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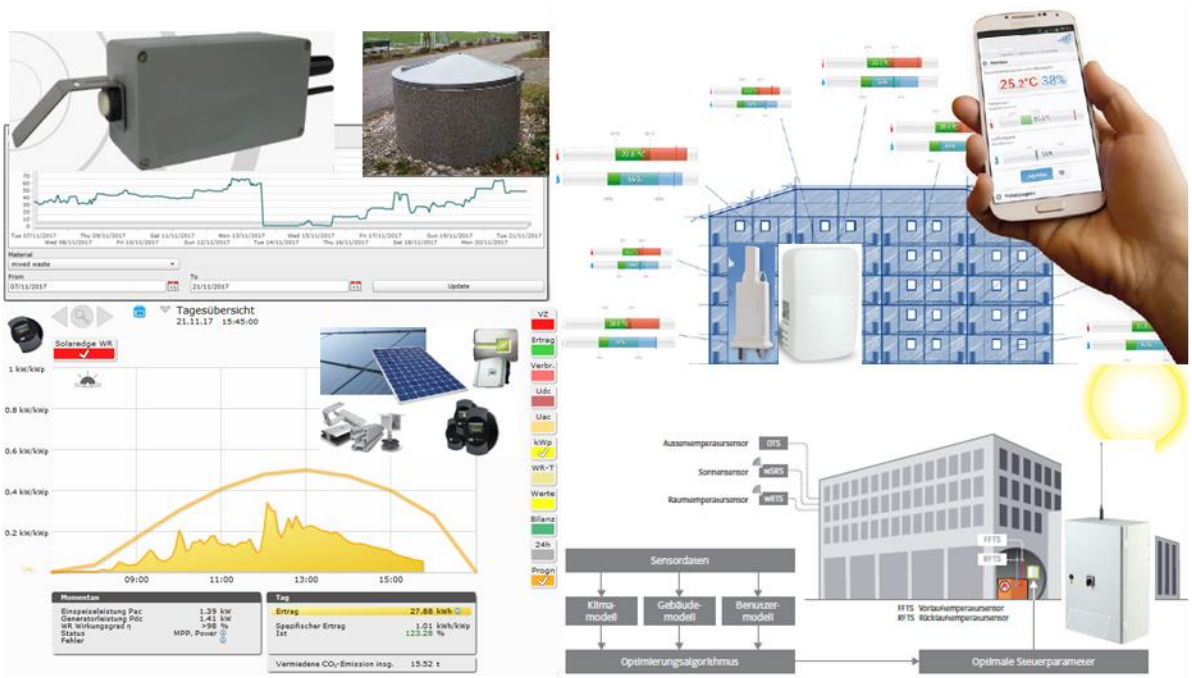
**Swiss Federal Office of Energy SFOE**
Energy Research

**Final report**

# Analysis of potential for Internet of Things (IoT) to act as an enabler for climate protection and the Energy Strategy 2050

## Impacts of IoT on energy consumption and $CO_{2eq}$ emissions in specific use cases

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## Abstract

The goal of this study was to investigate in four Swiss specific use cases whether the implementation of IoT equipment can act as an enabler for climate protection and the Energy Strategy 2050 in terms of reducing $CO_2$ emissions. Further, the potential quantity of $CO_{2eq}$ savings for Switzerland regarding the use cases for the year 2020 was analysed. The analysed use cases were remote PV monitoring, remote filling level monitoring of waste containers and heating optimisation, once for a service building and once for a multifamily house. The results clearly show that the grey energy of the IoT equipment is negligible in all investigated use cases compared to the avoided amount of $CO_{2eq}$ emissions. The upscaling of the results was based on assumption and gives a possible order of magnitude of annual savings in the year 2020 for Switzerland: 2.4 kt for PV monitoring, 115 t for level monitoring of waste containers, 0.3 Mt in the heating optimisation of service buildings and 2.3 Mt in the heating optimisation of domestic space.



## Zusammenfassung

Ziel dieser Studie war es, in vier konkreten Schweizer Anwendungsfällen zu untersuchen, ob der Einsatz von IoT-Geräten als Enabler für den Klimaschutz und die Energiestrategie 2050 zur Reduktion von $CO_2$-Emissionen dienen kann. Ferner wurde das $CO_{2eq}$-Einsparpotenzial für die Schweiz im Bereich der Anwendungsfälle für das Jahr 2020 analysiert. Die analysierten Anwendungsfälle waren PV-Fernüberwachung, Füllstandsfernüberwachung von Abfallbehältern und Heizungsoptimierung einmal für ein Dienstleistungsgebäude und einmal für ein Mehrfamilienhaus. Die Ergebnisse zeigen deutlich, dass die graue Energie der IoT-Geräte in allen untersuchten Anwendungsfällen im Vergleich zur vermiedenen Menge an $CO_{2eq}$-Emissionen vernachlässigbar ist. Die Hochskalierung der Ergebnisse basiert auf Annahmen und ergibt eine mögliche Größenordnung der jährlichen Einsparungen im Jahr 2020 für die Schweiz: 2.4 kt für die PV-Überwachung, 115 t für die Füllstandsfernüberwachung von Abfallbehältern, 0.3 Mt für die Heizungsoptimierung von Dienstleistungsgebäuden und 2.3 Mt für die Heizungsoptimierung von Mehrfamilienhäusern.

# Executive Summary

The Swiss population decided in 2017 to implement the Energy Strategy 2050. A main part of this strategy is to reduce $CO_2$ emissions. This can be achieved by both increasing efficiency and reducing the consumed amount of energy, as well as by substituting for fossil energy sources. A promising approach to facilitate energy reduction and increase efficiency may be offered by Internet of Things (IoT) applications [1] [2]. In this study, four different Swiss use cases, each equipped with IoT technologies, were analysed. Two of the four cases deal with automatic heating optimisation. Another addresses Swiss consumer power mix substitution with photovoltaic (PV) power, while the fourth deals with reduced waste collection routes due to remote waste level monitoring of underfloor containers. All four use cases were equipped with sensors according or similar to the definition of IoT. To be able to quantify the $CO_2$-equivalent savings of each use case, pre and post installation data were measured. Data collection and further calculation were based on a previous in-depth study of the $CO_{2eq}$ savings potential of an IoT-equipped system.

