Evaluation of the energy saving potential through systematic data collection of the electricity consumption and heating system operation in the building sector

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Abstract
The digital measurement of electricity and heat consumption of households and buildings offers the opportunity to systematically identify previously hidden energy efficiency and saving potentials in real time. But the required measurement and processing of the data is associated with negative environmental impacts, through the hardware of the devices and the data transmission and processing. The DETECTIVE project aims at quantifying the net saving potential of digital consumption metering for electricity and heat.

In the electricity sector, the framework for a wide smart meter rollout in Germany has been set up, but the installations have been running modestly since 2019. Soon, smart meters will create the technical infrastructure for the digitalization of the energy transition, which will enable and facilitate the integration of renewable energies, sector coupling and prosumer models. In the heating sector, digital metering of primary energy consumption is used by energy savings contractors to optimise the operation of the heating system.

In this paper, we analyse measured data from households and buildings, in which digital applications for electricity consumption and online monitoring of the heating system operation are installed, and evaluate the changes in energy consumption. We estimate the additional electricity consumption of the necessary digital devices and data flows to compare them with the energy savings. This enables a net balance between energy expenses and savings in order to quantify the ecological benefits.

In view of the upcoming large-scale smart meter rollout, this is essential information in order to regulate digitization in such a way that the greatest possible environmental benefit can be achieved.

Introduction
The ongoing transformation of the energy system in Germany goes through various aspects of the energy value chain: from generation, transmission and distribution to consumption. This transformation requires an intelligent, highly flexible and strongly interconnected interaction of several actors, e.g. between end users, energy suppliers, metering point operators. Various studies on technical and regulatory feasibility and on social acceptance and participation (Agora Energiewende 2017; Gährs et al. 2021) prove that digitization plays a crucial role: Digital applications are necessary for the collection, transmission and visualization of key figures and measured values and for the (remote) control and automation of applications and devices specific to the energy industry.

The DETECTIVE project analyses field data of digitally measured energy consumption data provided by companies offering Smart Meter (SM) systems with feedback for consumers or energy savings contracting for heating. We determine the savings' potential and compare it with an environmental assessment of the necessary devices and data transmissions.

The paper contains three parts. In the first section, we provide a short overview of the current state of the digitization of energy consumption metering in Germany. The second part deals with the environmental assessment of the energy saving potential through monitoring the electricity consumption and providing feedback to consumers. The third section evaluates

Table 1. Four sub-sets in Fresh Energy data.

Daily electricity consumption (low res)	Electricity consumption measured every two seconds (high res)	Household information	Device detection (NILM)	
955	0	0	0	Low res
98	98	59	98	High res
551	0	551	549	Household information
950	0	0	950	NILM

the energy saving potential through online monitoring of the heating system operation in large apartment buildings.

Background: current state of digitization of energy consumption metering in Germany

At the end of 2016, the Metering Point Operator Act (Messstellenbetreibergesetz, MsbG) (Deutscher Bundestag 2016) was passed, which restructures metering point operation in the grid-based energy industry, and regulates the rollout of SM systems and Modern Metering (MM) equipment in the electricity and heat sectors.

In the electricity sector, installation of SM systems is still only obligatory for certain predefined cases (Deutscher Bundestag 2016). The mandatory installation affects approx. 7 million end-consumers, while the optional installation comprises around 44 million end-customers. Since 2019, after a successful certification phase (BSI 2019), the rollout of certified SM has modestly started. At the same time, the installation of other SM, that are in the process of certification and that have more complex technical specifications in terms of data privacy standards and measurement frequency (metering systems according to §19 para. 5 MsbG – referred to as **non-certified SM** in the following), has been allowed for by the Act for specified cases. Due to their immediate availability, the installation of the latter has even adopted a much faster pace, especially for end-customers that fall into the optional rollout categories.

The yearly monitoring report published by the Federal Network Agency (Bundesnetzagentur 2021) provides a good basis for assessing the current stock, yearly development and overall potential of SM in Germany. As of 2020, the rollout reached 0.4 % for the obligatory cases, and 0.01 % for the optional ones. If **non-certified SM** are included, these values increase to 11.5 % and 6.8 %, respectively. Furthermore, the Act foresees the installation of MM systems for a wider range of predefined cases (Deutscher Bundestag 2016). These are defined as metering systems that are digitalized (in contrary to the Ferraris meters), yet still do not include a smart meter gateway for data processing and cloud storage. **MM systems** can be extended with the gateway component (Bundesnetzagentur 2021). As of 2020, the already installed MM systems sum up to 9.5 million, i.e., 14.9 % of the obligatory installation points and 19.4 % of the optional ones. Due to the strong increases in SM installations in comparison to previous years (Bundesnetzagentur 2021), the increased installation and ongoing certification of SM according to §19 para. 5 MsbG and the increased installation and possible extension of MM systems, significant increases in the SM rollout quotas can be expected in the coming years.

In the heating sector, a digital real-time recording of the energy consumption is currently mostly lacking, e.g., gas counters are read-out on site yearly. However, the market for energy savings contractors and energy management using digital solutions to monitor primary energy and heat consumption is growing (Gährs et al. 2021).

Environmental assessment of the energy saving potential through monitoring the electricity consumption

EXAMINED DATA

To estimate the changes in electricity consumption using a smart meter, two data sets were evaluated. These data sets were collected as part of two projects that took part in an energy savings program (Einsparzähler (BAFA 2021)) funded by the German government.

One of the data sets was generated by the company **Discovergy**[1]. In the program, Discovergy offered private households the installation of a smart meter free of charge and they voluntarily opted for this type of current measurement. The household electricity consumption was recorded every second. The collected data was sent to Discovergy via a gateway and processed for personal access via an online portal. The portal provides an overview of the customer's consumption, including live data and daily, monthly and annual averages in comparison. Customers can also select the detection of individual devices, obtained through algorithmic disaggregation, so called Non-Intrusive Load Monitoring (NILM) algorithms. This means that the company receives the data from the smart meter, pro-

1. Full-service provider for smart metering solutions with headquarter in Aachen. Company website: www.discovergy.com. The data was made available as part of a joint project.

cesses it for the NILM algorithm, makes the data available to customers in the portal and stores it.

The data set includes 1,288 customers. Further metadata was available for the individual households, such as the number of household members, living space, type of water heating and house/apartment type. The evaluation includes 1.065 households, for which the previous year's consumption was available as a baseline for calculating changes in electricity consumption. We did not take into account households with a very large deviation of plus/minus 70 % from their baseline. We adopted 70 % as a limit, as savings or additional consumption of more than 70 % were assumed to be implausible. In order to understand the data Discovergy was in contact with the households during the measurement period and asked them to report changes in their living conditions, such as e.g. change in household members.

Fresh Energy provided the second data set, which was published as open data in a project by Milojkovic (2021). The data set register households contributing to the program starting from November 01, 2017, and ending October 31, 2020. The data only contains the energy consumption after the installation of a SM. For some end-users, data is available for this entire period, i.e., three years. The data of customers joining later is registered starting with the first day after the smart meter installation. The data consists of four sub-sets with different information on the participating households (Milojkovic, 2021):

1) A data set with electricity consumption in a lower resolution of daily values (referred to hereafter as *lowres*) for 955 households, 2) a data set with a much higher resolution of one value every two seconds (referred to hereafter as *highres*) for 98 households, 3) a data set with the anonymized available information on household characteristics for 551 households (number of members, availability of specific appliances such as electric cars or heat pumps, heating type, etc.) and 4) a data set with the electricity consumption from specific appliances (washing machine, dryer, etc..) obtained through NILM for 950 households (also see Table 1).

