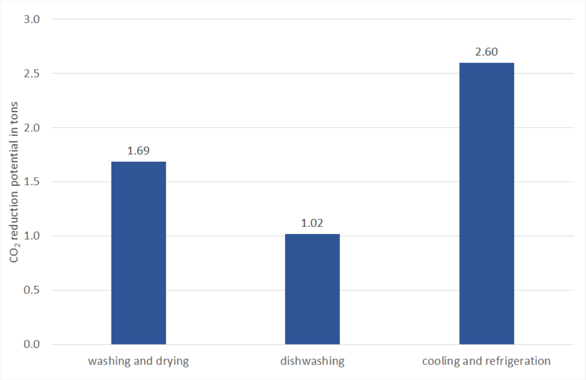

Figure 8: CO_2 reduction potentials through load shift of household appliances

In relative terms, the reduction of CO_2 emissions is 5.71 % (from washing and drying), 6.25 % (from dishwashing) and 5.83 % (from cooling and refrigeration).

4.2.4.2 Charging points for electric vehicles

Due to load shifting in the charging infrastructure for electric vehicles, there is a reduction potential of CO_2 emissions of 13.5 %. The absolute amount of CO_2 savings for time-optimized charging is relatively low with 1.37 t CO_2 for the eight charging points observed. This potential will increase significantly with the further rollout of electric vehicles and more charging points. For that reason, the eight charging points in the neighborhood (224 apartments) in fact reflect the current but not the long-term demand for a charging infrastructure in a residential area.

4.2.4.3 Combined heat and power plant and electric heating elements

One important factor that affects the reduction of CO_2 emissions is the operating hours of the gas furnace (fewer local emissions with decreasing operating hours). This is due to the supplementary operation with the CHP and electric heating elements (see Fig. 9). Although the usage of electric heating causes additional emissions of 4.27 tons of CO_2 compared to not using them, they do not occur when the indirect emissions of the electricity consumed is lower than the direct CO_2 emissions of CHP or the gas furnace. Reduced use of the gas furnace allows 22.68 tons of CO_2 to be saved.

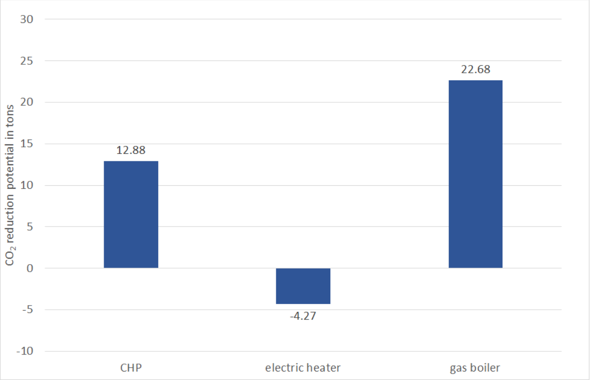

Figure 9: CO_2 reduction potentials through load shift in the heating sector

The CHP is able to reduce its CO_2 emissions by 12.88 tons by adapting its production hours to the situation (electricity mix) in the grid, or by being replaced by electric heating in times of low specific CO_2 emissions in the energy system.

4.3 Interpretation and limitations of the results

The modeling results from the test site clearly indicate that an adapted control scheme in buildings and neighborhoods can reduce CO_2 emissions with regard to system-wide availability of renewable energies. It is also evident that the highest potentials can be obtained in the heating sector with adapted operation schemes using the CHP and electric heater elements. An operating scheme using these devices that adapt to the current emission-specific energy mix in the electrical grid can contribute to significant reductions in CO_2 emissions, and the potential savings from the heating sector are many times higher than those from household appliances.

Furthermore, adapting heating through modulation of CHP and electric heaters in warm water buffer systems are measures that can easily and cost-efficiently be applied in preexisting infrastructures in the built environment [2]. This does not mean that the authors wish to overemphasize the relevance of adapted operation schemes and grid reactive behavior of residential buildings and neighborhoods for the reduction of CO_2 emissions. To achieve the long-term goals of 80-95% reduction of CO_2 emissions in the overall building sector, additional measures such as energy saving and maximum local production from renewable energies are also required. However, the shifting of load and production times can be a viable measure that reduces emissions and allows the integration of higher shares of renewable energies into the grid.

Finally, the approach can be valuable for further reducing CO_2 emissions in regions or countries with a similar climate (moderate to cold, see [1]), from residential building structures and heating systems, in particular, CHP with district heating.

It can be deduced that an adaptive and flexible energy consumption in residential neighborhoods depends largely on an ICT-enabled infrastructure in buildings and energy systems

(BAS, BEMS, etc., see also Section 2.2) and is far more likely to be implemented in countries that have a clear strategy and roadmap for the implementation of these technologies.

5 CONCLUSION AND OUTLOOK

Flexibility of buildings and residential neighborhoods is becoming more important due to the absolute amount of energy consumption in this sector and the increasing share of renewable energies in the grid, electrical flexibility of consumers, generators, and storage facilities in buildings is a viable option for allocating such flexibilities and to foster a sustainable and reliable energy supply with lower CO_2 emissions. A high potential lies in the heating sector and this can be mobilized through emission-adaptive and flexible operation of CHP plants, gas boilers, or electric warm water heating.

ICT plays a key role in mobilizing these potentials. A large number of distributed buildings and appliances need to be provided with information on the status of the energy system and prices on the energy market. The technologies required for the use of flexibility already exist but widespread application has been achieved to date due to the lack of political and financial incentives or reliable indicators for evaluating the buildings and their equipment.

Therefore, a dynamic CO_2 coefficient as described in this paper can provide a better basis for assessment of CO_2 emissions at system level. Using this method, high CO_2 emission reductions are possible through flexibilization, particularly in the area of heat supply. A transition to high shares of renewable energies in the electricity supply is difficult to implement without using this flexibility potential. In order to achieve the EU goals in climate policy for 2030 and 2050, there is a significant potential for emission saving in the building sector that can only be made accessible through the use of ICT. This potential should be unleashed as soon as possible.

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