### Use case-specific savings potential

The relative $CO_{2eq}$ savings for heating optimisation are 18 - 19 %. For remote PV monitoring, the savings are up to 6 %. For the remote level monitoring of underfloor containers, the savings had to be calculated based on assumptions in combination with theoretically underpinning scenario planning, which predicted savings of 1 %. The different savings cannot be compared with each other because they are use case-specific: three of the four use case types are very different. Furthermore, the absolute savings potentials cannot be based only on the relative high or low savings of the use cases due to their specific circumstances. The focus of the analysis was only on $CO_2$-equivalents and not on further implications which could occur by the use or manufacturing of the installed products.

### Potential for Switzerland

It must be said that in all use cases, the quantity of data did not allow precise upscaling; therefore, further data samples must be analysed. Nevertheless, an initial order of magnitude of potential $CO_{2eq}$ savings for Switzerland can be given in the context of the use cases. The upscaling and therefore the results depend on assumptions. For yearly savings in 2020 in Switzerland, the four use cases yielded the following figures: up to 2.4 kt/y $CO_{2eq}$ due to remote PV monitoring; 0.3–2.3 Mt/y $CO_{2eq}$ (service buildings - domestic space) due to heating optimisation; and 115 t/y $CO_{2eq}$ due to remote waste container level monitoring. In comparison, Switzerland emitted in the year 2016 50 Mt of $CO_{2eq}$ [3]. This means that in case of heating optimisation of domestic space roughly 5 % of these $CO_{2eq}$ emissions could be saved.

### Discussion

These results can be discussed both individually (case-specific) and comparatively (cross-case). International studies have documented a much higher reduction in $CO_{2eq}$ for optimised waste collection than in the studied use case. The reasons for the small amount of $CO_{2eq}$ savings in the specific Winterthur use case can be explained as follows: First, the collection area is densely populated, and therefore the collection routes are hard to optimise. Second, it would not be cost-efficient to optimise the driven kilometres if just a few kilometres could be saved. This means that collection must always be as cost-efficient as possible. This is why focus was placed on time saving by implementation, resulting in higher cost reduction through the retrenchment of a collection lorry or the more efficient collection of waste with the same staff members. Further, other reasons support a fixed collection route, such as odour, methane production and the attraction of animals. However, if the focus is mainly on $CO_{2eq}$

savings, an investment in areas other than the route optimisation of urban waste collection may be worth considering first. For the remote PV monitoring use case, no international numbers were found for validation. Surprisingly, in the investigated case the annual production losses caused by soiling weight were more than those caused by an annual service trip. However, in cases where the inverter is already equipped with a remote monitoring function allowing anomaly detection, some $CO_{2eq}$ savings can be guaranteed. This is because nearly no additional grey energy is needed to enable the monitoring function. Therefore, from the $CO_{2eq}$ reduction perspective, it is worth spreading this technology further and keeping the remote PV monitoring option open by installing IoT-ready inverters. Heating optimisation based on pre and post installation data yielded promising amounts of net $CO_{2eq}$ savings. These technologies should be developed further until they become standard in heating controllers. At the current stage of technology, the investigated technology should be implemented for low-cost, fast $CO_{2eq}$ savings gains. If the ultimate goal is to reduce as much $CO_{2eq}$ as possible until 2020 based on the four investigated use cases, it is worth considering the installation of additional heating optimisation systems. Finally, in all four use cases, the grey energy was negligible compared to the potential $CO_{2eq}$ savings. Further, if standard technology is updated further with IoT technologies, as was done in the investigated use cases, then the overall environmental and social impacts would most likely be smaller than they would be without IoT. These conclusions are based only on $CO_{2eq}$ monitoring investigations.

# Contents

# 1 Introduction

In May 2017, the Swiss population decided to implement the Energy Strategy 2050 [4], starting in 2018. This strategy is based on three main elements: First, to increase energy efficiency; second, to expand the implementation of renewable energies; and third, to phase out nuclear power. Furthermore, quality of life should be maintained and $CO_2$ emissions reduced. For increasing energy efficiency, focus was placed on buildings, mobility, industry and appliances. As widely known, a reduction of consumed energy can be achieved by using less energy and by increasing energy conversion efficiency. In regard to using less energy, computerisation and especially the Internet of Things (IoT) [1] [2] seem to be promising solutions according to GeSI [5]. A study in the mobility sector yielded 30% $CO_2$ savings due to reduced searching for parking spaces if the parking spaces are equipped with IoT sensors [6]. A further study yielded savings of 18% if waste collection routes are optimised with IoT sensor-equipped waste containers [7]. In the building context, especially the heating sector, savings of up to 26% can be achieved, according to Fraunhofer-IBP [8]. Often, the exact framework of the study is not clear, and the measures taken cannot be evaluated in close detail. In this study, similar use cases in Switzerland were analysed. Accordingly, the following questions arose: Can a reduction in $CO_{2eq}$ always be expected with an increase of IoT sensors and appliances? What about the grey energy used by IoT equipment? What is the trade-off between grey energy and energy saved? These questions were answered in this study via an in-depth analysis of four specific IoT use cases: two in a building context, one in the mobility sector, and one in the mobility/industry sector.

# 2 Framework

## 2.1 Project goals

The aim of this project was to quantify, based on four use cases, the contribution of IoT to increased energy efficiency and climate protection. Moreover, the total contribution to the energy efficiency and climate protection goals of Switzerland were evaluated. In-depth analysis of the available data and of the use cases before and after the implementation of IoT solutions allowed for the investigation of the energy demand and carbon footprint of these use cases. In addition, upscaling for the $CO_{2eq}$ saving potential for the year 2020 for all use cases was conducted. All calculations in this study were based on a previous life cycle analysis (LCA) study [9], and therefore no further LCA is provided in this study.

## 2.2 Study set-up

The $CO_{2eq}$ calculation was based on GeSI recommendations [10] but did not consider potential rebound effects [11]. For example, some side effects could occur caused by IoT based optimisation. These side effects could lead to change in $CO_{2eq}$ emissions. If these $CO_{2eq}$ emissions now reduce the $CO_{2eq}$ savings, this could lead to rebound effects. Presently, in Switzerland, waste is collected in containers, and single bags are placed on the sidewalk in front of buildings. If conventional individual bag collection is replaced by container collection in order to enable monitoring, this inevitably leads to some households having a longer way to discard their waste. This could lead to using cars for garbage drop-off (monitored containers should not be densely packed in order to enable route optimisation and the filling of containers in an adequate amount of time). Alternatively, in heating optimisation, priority-setting should be reflected: If the majority of buildings are equipped with heating monitoring devices instead of being renovated in an energy-efficient manner, a huge amount of $CO_{2eq}$ savings will be lost. An estimation of the possible rebound effects at the current implementation stage is not possible and must be investigated further.