In contrast to the Discovergy data sets, no information was provided as to whether there has been a change in the household meta data (e.g., increase in household members, addition of sector-coupling technologies) nor a replacement of devices (e.g., with a different efficiency class or size).

APPROACH TO EVALUATE THE DATA

Discovergy

The data collected from Discovergy's customers allows a comparison of the electricity consumption after installation of the smart meter with the annual value before installation. The first customers received the smart meter in the 3rd quarter of 2017, the last meters were installed in the 3rd quarter of 2021. The measurement period was at least two months, the longest period was about four years. There is only one value for each household for the entire measurement period (at the beginning and at the end and an information about the length of the period), so that the effects of the corona pandemic cannot be removed.

Fresh Energy

For the evaluation of the Fresh Energy data set, no reference consumption before the installation of a SM is available. We therefore analyse how the consumption evolves over time. The daily resolution is deemed sufficient to evaluate the saving potential. Therefore, we do not consider the *highres* data set any further. To exclude repercussions on the energy consumption due to the COVID-19-Pandemic and the imposed lockdowns, data from 2020 onwards is also not included. We further filtered the data set to enable a meaningful interpretation of the results: For instance, the *lowres* data is matched with the available meta data set, since interpretations of the saving potential are related to the household information in a later step of the evaluation (cf. Evaluation of energy savings in households). Furthermore, we omit households with a sector-coupling technology, i.e., an electric car or a heat pump from the analysis, due to a potentially higher and unusual electrical load profile. This leads to a total of 343 remaining households for the analysis.

To quantify the saving potential, we make two differentiations according to the timescale (i.e., yearly and monthly values) and the (dis)aggregation of the appliances' consumption (i.e., overall and appliance-specific consumption).

We calculate the yearly average of electricity consumption for the years 2018 and 2019, while, for the monthly considerations, the development is examined for the months of 2017, 2018 and 2019. The exclusion of the 2017 data from the yearly considerations is due to the fact, that it is only available for the last two months of the year, and therefore not sufficient for an entire upscaling.

The analysis goes beyond considerations of the aggregated consumption to include appliance-specific examinations from the *NILM* data set. Data is available for different appliances, either over a certain timeframe, e.g., for always on (stand-by) devices, lighting and refrigeration or per cycle (event appliances), e.g., dishwasher, washing machine or dryer. In contrary to the aggregated consumption, we do not evaluate the consumption of the chosen devices by its monthly or yearly kWh-value, but also, for the event appliances, by the number of occurrences, i.e., when these devices are used.

In general, changes are expressed as percentage values with 2018 as the reference year, i.e., the difference between values recorded in 2019 or 2017 and 2018 is divided by the value in 2018. For this, only households with data for 2018 are considered, i.e., 280 households. Averages are built separately from households recording an increase in consumption (defined as positive value) and households with a decrease in consumption, i.e., with savings (defined as a negative value). Although in the initial data set households with suspicious values were removed, too strong changes in the consumption patterns were excluded to avoid any distortion of the built averages. In analogy to the evaluation method of the Discovergy data set, this value is set to 70 %.

Furthermore, for an evaluation across households, specific indicators, such as the annual energy consumption per person and the annual number of occurrences of a certain appliance per person are also derived.

EVALUATION OF ENERGY SAVINGS IN HOUSEHOLDS

Discovergy

The evaluation of the consumption data shows that households can be divided into three groups. In the largest group with 568, consumption almost does not change. Another group consumes less electricity during the measurement period than before (273 households), while the third group consumes more

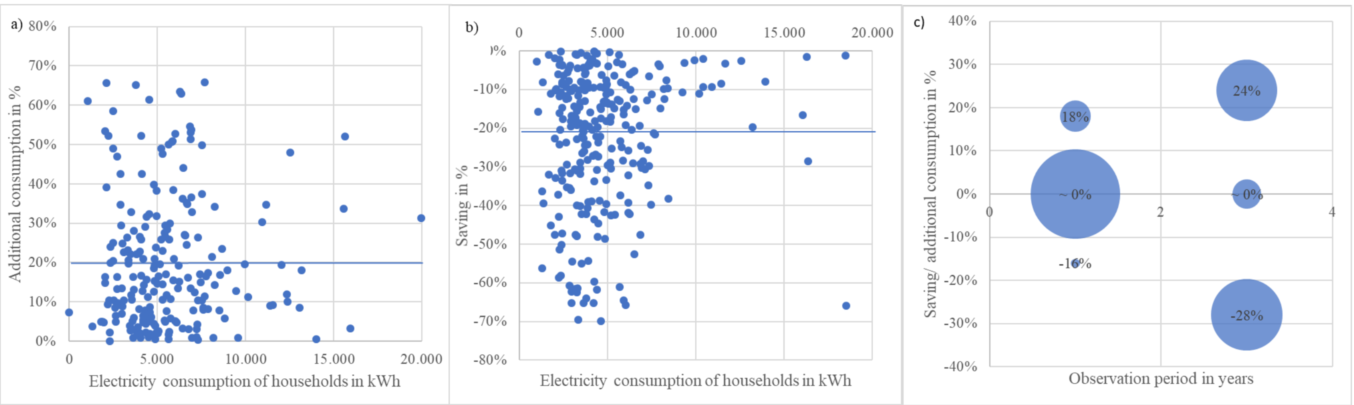

Figure 1. a) Additional consumption of the 215 households with an increase in electricity consumption referred to aggregated consumption values over at least 0.5 years b) Savings of the 273 households with a decrease in electricity consumption referred to aggregated consumption values over at least 0.5 years c) Average savings/additional consumption of households with different use times of the Smart Meter.

Table 2. Average additional consumption and saving in different customer groups.

Households with increased consumption after installation of SM		Households with reduced consumption after installation of SM		All households	
Water heating with electricity	Water heating without electricity	Water heating with electricity	Water heating without electricity	Water heating with electricity	Water heating without electricity
+ 16%	+ 21%	- 20%	- 23%	- 1%	- 2%
Prosumer[3]	Non-prosumer[4]	Prosumer	Non-prosumer	Prosumer	Non-prosumer
+ 22%	+ 20%	- 20%	- 23%	0%	- 1%

(215 households). Figure 1a) and b) show the savings and additional consumption of individual households in the two groups with changed consumption as a function of annual consumption. The average value of the additional consumption is 20 %, while the average value for the saving is -22 %. The total savings across all customers are -1 %.

The recorded savings clearly differ depending on the level of electricity consumption. For the evaluation, the households were divided into three groups with low, average and high consumption. The allocation was based on the so-called *Stromspiegel*[2] (co2online 2021) depending on the number of household members, water heating system and living situation. The group with low electricity consumption (149 households; categories A and B in the Stromspiegel) had the largest savings with 5 %. The households with average consumption (207 households; categories C, D and E in the Stromspiegel) saved over 2 % overall, while the households with high consumption (709 households; categories F and G in the Stromspiegel) saved only 1 %. These values are relative and do not allow an information about the absolute values.

The customers had different measurement periods that began immediately after the Smart Meter was installed. In order to assess how the smart meter affects consumption behaviour in the long term, the customers were divided into two groups: in one group the measurement period was between 0.5 and 2 years, in the other group between 2 and 4 years (Figure 1c)). The analysis shows a strengthening of trends for savings or additional consumption over time: While the majority (76 %) of the first group showed almost no change in consumption, this proportion was significantly smaller in the second group (9 %). For the group, which showed almost no change in electricity consumption, a threshold of 2 % was set. In this group with at least 2 years of SM use, power consumption is either significantly reduced (-28 %) or increased by (+24 %), with a light weight to customers who save. Furthermore, the households were examined based on their characteristic features, e.g. households with and without electric water heating or prosumers. Table 2 shows the savings/additional consumption of these groups as well as the values of all households.

Fresh Energy

The evaluation of the data set shows an approximately equal distribution of the households between patterns of electricity savings and additional consumption. On the one hand, an increase of consumption is recorded across half of the 280 examined households with data for 2018 and amounts to an average of 12 %. On the other hand, the other half of the households records a decrease in consumption by on average -11 %.

The point cloud in Figure 2 portrays this distribution along the per-person annual electricity consumption of the household. The figure shows that households with an annual electric-

2. The Stromspiegel compares the electricity consumption of private households and gives information how the respective consumption is to be classified in comparison to other households in Germany.

3. People that consume and produce energy e.g. with PV-collectors.

4. People that only consume energy.

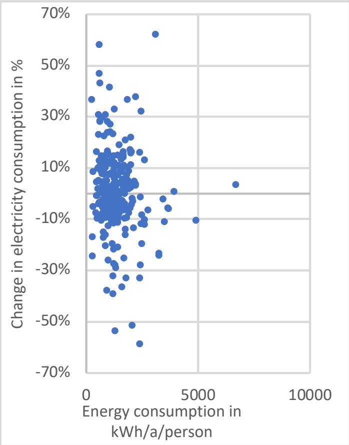

Figure 2. Point cloud of the relative change in electricity consumption in 2019 compared to 2018 over the households' annual electricity consumption per person (Source: own compilation).

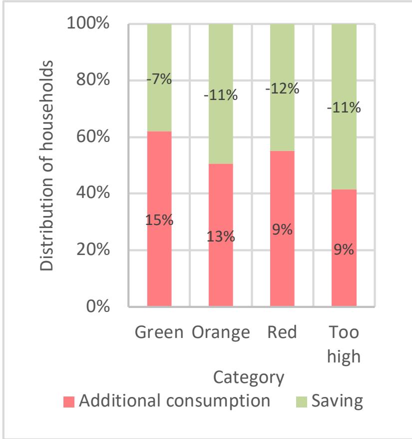

Figure 3. Distribution of the households between additional consumption (red) and saving (green) for each category of electricity consumption efficiency. The numbers inside the bulks represent the respective average change in consumption (Source: own compilation).

ity consumption lower than 2,000 kWh/person/a are scattered in both the positive range of the graph (additional consumption) as well as the negative range (saving), whereas households with annual consumption above 2,000 kWh/person mainly record electricity savings.

In addition, to account for the type of housing, i.e., house or flat, the categories of the *Stromspiegel* (co2online 2021) are matched with the households' meta data to derive the respective electricity efficiency category. Figure 3 displays the distribution of the households across the different categories: green: categories A and B, orange: categories C-E, red: categories F and G, and too high: outside the scope of the tables provided in (co2online 2021).

Households in the green category have the slight tendency to increase their consumption, i.e., 60 % of the households record an average increase of 15 %, while the rest manages to achieve moderate savings of -7 %. Households in the orange and red categories tend to have similar tendencies, with an equal distribution across the opposing consumption patterns, with the red category registering a lesser average additional consumption of 9%, compared to 13 % for the orange category. The saving potential is somewhat similar at around -11 to -12 %. Households with an electricity consumption that is too high and falling outside of the scope as defined in co2online (2021) showcase a slightly stronger tendency to saving patterns, i.e., approx. 60 % reach an average decrease of -11 %, while the remaining 40 % record an additional consumption of 9 %. The recorded lower saving ratios for high-efficiency households may be due to the efficiency of their consumption reaching a limit and become more volatile near this optimal value, while households with the worst efficiency have a larger margin for behavioural adjustments of the consumption.

To examine the development of consumption patterns with the monthly advancement of the program, as well as the effects of seasonality on the tendency for savings or additional consumption, the monthly changes are considered by calculating the relative change in consumption for one month in 2019 compared to the value of that same month in 2018. The resulting percentages confirm the aforementioned almost equal distribution of the consumption patterns. Figure 4 shows the development of participating households and the share of energy-saving households and additional-consumption households. In terms of relative change (see Figure 4), the increase varies between 14 % and 21 % with the highest value recorded in February, while the decrease ranges between -13 % until -19 % with the lowest value recorded in January. 80 % of the households fluctuate between additional consumption and saving from month to month, yet do not display any uniform pattern.

Furthermore, the effects of the forerun in the program for the 66 early-bird households installing their smart meters already from November 2017 are investigated. In terms of average relative changes compared to 2018, the averages across the 66 households remain the same as for the data set of 280 households, i.e., an additional yearly consumption of 12 % and yearly saving of -11 % in 2019 is recorded. Since no data is available for the entire year of 2017, no solid comparison can be conducted for the trends of the yearly changes from 2017–2018 and 2018–2019, as explained in the methodology section earlier.

When looking at the consumption patterns of specific appliances, provided by the NILM data set, various tendencies from 2018 to 2019 are observed with varying extent. On the one hand, the stand-by appliances and lighting, where only the energy consumption is considered due to their continuous usage across a certain timeframe, show an overall average increase of consumption by 4 % and 16 %, respectively. On the other hand, values for the refrigeration consumption display a stronger tendency to savings with 70 % of households saving -25 % on average, leading to a net decrease by -12 % across all households.

Furthermore, the appliances measured per cycle (event appliances), i.e., washing machine, dryer and dishwasher, are considered. For the washing machine and the dryer, around 66 % of households manage to use the devices less leading to an overall decrease of -1 % and -5 %, respectively, whereas for the dishwasher, around 50 % of households register overcon-

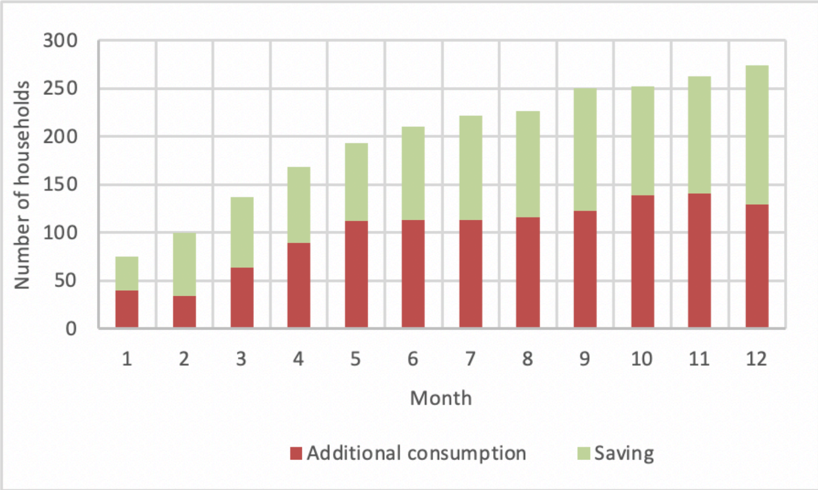

Figure 4. Monthly development of the number of participating households and the respective distribution of the tendencies for additional consumption (red) or saving (green) (source: own compilation).