Therefore, the net $CO_{2eq}$ savings are calculated as shown in Table 1.

*Table 1: Formula to calculate the net $CO_2$ savings*

$$net\ CO_2\ savings = gross\ CO_2\ savings - CO_2\ emissions\ of\ the\ system$$

The calculation of the $CO_{2eq}$ emissions of the used IoT systems was based on the results of a previous study [9], and therefore no LCA was conducted in this study. The calculated $CO_{2eq}$ emission values were based on weight-specific up- or down-scaling of the previous study's results. Data collection for all four use cases took place in different ways. However, all companies behind the four use cases were orally interviewed according to guideline provided in the Appendix. Further data collection subsequently occurred according to the best available sources, mainly via desk research and written inquiries to different stakeholders. The outcome of the previous study [9] showed that no investigated life stages, such as usage or disposal, were relevant in terms of $CO_{2eq}$ emissions compared to the production of the sensor; thus, only the production phase was considered in this study.
To enable $CO_{2eq}$ calculation related to IoT hardware, measurements were based on the following reference values in Table 2, which are in relation to a life expectancy of 4.5 years.

*Table 2: Reference values for calculating the $CO_2$ emissions of the use case-specific IoT hardware*

| Component | Weight [kg] | $CO_{2eq}$ emissions [kg$CO_{2eq}$/a] |
|---|---|---|
| Sensor housing | 0.23 | 0.46 |
| Sensor electronic | 0.05 | 2.72 |
| Sensor battery | 0.10 | 0.16 |

To deal with different life expectancies, this value was adapted as well. Because lifespan and $CO_{2eq}$ emissions are almost linearly related (double the lifespan reduces $CO_{2eq}$ emission by one-half), adoption could be performed by a rule of proportion. All calculations for this study were made with Microsoft Excel (2016).

# 3 Use case 1: Remote level monitoring of underfloor containers

In this use case, focus was placed on $CO_{2eq}$ savings due to optimised waste collection routes based on filling level sensor-equipped underfloor containers. The analysis was based on data from an ongoing pilot project in the city of Winterthur. In this project, 60 underfloor containers were equipped with ultrasonic sensors to measure the filling level. The used system was provided by a company called Swisslogix [12]. At the time of the investigation of this use case, the monitoring system was used for time optimisation, not for route optimisation. This means that at the time, no route optimisation had taken place based on the IoT system. Therefore, no pre and post installation dates regarding route optimisation were available. The necessary data were collected by oral and written interviews with the system user and system provider. Further, the filling level of each sensor-equipped container was extracted from the monitoring website provided by the system operator. To enable the calculation of possible $CO_{2eq}$ savings, a theoretically optimised route was assumed based on the theoretically possible emptying cycles of four container locations. Today, waste collection takes place once per week on every collection route. A literature review, internet research and a previous LCA study [9] delivered additional necessary data. The results and calculations presented in this specific use case were generated by B. Shala and are based on his study [13].

## 3.1 Gross $CO_{2eq}$ savings

Because no data regarding an optimised route created by the installed system in this use case were available, the gross $CO_{2eq}$ savings were calculated once by investigating a single sensor-equipped container located slightly off the standard collection route and once by a theoretically optimised traditional collection route.

### 3.1.1 $CO_{2eq}$ savings of a single sensor-equipped container

To calculate the reduced $CO_{2eq}$ emissions for a single sensor-equipped container, the filling level of this container was investigated throughout one whole year based on data from the monitoring website of the system provider. With this information, the change in filling level within each week was calculated. As long as the sum of the weekly difference was smaller than 100% of the filling level, the container could be skipped from the collection route. The $CO_{2eq}$ savings were calculated according to the formula in Table 3 based on numbers provided in Table 4.

*Table 3: Formula to calculate the gross $CO_{2eq}$ savings of a single sensor-equipped container*

$$CO_{2eq,sc} = (C0_{2km} \times d \times 2 \times n_l)$$

| | |
|---|---|
| $CO_{2eq,sc}$ | $= CO_2\ savings\ of\ a\ single\ sensor-equipped\ container\ [\frac{kg\ CO_{2eq}}{y}]$ |
| $CO_{2eqkm}$ | $= CO_{2eq} emissions\ per\ km$ |
| 2 | $= Factor\ for\ collection\ trip\ (there\ and\ back)$ |
| $d$ | $= Distance\ between\ collection\ route\ and\ container$ |
| $n_l$ | $= Number\ of\ left-outs$ |

*Table 4: Variables to calculate the gross $CO_{2eq}$ savings of a single sensor-equipped container*

| Variable | Value | Source |
|---|---|---|
| Distance between collection route and container | 1.55 km | Google maps |
| Number of left-outs within a year | 12 | Monitoring website [14] |
| Average $CO_{2eq}$ emission per km | 2.25 $kgCO_{2eq}$/km | [15] |

The outcome of this calculation is the gross $CO_{2eq}$ savings of a single sensor-equipped container, which was 84 $kgCO_{2eq}$/y. As can be seen in the formula, the distance between the collection route and the container plays an important role.

### 3.1.2 $CO_{2eq}$ savings of a theoretically optimised collection route

To account for the fact that more than one container along a collection route is equipped with sensors, a traditional collection route with four sensor-equipped container places (total eight sensors) among all non-sensor-equipped containers was taken into the calculation. The possible left-outs of each of the four investigated containers was calculated the same way as with one container (see 3.1.1). The calculation of the saved $CO_{2eq}$ emissions was then completed according to the formula in Table 5 and the numbers in Table 6. The gross $CO_{2eq}$ savings of this calculation was 75 $kgCO_{2eq}$/y.