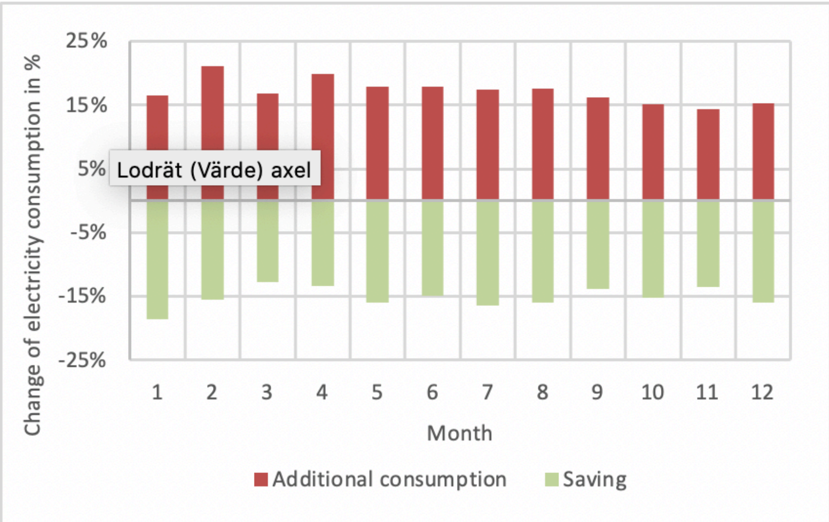

Figure 5. Monthly average change in electricity consumption towards additional consumption (red) or saving (green) (source: own compilation).

sumption, leading to an overall slight increase of 4 %. In terms of energy consumption per occurence, savings for the washing machine and the dryer are -1 % to 0 %, while a net increase by 4 % is observed for the dishwasher.

For the customers within the Fresh Energy set-up, no feedback on NILM applications was provided to the customers and the data set was only generated later on to allow subsequent analyses (Milojkovic 2021), the tendency towards additional consumption for some appliances can therefore be limited by providing NILM-feedback to the households in real-time.

As mentioned earlier, no information is available for the Fresh Energy data set on changes in the household characteristics over the period of the program. Since changes in energy consumption cannot be matched with changes in the household size or equipment, the aforementioned results are only preliminary and need to be consolidated with respect to possible influential changes.

Placement in existing literature

Various studies have already been carried out with the aim of looking at different digital applications and investigating specific effects on electricity consumption. Figure 6 shows an overview of the saving potential for various applications. There, the range of savings in the evaluated literature is shown, as well as their mean values. Our considered applications are discussed in the literature under “Feedback with NILM” for the Discovergy data and “Feedback without NILM” for the data from fresh energy. This shows that the expected savings cannot be confirmed by our data set evaluations.

ENVIRONMENTAL ASSESSMENT OF THE DIGITAL APPLICATION FOR RECORDING ELECTRICITY CONSUMPTION

The environmental assessment is based on international standards (DIN EN ISO 14044 2006). For the assessment of digital applications, households with a NILM system are examined.

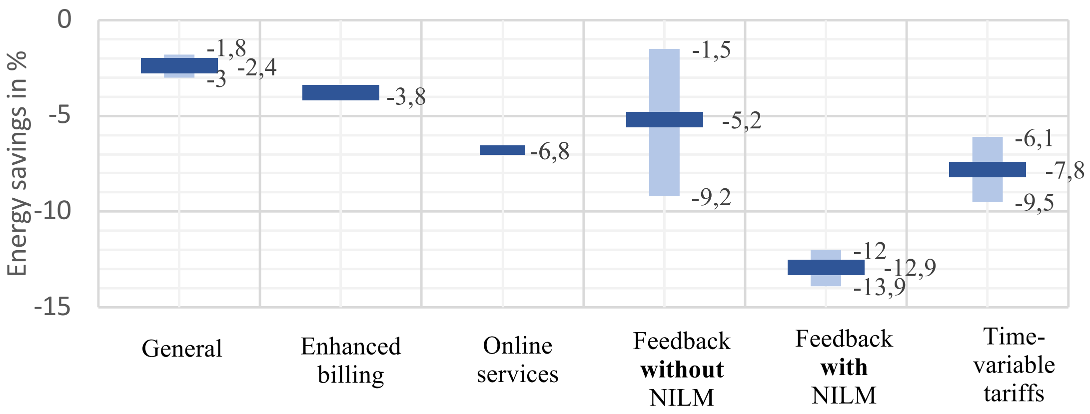

Figure 6. Literature values on the energy saving potential of smart meters (Meinecke 2017, Fraunhofer ISE 2011, Armel et al. 2013, Klopfert et al. 2011).

The considered ecological effects include the technical equipment that has to be installed (production, transport, use and disposal) as well as the collection, transfer, processing and storage of recorded data. The analysis of the system is based on a time unit of one year. Furthermore, the evaluation of ecological effects focuses on the category of climate impact expressed in Green House Gas (GHG) emissions (kgCO_{2eq}), as this is most relevant in the context of energy consumption and climate protection. The SimaPro software 9.0 is used to calculate the effects, and ecoinvent 3 serves as the data base (Wernet et al. 2016). The CML method (CML-IA baseline, version 4.7) is utilized as the method for impact assessment (CML 2016).

As part of the life cycle inventory, first, the equipment data required for the NILM system is gathered. The study by Sias (2017) serves as a basis for this purpose. The assumptions for the composition and lifetime of 12 years for the smart meter is taken from this study as well as the assumptions of a premature removal of the analogue electricity meter. For the smart meter gateway, which enables communication between the household and the external service provider, manufacturer information available online is used to determine the composition (Sagemcom Dr. Neuhaus GmbH 2016). The lifetime is assumed the same as for the smart meter. The energy consumption of the SM and the SM gateway and the use of the service provider platform in the household are taken from Gährs et al. (2021). To estimate the data flows (transfer, processing and storage), a questionnaire with required information was completed by Discovergy's IT department. Thus, the amount of data collected in the household and the amount of data stored could be determined, as well as the energy consumption of the processing in the data centre. According to Discovergy, data transfer from the household to the service provider takes place in most cases via radio transmission, which is also assumed in this study. To estimate the energy consumption of data transfer via radio transmission, the values from Gröger (2020) are applied. All of these processes are modelled using the aforementioned methods and tools.

Figure 7 shows the results of the life cycle assessment. The focus lays on ecological expenses, not on benefits from supposed energy savings after the installation of a NILM system. In total, around 17 kgCO_{2eq} are emitted in one year. The life cycle assessments of the devices (SM, gateway and analogue electricity meter) account for approximately 25 % of the total environmental impact of 17 kgCO_{2eq}. The largest share is accounted for by the electricity consumption of metering in the household (data collection), which arises from the operation of the smart meter and smart meter gateway (66 %). Transfer, storage and processing of the data collected in the household account for a total of only 8 %. Of this, 25 % can be attributed to the processing of data in the computing centre.

OVERALL BALANCE OF ENERGY SAVINGS

The environmental impact of implementing a NILM system is 17 kgCO_{2eq}/a. If we consider a 3-person household with an electricity consumption of 3,500 kWh/a, a saving of 1 % can save 35 kWh in one year. With an emission factor of 0.437 kgCO_{2eq}/kWh (own calculation with abovementioned methodology), this results in a saving of emissions of 15 kgCO_{2eq}/a, which is less than the calculated ecological expenses. Only from a saving of just under 40 kWh per year does the total balance break even. If a larger household is considered (5,000 kWh electricity consumption per year) and the saving of 1 % is applied, the environmental balance becomes positive and almost 5 kgCO_{2eq}/a can be saved.

Environmental assessment of the energy saving potential through online monitoring of the heating system operation

BACKGROUND

The energy consumption and efficiency of heating systems based on heating water in one spot of the building and distributing the heat through water piping and connected radiators (hydronic central heating systems) depends on the interaction of the systems components and various parameter settings. Often, the energy efficiency is below optimal values (Gährs et al., 2021). Online digital operation monitoring, as currently offered by specialized energy saving contracting companies, continually measures and transmits the primary energy and heat consumption, sometimes with data from additional temperature sensors. The data is used to identify malfunctions and possible parameter setting optimization. While the data collection process is automatic, the optimization requires human action: an expert analyses the data with specific software and deduces

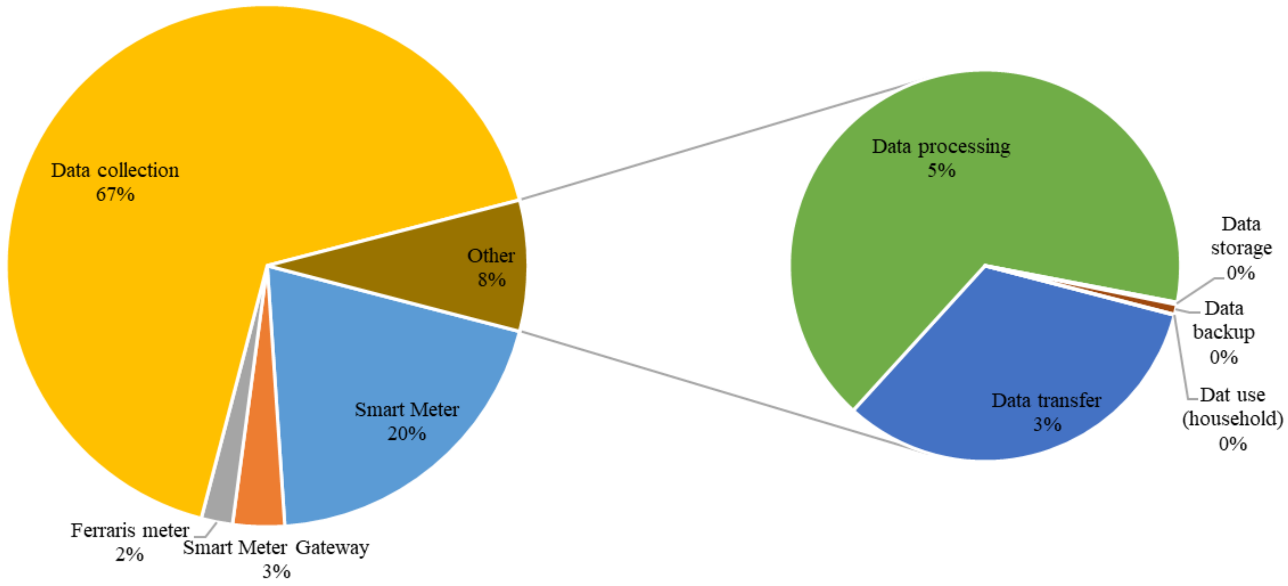

Figure 7. Shares of the components and data streams on the ecological impact of the NILM system (Source: own compilation).

appropriate measures. Critical parameters are e.g., the settings of the heating curve, the spread between the supply and return flow temperature, the duration and temperature of the night setback and the outdoor-temperature triggering the switch between summer and winter operation mode. Also, often the hydraulic system is not working optimally. In some cases control setting parameters can be adjusted online, if the contractor has the necessary access. However, usually on-site intervention by a craftsmen is required, in particular to resolve problems of the hydraulic system. Here, we examine field-data provided by energy saving contracting companies, compare the energy savings with the environmental impact of the technology and use a model to extrapolate the potential savings on the building stock in Germany.

DATA AND METHODS

We consider the case of apartment buildings with gas central heating located in Germany. Two sets of data are analysed. The data was acquired by two energy savings contractor companies, also for the energy savings program (Einsparzähler (BAFA 2021)) funded by the German government.

The first data set consists of energy savings recorded by the energy savings contractor Effiziente Wärme und Stromlieferung GmbH (EWUS). EWUS collects digitalized data on the natural gas consumption from the gas meter, the heat consumption, supply and return temperatures, as measured by a heat meter, via a mobile gateway. The frequency of the data transmission is 15 minutes. EWUS combines this data with outdoor temperature information from the nearest measurement spot of Deutscher Wetterdienst (German Meterological Service – DWD), determines the gas consumption as a function of the outdoor temperature and deduces possible measures to optimize the control parameters settings of the heating system. The proposed new settings are send as a recommendation to the building manager. The responsibility to implement the new settings lies with maintenance technician acting on behalf of the building management. The energy savings are determined by comparing the gas consumption with the values expected from the relation between gas consumption and outside temperature established prior to the change of the heating system settings. The data includes the recorded energy savings for 197 buildings with 6 to 158 apartments, their annual climate corrected gas consumption prior to the recommendation for new settings and the total living area. In the case of 65 buildings, the measured gas consumption is used solely for heating. In the other 132 buildings, the gas consumption includes the energy used for domestic hot water, which does not depend on the outside temperature. For these building the application of the climate correction factor on the gas consumption might introduce a small systematic error. Therefore, the two groups of building are analysed separately.