*Table 5: Formula to calculate the gross $CO_{2eq}$ savings of one collection route with four places with sensor-equipped containers*

$$CO_{2eq,sr} = (\sum_{C1}^{C5} d_{cn} \times n_{lcn}) \times C0_{2eqkm} \times 2$$

$CO_{2eq,sr}$ $= CO_{2eq}\ savings\ of\ one\ single\ route\ [\frac{kg\ CO_{2eq}}{y}]$

$CO_{2eqkm}$ $= CO_2 emissions\ per\ km$

$2$ $= Factor\ for\ collection\ trip\ (there\ and\ back)$

$d$ $= Distance\ between\ collection\ route\ and\ container$

$n_l$ $= Number\ of\ left-outs$

*Table 6: Variables to calculate the gross $CO_{2eq}$ savings of one collection route with four places with sensor-equipped containers*

| Variable | Value | Source |
|---|---|---|
| Distance between collection route and container 1 | 0.15 km | Google maps |
| Distance between collection route and container 2 | 0.55 km | |
| Distance between collection route and container 3 | 0.05 km | |
| Distance between collection route and container 4 | 0.50 km | |
| Number of left-outs within a year container 1 | 8 | Monitoring website [14] |
| Number of left-outs within a year container 2 | 16 | |
| Number of left-outs within a year container 3 | 12 | |
| Number of left-outs within a year container 4 | 12 | |
| Average $CO_{2eq}$ emission per km | 2.25 $kgCO_{2eq}$/km | [15] |
| Sum of the annual driven kilometres without optimisation | 2017 km | $52\ tours \times 38.78 km/tour$ |

## 3.2 $CO_{2eq}$ emissions of the installed system

To enable a calculation based on values of the previous LCA (see Table 7), the Swisslogix ultrasonic sensor was treated like an IoT sensor. Table 8 shows the main input parameters for this calculation, and Table 9 shows the calculated $CO_{2eq}$ emissions caused by the used system per ultrasonic sensor.

*Table 7: Used values from existing LCA study for up/down scaling*

| Component | Weight [kg] | $CO_{2eq}$ emissions [kg$CO_{2eq}$/y] |
|---|---|---|
| Sensor housing | 0.23 | 0.46 |
| Sensor electronic | 0.05 | 2.72 |
| Sensor battery | 0.10 | 0.16 |
| | | |
| Life expectancy | 4.5 years | |

*Table 8: Used components, specifications and data sources for calculation*

| Component | Specification | Data source |
|---|---|---|
| Sensor housing | 0.25kg | Interview Swisslogix |
| Sensor electronic | 0.10kg | |
| Sensor battery | 0.05kg | |
| Life expectancy | 9 years | |

*Table 9: Calculated $CO_{2eq}$ emissions of hardware and service/maintenance trips caused by the system*

| Component | $CO_{2eq}$-emissions per year [kg$CO_{2eq}$/y] | Calculation: $\frac{kgCO_{2eq}(LCA) \times kg(this\ study)}{kg\ (LCA) \times LCF}$ |
|---|---|---|
| Sensor housing | 0.10 | |
| Sensor electronic | 2.72 | |
| Sensor battery | 0.04 | |
| Total1 | **2.86** | |
| Life correction factor (LCF) | 2 | |

## 3.3 Net $CO_{2eq}$ savings

The net $CO_{2eq}$ savings were then calculated according to the formula in Table 1. The outcome of this calculation was, for the single container, 81 kg$CO_{2eq}$/y, and for the optimised route, 72 kg$CO_{2eq}$/y. The percentage change was then calculated according to the formula in Table 10 and the numbers in Table 11.

*Table 10: Formula to calculate the percentage change pre and post route optimisation of $CO_{2eq}$ emissions*

$$percentage\ change = \frac{kgCO_{2e,post} - kgCO_{2e,pre}}{kgCO_{2e,pre}}$$

$kgCO_{2e,post} \quad = CO_{2e}\ emission\ post\ installation$

$kgCO_{2e,pre} \quad = CO_{2e}\ emissions\ pre\ installation$

*Table 11: Pre and post route optimisation numbers*

| Variable | $kgCO_{2eq}/y$ | |
|---|---|---|
| $CO_{2eq}$ emission pre installation one single container | 363 | |
| $CO_{2eq}$ emission post installation one single container | 282 | 363 $kgCO_{2eq}/a$ – 81 $kgCO_{2eq}/y$ |
| $CO_{2eq}$ emission pre installation collection route | 4538 | |
| $CO_{2eq}$ emission post installation collection route | 4486 | 4538$kgCO_{2eq}/y$ + 8*2.86 $kgCO_{2eq}/y$ - 75 $kgCO_{2eq}/y$ |

The outcomes of these calculation are as follows. For a single container, the percentage change was -22%. This means that the single monitored container allows a $CO_{2eq}$ reduction of 22%. In the case of the whole route, a savings of 1.1% occurred. This means that if a whole route is taken into consideration, the savings compared to that by a single container are close to zero.

## 3.4 Upscaling for Switzerland

The upscaling was conducted based on the annual amount of $CO_{2eq}$ emissions caused by the kilometres driven by the waste collection fleet of Winterthur (359,837 kg $CO_{2e}/y$) multiplied by the potential savings of 1.1%. The outcome was 4123 $kgCO_{2eq}/y$ or 3.8 gr $CO_{2eq}/y$ and capita [16]. For the upscaling, the total population of Swiss cities larger than 15,000 inhabitants [16] was taken and multiplied by 3.8 gr $CO_{2eq}/y$ and capita. Based on this number, the amount of $CO_{2eq}/y$ that could be saved in Switzerland in 2020 is 115 t $CO_{2eq}/y$.

## 3.5 Conclusions

Despite the fact that in Switzerland, community-operated waste collection systems are in operation on fixed routes, the implementation of IoT-based route optimisation can lead to some $CO_{2eq}$ savings from the beginning. Even though the savings are small at the beginning, they could grow with the number of IoT-ready bins because per sensor and year, only 1.3 km needs to be avoided for the system to work efficiently in terms of $CO_{2eq}$ emissions. Therefore, the savings for 2020 are most likely higher than that estimated in this study. If it is further taken into consideration that waste not only needs to be collected in relatively densely populated cities with some limitation in route optimisation but in rural areas as well, then the savings could easily amount to 22%, as seen in the investigation of a single container. Further, the optimisation has some technical limitations as well as hygienic complications (the attraction of rats and other animals) and the unwanted formation of methane or other odours, which in the worst case could lead to rebound effects. The calculation of this use case was based on some general numbers from the city of Winterthur, and therefore the outcome must be viewed in this context. To enable more in-depth analysis, the whole collection process should be analysed step by step because $CO_{2eq}$ emissions per kilometre during waste collection seems to be rather high. It could well be that the number of emptied containers and the compression of waste, not the saved kilometres, are the relevant parts in terms of $CO_{2eq}$ savings. This question could be addressed in a future investigation. Despite the $CO_{2eq}$ thematic, it must be said that the IoT system used could save time in the case of Winterthur.