The energy savings contractor Energiezentrale Nord (EZN) provides the second data set. Additionally to the consumption data from the gas and heat meters, EZN collects data from a varying number – usually around 20 – temperature sensors at various positions in the heating system, e.g., hot water storage tanks and domestic hot water circulation system. The data transmission via mobile gateway occurs every minute. The comparatively high data frequency allows EZN to recognize switching operations almost in real time. EZN uses the gathered data – in combination with outdoor temperature data from the closest weather station – as input for an operation analysis of the heating system, supported by a learning software algorithm. EZN closely cooperates with the operators and thereby has direct access to the heating systems to implement optimized control parameter settings. For systems installed after ca. 2010 control parameters are usually optimized remotely. Problems concerning the hydraulic system or faulty components are resolved on site. The energy savings are determined by comparing the gas consumption in the year after the optimization to the average of three prior years – with climate corrections applied for the gas share used for heating, but not for domestic

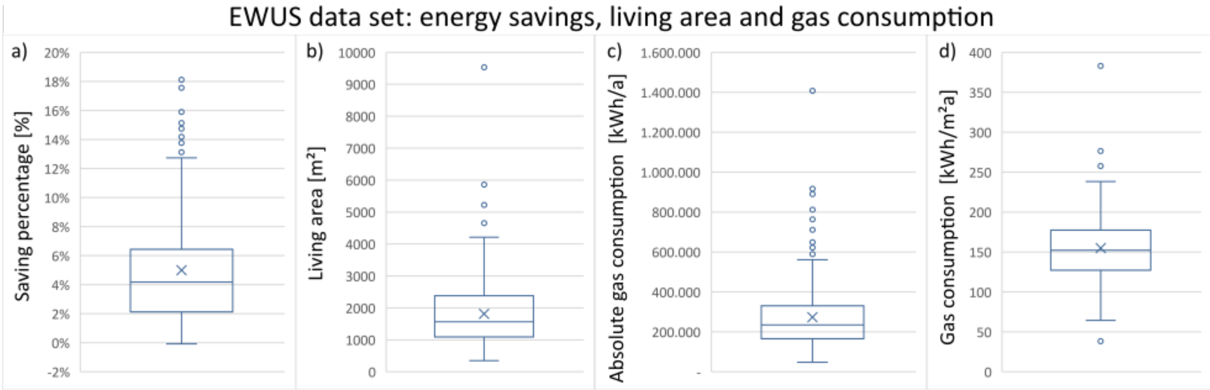

Figure 8. Saving percentage, living area, absolute gas consumption and gas consumption per square meter of the EWUS data set.

hot water. The data includes the measured energy savings and climate corrected annual consumptions for 34 buildings.

Similar to the ecological assessment of digital applications for the recording of electricity consumption, we calculate the yearly GHG emissions that can be attributed to the additional technical devices and data flows required for the online monitoring of heating systems. The considered devices are a heat meter, temperature sensors, an impulse adapter that converts the rotations of the gas meter, a data logger, a gateway and a mobile router that sends the collected data to the service provider. For all devices, as in the electricity sector, a lifetime of 12 years was assumed. The data is transmitted by mobile radio between the building and the energy savings contractor. Data evaluation and data storage takes place at the contractor's computer center. When the available data on the composition of a device is insufficient, we use a generic electronic component of the same weight, a method to estimate the ecological effects proposed by Gährs et al. (2021).

To extrapolate the savings potential of digital monitoring of heating systems operation in apartment buildings to the German building stock we use the GEMOD building model developed at ifeu (Jochum et al. 2017). GEMOD models the heat consumption of the German building stock for space heating and domestic hot water up to the year 2050. The model uses a number of different building types based on the building classifications of the Institut Wohnen und Umwelt[5], among them "small" and "large" apartment buildings from thirteen different construction periods. The modelling of the future evolution of the heat consumption takes into account new construction, demolition and renovation, as well as forecasts of demographic developments and living area per person. Renovations take place according to life times of building components calculated with a Weibull-distribution. The model differentiates between renovations without effect on the energy performance, renovations according to standard energy performance requirements and energetically ambitious renovations. The ambition levels for construction and renovation standards, as well as the number and share of the different renovation types are model variables. Based on the heat consumption GEMOD calculates the primary energy consumption and greenhouse gas emissions from different energy sources according to the share of the corresponding heating system types in the modelled building stock. The share of heating system types in the base year 2011 is derived from energy and market statistics. The future primary energy consumption is predicted depending on the assumed evolution of the share of different heating system types in new buildings and for boiler replacements. We use two variants for future evolution of final heat consumption, heating system changes and primary energy factors for greenhouse gas emissions: a "business-as-usual" evolution extrapolating current trends ("BAU scenario") and a development achieving an almost complete elimination of greenhouse gas emissions by 2050[6] with a strong increase in the use of ambient heat with heat pumps ("climate protection scenario").

RESULTS AND DISCUSSION

Savings potentials calculated from field data

EWUS data

The calculated climate corrected gas savings percentage in relation to the previous annual consumption is 5.0 % on average for the EWUS data[7]. The average for the buildings with integrated domestic hot water (DHW) was 4.8 % and for the rest it was 5.4 %[8]. Figure 8a) shows a boxplot of the savings for all buildings. For half of the buildings the savings are in the range of 2 % to 6 %, while some outliers achieved significantly higher values. Figure 8b) represents the distribution of the living area (average value 1,814 m²), Figure 8c) the absolute gas consumption (average value 273, 426 kWh/a) and Figure 8d) the consumption per square meter (average 155 kWh/m²a) of the data set as box plots. Scatter plots of the savings percentage as a function of these variables do not reveal any clear trend (Figure 9). No information is available on possible renovations

5. https://www.iwu.de/publikationen/fachinformationen/gebaeudetypologie/

6. https://langfristszenarien.de/enertile-explorer-de/index.php

7. If the data of a building included saving for two years, the average of these values was used as contribution from this building.

8. The application of the climate correction factor (see data and methods section) to an annual gas consumption including the energy used for hot domestic water – which is not affected by the outside temperature - introduces a systematic error that could contribute to different values for these two subsets.

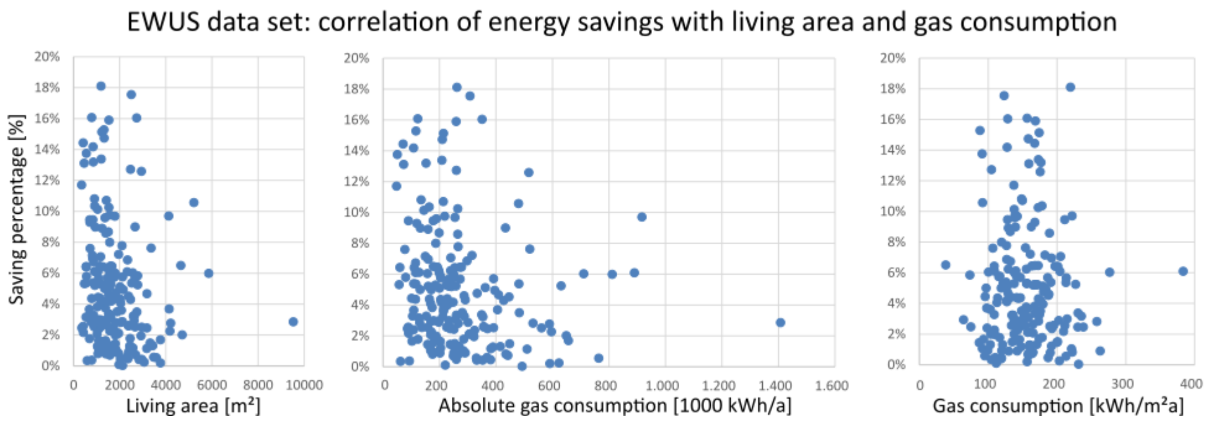

Figure 9. EWUS data set shows no correlation between savings percentage and living area or gas consumption.

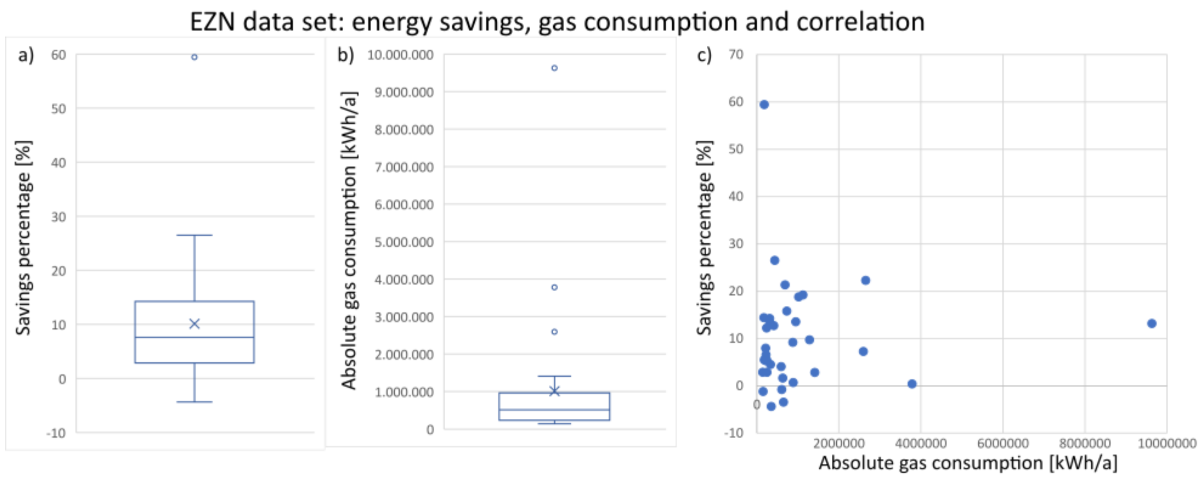

Figure 10. EZN data set: energy savings, gas consumption and correlation.

during the measurement period. However, we would expect higher savings from improvements of the building envelope than observed for the majority of the data set.

EZN data

Figure 10a) depicts a boxplot of the climate corrected saving percentage resulting from the EZN data. The average saving is 10.1 % (8.6 % if the outlier at 59.4 % is not considered), with half of the buildings achieving between 2.9 % and 14.3%. In four buildings, an increase of the gas consumption between 0.8 % and 4.4 % was detected, lowering the average of the savings. A boxplot in Figure 10b) shows the distribution of the annual gas consumption of the buildings – the average of 1,014,561 kWh lies above the median of 515, 472 kWh due to a few outlier buildings with a high consumption of several million kWh. The scatter plot in Figure 10c) shows no correlation between the saving percentage and the gas consumption.

In the buildings attended to by EZN, no heating replacements or relevant renovation of the building envelope took place in the measurement period. Only the hydraulic system was improved in some cases, following recommendations based on the online monitoring. Therefore, we directly attribute the recorded savings to the online monitoring.

Greenhouse gas saving potential compared to the emissions due to the digital devices and data transfer

Based on the empirical energy savings data from EWUS and EZN we assume two types of digital operation monitoring: a "low intensity" application achieving about 5 % and a "high intensity" application resulting in around 10 % primary energy savings for apartment buildings with gas central heating[9]. For other relevant heating types in apartment buildings, there is a lack of data. However, we can estimate the savings potentials (EZN, 2021): oil condensing boilers are less efficient than gas condensing boilers. Therefore, they benefit less from a reduced return temperature. We assume a saving potential of 80 % of the values for gas central heating, resulting in 8 % ("high intensity" operation monitoring) and 4 % ("low intensity" operation monitoring) for oil central heating. District heating (DH) supply can suffer from efficiency losses at the energy transfer station and problems in the hydraulic system. We assume a saving

9. We choose to use the savings percentage achieved by EZN including the outlier, because the original dataset contains another outlier of more than 50 % savings - not included in the analysis because it corresponds to one of the few building with district heating in the dataset - showing that savings of this magnitude are not a singular occurence.

Table 3. Energy savings by digital heating operation monitoring assumed for extrapolation of the savings potential on the building stock. Values for gas central heating based on empirical data. Estimates for oil and district heating.

	Applied saving percentage	
Operation monitoring type	low intensity	high intensity
Gas central heating	5%	10%
Oil central heating	4%	8%
District heating	3.3%	6.7%

Table 4. Yearly energy and greenhouse gas savings with operation monitoring in 2022 for a representative large apartment building from the GEMOD model.

Yearly energy and CO_2 equivalent savings for representative large apartment building in 2022				
Operation monitoring type	low intensity		high intensity	
Gas central heating	6 534 kWh/a	1,3 tCO_{2eq}/a	13 067 kWh/a	2,6 tCO_{2eq}/a
Oil central heating	4 788 kWh/a	1,3 tCO_{2eq}/a	9 721 kWh/a	2,6 tCO_{2eq}/a
District heating (DH)	4 512 kWh/a	1,1 tCO_{2eq}/a	9 025 kWh/a	2,1 tCO_{2eq}/a

potential of two-third compared to gas central heating: 6.7 % ("high intensity" operation monitoring) and 3.3 % ("low intensity" operation monitoring). Table 3 gives an overview of the different saving percentages.

GEMOD models the apartment building stock with two building types – "small" and "large" – each divided into subsets of thirteen construction periods with slightly different sizes. The average living area of the "large apartment building" is 1372 m² and the average gas consumption in the "BAU scenario" is 130,673 kWh/a (95 kWh/m²a) in 2022. All three values are smaller than the average values from the EWUS data. However, according to the data the savings appear to be independent of the size and gas consumption (see Figure 9 and Figure 10c). Here, we limit the calculation to "large apartment" buildings, because energy savings contractors currently appear to attend mostly this group. However, the target group of online monitoring of heating systems could potentially be increased in the future e.g., to smaller apartment buildings. For the representative "large apartment building" of the GEMOD model in the "BAU scenario", the savings percentage from Table 3 translate the consumption reductions and greenhouse gas savings shown in Table 4.

We compare the potential savings with the estimated yearly greenhouse gas emissions caused by the technical components for low and high intensity online monitoring: additional devices, data transfer, processing and storage result in GHG emissions of 7 $kgCO_{2eq}$/a ("low intensity" operation monitoring) and 14.5 $kgCO_{2eq}$/a ("high intensity" operation monitoring). For the "low intensity" case, 99 % of the emissions are due to the additional equipment. The data volume barely has an impact for this application. For the "high intensity" operation monitoring, the emissions attributable to the devices decrease to 95 %, as more data is collected, transferred, processed and stored. Hence, the estimated emissions amount to only about 0.5 % to 1 % of the calculated savings.