# 4 Use case 2: Remote photovoltaic (PV) monitoring

In this use case, the focus was on possible $CO_{2eq}$ savings by reduced service and maintenance trips on the one side and by upgrading the Swiss consumer power mix with more PV power by shortening the periods of failure with remote monitoring on the other. The analysis was done based on data provided by RESiQ, a PV installation and service company. This company was selected because it equips every PV plant with the option for remote monitoring. The product used is called SolarLog [17], a device which enables the transfer of PV parameters by the internet or mobile communication networks. This way, it is possible to analyse and display the performance of the PV plant at any time and place. All the needed data for this use case were obtained by written or oral interviews with the installation company and the hardware provider. Further data were extracted from the monitoring website of RESiQ [18], a previous LCA study [9] and a literature and internet research. Unfortunately, no pre and post installation data could be compared because no pre installation data were available. Therefore, some data had to be estimated. To calculate the mean service travel distance, 61 monitored PV plants were taken, and the length between the two RESiQ subsidiaries was calculated. The mean value (see Table 12) was then calculated for the shortest routes from the PV plant to one of its branches.

*Table 12: Mean service trip and number of PV plants*

| Variable | Value | Source |
|---|---|---|
| Number of PV plants | 61 | https://home.solarlog-web.ch/6.html?myfilter=1&filtervalue=CH-647 |
| Annual PV production (RESiQ PV plants) | 2,144,782 kWh/a | |
| Mean annual PV production per PV plant | 35,160 kWh/a | |
| Life expectancy PV plant | 25 a | |
| Mean service trip | 34 km | |
| $CO_{2eq}$ emission CH pick up <3.5t | 0.33 kg$CO_{2eq}$/km | [19] |

## 4.1 Gross $CO_{2eq}$ savings

### 4.1.1 $CO_{2eq}$ savings through reduced service and maintenance trips

To first investigate whether monitoring can lead to a reduction of annual service trips to clean the PV plants, the tipping point between $CO_{2eq}$ emissions and PV yield loss due to soiling and emissions from an average service trip was calculated based on the numbers in Table 12 and Table 14 with the formula in Table 13.

*Table 13: Formula to calculate tipping point between $CO_{2eq}$ emissions due to soiling and the average service travel distance*

$$TP = (M_{st} \times 2 \times \gamma_{sc})/\gamma_{spm}$$

| | |
|---|---|
| $TP$ | $= Tipping\ point\ [\frac{kWh}{incident}]$ |
| $M_{st}$ | $= Mean\ service\ travel\ distance$ |
| 2 | $= Factor\ for\ service\ trip\ (there\ and\ back)$ |
| $\gamma_{sc}$ | $= CO_{2eq}/km\ emission\ service\ car$ |
| $\gamma_{spm}$ | $= CO_{2eq}/kWh\ emission$ of Swiss consumer power mix |

The result of this calculation was 124 kWh/incident. This means that if the yield loss due to soiling is above this value, then the $CO_{2eq}$ emissions of the service trip are smaller than the $CO_{2eq}$ emissions from 'lost' PV yield. This value refers to 0.3% of the annual PV production of an average RESiQ PV plant (see Table 12). A comparison to the literature shows that the average yearly PV yield loss due to soiling is between 0.5% and 10% [20]–[23]. In other words, a reduction of annual service trips from a $CO_{2eq}$ emission point of view is not target-oriented. Therefore, the initial intention to calculate the $CO_{2eq}$ savings throughout reduced service trips for cleaning PV plants was disregarded.

### 4.1.2 $CO_{2eq}$ savings through substitution of Swiss consumer power mix

For the substitution of the Swiss consumer power mix with PV power, the values in Table 14 and Table 12 were used in the formula in Table 15 to calculate the $CO_{2eq}$ savings per kWh of produced PV power. The results of these calculations are shown in Table 16.

*Table 14: Variables to calculate the $CO_{2eq}$ savings through substitution of Swiss consumer power mix with PV power*

| Variable | Value | Source |
|---|---|---|
| Average failure time pre | 0.12 (45 days/failure event) | Based on the assumption that at the quarterly meter readings for billing, failures will be detected, with an average failure time of 45 days |
| Average failure time post | 0.004 (1.5 days/failure event) | Interview RESiQ |
| Failure of inverter during lifetime of PV plant | 1 | [24] |
| Other failure rate during lifetime of PV plant | 0.20 | [24], [25] |
| $CO_{2eq}$ emission of Swiss consumer power mix | 0.182 $kgCO_{2eq}$/kWh | [26] |
| $CO_{2eq}$ emission of Swiss PV power | 0.013 $kgCO_{2eq}$/kWh | [26] |

*Table 15: Formula to calculate the $CO_{2eq}$ savings through substitution of Swiss consumer power mix with PV power per kWh of produced PV power*

$$CO_{2eqs,su2} = \frac{(ft_{pre} - ft_{post}) \times (\gamma_{spm} - \gamma_{pvp})}{LE}$$

$CO_{2eqs,su2}$ $= CO_{2eq}$ saved substitution Swiss consumer power mix $[kgCO_{2eq}/kWh]$

$ft_x$ = failure time pre or post installation

$\gamma_{spm}$ = Emission factor for Swiss consumer power production

$\gamma_{pvp}$ = Emission factor for PV power production

$LE$ = Life expectancy PV plant

*Table 16: Main results of gross $CO_{2eq}$ savings through substitution of Swiss consumer power mix*

| Variable | Result |
|---|---|
| Gross $CO_{2eq}$ savings through substitution | 0.001 $kgCO_{2eq}$/kWh |

## 4.2 $CO_{2eq}$ emissions of the installed system

To enable a calculation based on values of the previous LCA (see Table 17), the SolarLog device was treated like an IoT sensor. Table 18 shows the main input parameters for this calculation, and Table 19 shows the calculated $CO_{2eq}$ emissions caused by the used system once per PV plant and once per kWh of PV production based on an average RESiQ PV plant.

*Table 17: Used values from existing LCA study for up/down scaling*

| Component | Weight [kg] | $CO_{2eq}$ emissions [$kgCO_{2eq}/y$] |
|---|---|---|
| Sensor housing | 0.23 | 0.46 |
| Sensor electronic | 0.05 | 2.72 |
| Sensor battery | 0.10 | 0.16 |
| | | |
| Life expectancy | 4.5 years | |

*Table 18: Used components, specifications and data sources for calculation*

| Component | Specification | Data source |
|---|---|---|
| Sensor housing | 0.36kg | [27] |
| Sensor electronic | 0.38kg | |
| Sensor battery | -- | |
| Life expectancy | 25 years | |

*Table 19: Calculated $CO_2$ emissions of hardware and service/maintenance trips caused by the system.*

| Component | $CO_{2eq}$-emissions per year [$kgCO_{2eq}/y$] | Calculation: $\frac{kgCO_{2eq}(LCA) \times kg(this\ study)}{kg\ (LCA) \times LCF}$ |
|---|---|---|
| Sensor housing | 0.13 | |
| Sensor electronic | 3.70 | |
| Sensor battery | -- | |
| Total1 | **3.83** | |
| | | |
| Total2 | **0.0001** $kgCO_{2eq}/kWh$ | Total1/Average PV production |
| | | |
| Life correction factor (LCF) | 5.56 | |

## 4.3 $CO_{2eq}$ emissions of the triggered service trips

On the one hand, the detection of a breakdown at a PV plant triggers a service trip; but on the other hand, this service trip must be done anyway, if not at the moment of detection than at a later stage. Therefore, the detection of a breakdown does not trigger additional service trips and thus no additional $CO_{2eq}$ is emitted.

## 4.4 Net $CO_{2eq}$ savings

The net $CO_{2eq}$ savings were then calculated according to the formula in Table 1. The result is shown in Table 20.

*Table 20: Net $CO_{2eq}$ savings per kWh of produced PV power*

| Variable | Result |
|---|---|
| Net $CO_{2eq}$ savings per kWh of produced PV power | 0.0009 $kgCO_{2eq}/kWh$ |

The percentage change in $CO_{2e}$ emissions was calculated based on numbers in Table 21 and the formula in Table 10. The result of this calculation was 6%. This means that 6% of the $CO_{2e}$ emissions could be saved if the PV plants are equipped with IoT monitoring systems.

*Table 21: Numbers to calculate the percentage change in $CO_{2e}$ emissions*

| Variable | Value | Remark |
|---|---|---|
| $CO_{2e}$ emission pre installation | 30,186 $kgCO_{2e}/a$ | Sum of regular PV production and lost PV production |
| $CO_{2e}$ emission post installation | 28,352 $kgCO_{2e}/a$ | Sum of increased regular PV production and reduced lost PV production by IoT and IoT equipment |

Furthermore, the $CO_{2eq}$ break-even point was calculated. This is the point at which the $CO_{2eq}$ savings and the $CO_{2eq}$ emissions from the hardware are balanced; accordingly, if more $CO_{2eq}$ is reduced, then the savings will become positive. This was calculated for the substitution of the Swiss consumer power mix by dividing the $CO_{2eq}$ emissions of the used IoT hardware by the net $CO_{2e}$ savings (see Table 20). The result shown in Table 22 indicates that if, per PV plant and year, 4486 kWh of Swiss consumer power mix could be substituted by PV power, the system will work efficiently in terms of $CO_{2eq}$ savings.

*Table 22: $CO_{2eq}$ break-even point per energy carrier*

| Variable | Result |
|---|---|
| $CO_{2eq}$ break-even point for substitution | 4486 kWh/y |

## 4.5 Upscaling for Switzerland

The upscaling for Switzerland was done on the numbers provided by Swissolar, a Swiss solar energy association. Their roadmap has foreseen that by 2020, PV power will deliver 2.8 TWh per annum [28]. The net savings were then calculated by multiplying this number with the net savings per kWh of PV power (see Table 20). The outcome of this calculation can be seen in Table 23.

*Table 23: Calculated $CO_{2eq}$ savings in 2020*

| Variable | Result [$kgCO_{2eq}/y$] |
|---|---|
| $CO_{2eq}$ savings total PV power in 2020 | 2,393,589 |

If only the PV plants installed by RESiQ in 2017 are considered, the total amount of savings is 1833 $kgCO_{2eq}/y$.

## 4.6 Conclusions

The analysis of this use case shows that a promising $CO_{2eq}$ savings potential exists in the PV monitoring sector. A very interesting feature in this sector is that new inverters already have a built-in monitoring function, and therefore no additional device needs to be installed. Although the estimated savings for 2020 must be approached cautiously, this technology nevertheless contributes overall to some $CO_{2eq}$ savings, as the more reliable results, if just the PV plants installed by RESiQ are considered, show. A major problem in the field of PV is that production is dependent on many variables, which makes the calculation of a factor usable for all kinds of PV systems nearly impossible. Therefore, the numbers in this use case must be approached with caution, and the $CO_{2eq}$ savings of other PV systems should be calculated as well. Further, in terms of substitution, the savings decreased with an increased share of PV power in the Swiss consumer power mix.

# 5 Comparison of investigated IoT equipment for heating optimisation

The two IoT systems for heating optimisation described below in sections 6 and 7 work according to two different approaches. However, they are similar in that both are an add-on to existing heating controllers. These add-ons interact with the existing controllers by replacing the signal of the outdoor temperature sensor with a calculated value. Approach 1 in section 6 is a cloud-based system that works with professional weather forecast data comprising temperature, precipitation, wind speed and direction, solar irradiance, angle and reflection. Further sensors for measuring interior temperature and humidity, building specifications and thermodynamic calculations are mathematically linked to a learning algorithm [29]. Approach 2 in section 7 is a system based on Model-Predictive Control (MPC) [30]. This system uses sensors to measure indoor and outdoor temperature, return and flow temperature of the heating system, and solar irradiance. But instead of forecasted weather data, this system calculates outdoor conditions based on sensor information with the help of a learning algorithm [30]. Roughly, it can be said that approach 1 is based on professional weather forecasts, while approach 2 relies on predictive calculated weather data.