Extrapolation of potential energy and greenhouse gas savings on the German building stock

We use the GEMOD model data to estimate the potential energy and greenhouse gas savings from 2023 up to the year 2050, which could be achieved by applying digital operation monitoring on a larger scale. The evolution of the coverage rate of

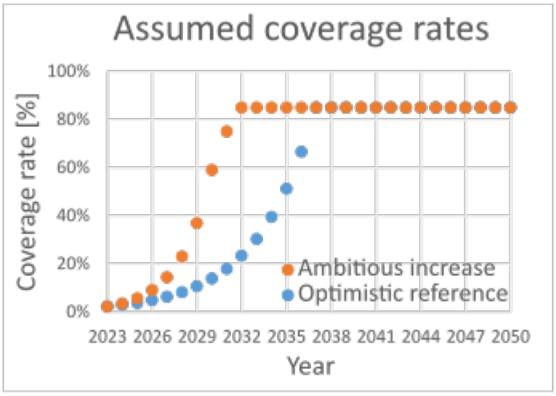

Figure 11. Assumed coverage rates for the two growth scenarios of digital operation monitoring in large apartment buildings.

digital heating operation monitoring is critical for the potential total primary energy and greenhouse gas savings. The number of large apartment buildings with digital operation monitoring was estimated at 3000 in 2020 (Gährs et al. 2021), corresponding to 1 % in the GEMOD model. With an estimated yearly growth rate of 30 % (Gährs et al. 2021), a 2,2 % coverage rate is assumed for 2023. We calculate two scenarios: 1) An "optimistic reference" - an extrapolation of the 30 % yearly growth rate until reaching a 85 % coverage in 2037 with a subsequent plateau; 2) An "ambitious increase" with a doubled growth rate of 60 % up to 2030, with a further increase to a coverage of 75 % in 2031 and 85 % in 2032 (see Figure 11).

We calculate the accumulated potential savings from 2023 to 2035 and 2023 to 2050 in TWh primary energy and CO_{2eq} for gas only and the combined potential of gas, oil and district heating. Table 5 shows the results for both operation monitoring growth scenarios for the "BAU scenario" of the large apartment building stock in GEMOD. The results for a building stock adapting to the objective of greenhouse gas neutrality in 2050 ("climate protection scenario") are listed in Table 6. As expected from the savings percentage in Table 3, the savings from the "high intensity" operation monitoring case double the savings from the "low intensity" case.

Table 5. Results of calculated savings potentials of operation monitoring in large apartment buildings for a business-as-usual evolution of the building stock.

"Business-as-usual" building scenario: savings from operation monitoring								
Coverage:	**Optimistic reference**				**Ambitious increase**			
Operation monitoring	**low intensity**		**high intensity**		**low intensity**		**high intensity**	
2023-2035: gas	2.3 TWh	0.5 Mt CO_2	4.8 TWh	1.0 Mt CO_2	6.3 TWh	1.3 Mt CO_2	12.6 TWh	2.5 Mt CO_2
2023-2035: gas, oil and DH	3.6 TWh	0.8 Mt CO_2	7.1 TWh	1.5 Mt CO_2	9.4 TWh	2.0 Mt CO_2	18.8 TWh	4.0 Mt CO_2
2023-2050: gas	16.1 TWh	3.2 Mt CO_2	32.3 TWh	6.5 Mt CO_2	20.3 TWh	4.1 Mt CO_2	40.5 TWh	8.1 Mt CO_2
2023-2050: gas, oil and DH	24.4 TWh	4.9 Mt CO_2	48.9 TWh	9.8 Mt CO_2	30.5 TWh	6.2 Mt CO_2	61.2 TWh	12.4 Mt CO_2

Table 6. Results of calculated savings potentials of operation monitoring in large apartment buildings for an evolution of the building stock adapting to greenhouse gas neutrality in 2050.

"Climate protection" building scenario: savings from operation monitoring								
Coverage:	**Optimistic reference**				**Ambitious increase**			
Operation monitoring	**low intensity**		**high intensity**		**low intensity**		**high intensity**	
2023-2035: gas	1.4 TWh	0.3 Mt CO_2	2.7 TWh	0.5 Mt CO_2	3.7 TWh	0.7 Mt CO_2	7.4 TWh	1.5 Mt CO_2
2023-2035: gas, oil and DH	2.3 TWh	0.5 Mt CO_2	4.7 TWh	1.0 Mt CO_2	6.3 TWh	1.3 Mt CO_2	12.7 TWh	2.7 Mt CO_2
2023-2050: gas	3.3 TWh	0.7 Mt CO_2	6.6 TWh	1.3 Mt CO_2	5.7 TWh	1.2 Mt CO_2	11.5 TWh	2.3 Mt CO_2
2023-2050: gas, oil and DH	9.2 TWh	1.7 Mt CO_2	18.5 TWh	3.4 Mt CO_2	13.4 TWh	2.6 Mt CO_2	26.8 TWh	5.2 Mt CO_2

The results show that active operation monitoring of the heating system provide the potential for very significant energy and green house emission savings. Introducing "high intensity" monitoring on the "ambitious increase" path only for the building type "large apartment" could save between 26.8 TWh (5.2 Mt CO_{2eq}) in the "climate protection" scenario and 61.2 TWh (12.4 Mt CO_{2eq}) in the "business-as-usual scenario until 2050. For comparison, the energy consumption in Germany for space heating and warm water in private households was 560 TWh in 2019 (BMWi 2021). The additional savings of an "ambitious increase" are especially relevant in the next one and a half decade. Until 2035, almost three times more energy can be saved with an accelerated introduction of operation monitoring comparted to the "optimistic reference" evolution. To achieve such an ambitious spread, future regulation must make active operation monitoring for heating systems in large apartment buildings necessary or very advantageous for owners – e.g., through new requirements on yearly efficiency and operation reports to tenants and increasing cost share of CO_2 taxes for landlords. Additionally, this path requires more professionals to implement the operation monitoring: one possibility could be to expand the scope of tasks for chimneysweepers.

The above calculations focus on fossil fuel and district heating. However, operation monitoring can also significantly improve the efficiency of heating systems run with heat pumps – e.g., by assuring the supply and return flow temperatures are as low as possible – or increase the share of renewable energy use in hybrid systems, for example with solar heat (EZN 2021). Therefore, operation monitoring should be applied to all types of heating systems to achieve the maximal environmental benefit.

Conclusion

The sequential recording of electricity consumption and feedback to customers achieve only very small savings across all measured households. Taking into account the additional effort caused by the smart meters and data processing, this results in almost a zero-sum game. Nevertheless, there has been a group of households that have significantly reduced their electricity consumption. We therefore suspect that there are households for which the digital application is suitable in order to save energy. At the same time, consumption in some households has increased. However, the reasons can be diverse. To mitigate this trend, more effort is required than this digital application can provide. It should be noted that the households that participated in this measurement made an active effort. This does not call into question the fundamental spread of smart meters for the energy transition, because they are needed for them. But they will probably be used mainly for other purposes, such as the control of variable consumers. Energy saving is not in the foreground, at least for the majority of households.

In contrast, our calculations, based on the data from two energy savings contractors on large apartment buildings, clearly show the ecological benefit of the digital recording and transmission of data on the energy use for heating as part of an online monitoring of the heating system operation. The average savings are about a 100 times higher than the additional greenhouse gas emissions from the devices and data transmission. However, to realise these energy savings, the recorded data on consumption needs to be analysed and the derived optimization measures have to be implemented. Regulation e.g., on regular optimization efforts in large apartment buildings should facilitate the upscaling of online monitoring of heating system operation.

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