# 6 Use case 3: Heating optimisation based on weather forecast

In this use case, the focus was on possible $CO_{2eq}$ savings due to reduced heating energy, such as oil or gas, during the heating period (Oct year A - May year B). The investigated building was a residential complex located in the city of Zürich. The building has an energy reference area of approximately 5000 $m^2$, and the optimised system went into operation on 1 January 2016. The pre installation energy consumption was 150 $kWh/m^2$, while energy consumption post installation was 121 $kWh/m^2$. The reduction of heating energy was achieved by the installation of wireless temperature and humidity sensors within the building and the replacement of the external temperature sensor by a weather forecast data receiver. After reconditioning all sensor information, the existing heating system was controlled with the updated values. No other energy-related refurbishment took place, and therefore the savings can be attributed only to the optimised heating system. The system can be connected by internet or mobile network to the main server of the providing company and can be monitored and controlled by an online dashboard. Thanks to such improvements being implemented, malfunctions can be detected as soon as they occur, and most importantly, heating can be optimally maintained. In this use case, pre and post installation data on fuel consumption by the heating system were compared to calculate the savings. The pre installation data comprised monthly energy consumption data from the year 2015. The post installation data were more or less monthly readings starting on 26 January 2016 and ending on 28 April 2017. To account for different weather conditions, all data were weather-adjusted with the following formula (see Table 24), which is often used in Switzerland, according to E.A. Müller et.al. [31].

*Table 24: Weather-adjustment formula*

$$E_{adj} = \frac{E_{mea} \times \alpha \times HDD_{avr}}{HDD_{mea} + E_{mea} \times (1-\alpha)}$$

$E_{adj}$ = *Energy adjusted*

$E_{mea}$ = *Energy measured*

$\alpha$ = *Factor for the share of temperature − dependent consumption in the total consumption of fuel*

$HDD_{avr}$ = *Heating Degree Days average*

$HDD_{mea}$ = *Heating Degree Days measured*

Often, the value of 0.75 is used for α. This means that 75% of the energy used for heating is dependent on the weather condition, while 25% is independent (for example, warm water, user behaviour). In this study the value 1 was taken for α because the weather independent energy was known (24.5 MWh/month) and subtracted from the heating energy before weather adjustment. The weather data were taken from the municipality of Zürich [32], and the long-term mean values were extracted from [33], [34]. To enable a monthly pre and post comparison, the consumption values had to be adapted to full months whereby the readings were not taken exactly at the last day of each month. The readings varied between five days ('too early') and seven days ('too late'). To enable this configuration, the assumption was made that the weather at the end or at the beginning of a month was on average the same as during the rest of the considered month. Accordingly, the energy consumption per month was calculated in Excel according to the following formula.

Monthly heating energy = IF(O5-N5>0;S5*Q5+ABS(P5)*S6;IF(AND(O5-N5<0;P3>=0);R5-ABS(P5)*S5-P3*S5;IF(AND(O5-N5=0;Q5=M5);S5*Q5;S5*(Q5-ABS(P5))+ABS(P3)*S3)))

To see the values for the matrix positions, see Table 25 below.

*Table 25: Example for used values for month-wise adaption*

| M | N | O | P | Q | R | S | T |
|---|---|---|---|---|---|---|---|
| Days of Month | Reading date | month-end date | early/late days | Days within reading period | Energy reading | R/Q | Mothly heating energy |
| 31 | 26.01.2016 | 31.01.2016 | 5 | 26.0 | 136.0 | 5.2 | 153.9 |
| 29 | 01.03.2016 | 29.02.2016 | -1 | 35.0 | 125.0 | 3.6 | 103.6 |
| 31 | 07.04.2016 | 31.03.2016 | -7 | 37.0 | 116.0 | 3.1 | 97.6 |

## 6.1 Gross $CO_{2eq}$ savings

After the monthly heating energy use was adapted, the percentage change between pre and post installation data was calculated month by month between 2015/2016 and 2015/2017 (see Table 26).

*Table 26: Calculation of percentage change*

$$percentage\ change = \frac{E_{post} - E_{pre}}{E_{pre}}$$

In a further step, the percentage change in the mean value of each month was calculated over the system operation period. Considering that the total saved amount of $CO_{2eq}$ is dependent on the monthly percentage savings and the amount of consumed fuel, the mean percentage change of each month was weighted with the formula in Table 27 to calculate the monthly weighting factor.

*Table 27: Formula to calculate monthly weighting factor*

$$mwf = \frac{\sum_{2015}^{2017} mhe}{\sum_{2015}^{2017} heh}$$

$mwf \quad = monthly\ weighting\ factor$

$mhe \quad = monthly\ heating\ energy$

$heh \quad = heating\ energy\ heating\ period$

For the overall percentage saving, the weighted percentage change of each month was summed over the heating period. To calculate gross $CO_{2eq}$ savings, $CO_{2eq}$ emissions of the oil and gas energy carriers, the most common fuels for heating in Switzerland [35], were assessed. The specific emissions per kWh of these energy carriers are shown in Table 28. With these values and the used amount of heating energy in the years 2015 and 2016, the gross $CO_{2eq}$ savings were calculated using the formula in Table 29. In Table 30, the main results regarding gross $CO_{2eq}$ savings are shown.

*Table 28: $CO_2$ emissions of the two most common energy carriers for heating in Switzerland*

| Energy carrier | $CO_{2eq}$ emissions [$kgCO_2$/kWh] | Share in heating sector | Source |
|---|---|---|---|
| Oil | 0.317 | 47% | [36], [37] |
| Gas | 0.259 | 16% | |

*Table 29: Formula to calculate the gross $CO_{2eq}$ savings*

$$CO_{2eqs} = \gamma_{ec} \times (\sum_{Jan}^{May} E_{month,pre} + \sum_{Oct}^{Dec} E_{month,pre} - \sum_{Jan}^{May} E_{month,post} + \sum_{Oct}^{Dec} E_{month,post})$$

$CO_{2eqs} \quad = CO_{2eq} savings$

$\gamma_{ec} \quad = Emission\ parameter\ of\ energy\ carrier\ (oil\ or\ gas)$

$E_{month,x} \quad = Energy\ consumption\ per\ month\ pre\ or\ post\ intstallation$

*Table 30: Main results of gross $CO_{2eq}$ savings*

| Variable | Result |
|---|---|
| weighted percentage reduction of heating energy | -19.3% |
| $CO_{2eq}$ savings per heating period oil | 38,776 $kgCO_{2eq}$/a |
| $CO_{2eq}$ savings per heating period gas | 31,726 $kgCO_{2eq}$/a |

## 6.2 $CO_{2eq}$ emissions of the installed system

To calculate the $CO_{2eq}$ emissions of the installed system, all temperature and humidity sensors as well as the forecast receiver were treated as a single IoT sensor to enable upscaling based on the data from the previous LCA study (see Table 31). Table 32 shows the main inputs for the up/down scaling, and Table 33 shows the $CO_{2eq}$ emissions of the installed system. To install and maintain the system, some service traffic is caused, so resultant $CO_{2eq}$ emissions must be considered as well. Because no heavy equipment for installation was needed, this calculation was done with the average $CO_{2eq}$ emissions of a Swiss passenger car.

*Table 31: Used values from existing LCA study for up/down scaling*

| Component | Weight [kg] | $CO_{2eq}$ emissions [$kgCO_{2eq}$/y] |
|---|---|---|
| Sensor housing | 0.23 | 0.46 |
| Sensor electronic | 0.05 | 2.72 |
| Sensor battery | 0.10 | 0.16 |
| | | |
| Life expectancy | 4.5 years | |

*Table 32: Used components, specifications and data sources for calculation*

| Component | Specification | Data source |
|---|---|---|
| Forecast receiver housing | 0.51kg | Interview eGain |
| Forecast receiver electronic | 0.11kg | |
| Forecast receiver battery | -- | |
| Life expectancy forecast receiver | 30 years | |
| Sensor housing | 0.05kg | |
| Sensor electronic | 0.05kg | |
| Sensor battery | 0.30kg | |
| Life expectancy battery | 17 years | |
| Average $CO_{2eq}$ emissions/km CH car | 0.32kg$CO_{2eq}$/km | [38] |
| Length of service tour/system life | 120km | Interview eGain |

*Table 33: Calculated $CO_{2eq}$ emissions of hardware and service/maintenance trips caused by the system.*

| Component | $CO_{2eq}$-emissions per year [$kgCO_{2eq}$/y] | Calculations: |
|---|---|---|
| Forecast receiver housing | 0.16 | $\frac{kgCO_{2eq}(LCA) \times kg(this\ study)}{kg\ (LCA) \times LCF}$ |
| Forecast receiver electronic | 0.92 | |
| Forecast receiver battery | -- | |
| | | |
| Sensor housing | 0.01 | $\frac{kgCO_{2eq}(LCA) \times kg(this\ study)}{kg\ (LCA) \times LCF} \times RFB$ |
| Sensor electronic | 0.43 | |
| Sensor battery | 0.22 | |
| Service/maintenance trips | 1.23 | |
| Total | **3.01** | |
| | | |
| Life correction factor forecast receiver(LCF) | | 6.67 |
| Life correction factor battery (LCF) | | 3.78 |
| Replacement factor battery (RFB) | | 1.76 |

## 6.3 Net $CO_{2eq}$ savings

The net $CO_{2eq}$ savings were then calculated according to the formula in Table 1. The results are shown in Table 34. Furthermore, the $CO_{2eq}$ break-even point was calculated. This is the point at which the $CO_{2eq}$ savings and the $CO_{2eq}$ emissions from the hardware are balanced – if more $CO_{2eq}$ is reduced, then the savings will become positive. This was calculated by dividing the $CO_{2eq}$ emissions of the used IoT hardware by the $CO_{2eq}$ emissions of the energy carrier. The results shown in Table 35 indicate that if roughly one litre of oil or one cubic meter of gas is spared, the system will work efficiently in terms of $CO_{2eq}$ savings.

*Table 34: Net $CO_{2eq}$ savings depending on energy carrier and per energy reference area (era)*

| Variable | Result |
|---|---|
| Net $CO_{2eq}$ savings per heating period oil | 38,773 $kgCO_{2eq}/y$ |
| Net $CO_{2eq}$ savings per energy reference area oil | 8 $kgCO_{2eq}/m^2era$ |
| Net $CO_{2eq}$ savings per heating period gas | 31,723 $kgCO_{2eq}/y$ |
| Net $CO_{2eq}$ savings per energy reference area gas | 6 $kgCO_{2eq}/m^2era$ |

*Table 35: $CO_{2eq}$ break-even point per energy carrier*

| Variable | Result |
|---|---|
| $CO_{2eq}$ break-even point for oil per heating period | 11.6 kWh/y |
| $CO_{2eq}$ break-even point for gas per heating period | 9.5 kWh/y |

## 6.4 Upscaling for Switzerland

The estimation of how much $CO_{2eq}$ could be saved in 2020 in Switzerland by using this heating optimisation technology was completed as follows. The energy reference area in 2020 for habitual space was determined (see Table 36) and then multiplied by the estimated share of non-renovated energy reference areas (80%) according to [39]. The remaining non-renovated area in 2020 (see Table 36) was then multiplied by 19.3% of the pre installation energy use of 190 $kWh/m^2$ (see Table 37).

*Table 36: Energy reference area in total in 2020 and non-energetically renovated*

| Year | $[m^2]$ | Source |
|---|---|---|
| 2020 | 507102000 | [40] |
| 2020 | 405681600 | non-renovated |

*Table 37: Formula to calculate the energy savings in 2020*

$$E_s = ERA_{nr} \times EC_{pre} \times abs(pc)$$

$E_s$ $= Energy\ savings$

$ERA_{nc}$ $= Energy\ reference\ area, non - renovated$

$EC_{pre}$ $= Energy\ consumation\ pre\ intstallation$

$pc$ $= percentage\ change$

For the upscaling, only buildings with heating systems based on gas or oil were considered, primarily because these energy carriers have the highest share but also because the investigated heating system is based on one of these carriers. Finally, the saved amount of energy was multiplied by the $CO_{2eq}$ emissions of oil and gas and their share in the heating sector (see Table 28). To consider the $CO_{2eq}$ emissions of the installed heating optimisation systems, the non-renovated energy reference area was divided by the number of an average sized building. This value was then multiplied by the $CO_{2eq}$ emissions of the hardware and thereafter subtracted from the gross $CO_{2eq}$ savings in 2020. The estimated net $CO_{2eq}$ savings are shown in Table 38.

*Table 38: Estimated $CO_{2eq}$ savings in 2020 by a share of oil and gas in the heating sector as it was in 2016*

| Variable | $[MtCO_{2eq}/y]$ |
|---|---|
| Net $CO_{2eq}$ savings per heating period in 2020 | 2.3 |

## 6.5 Conclusions

The analysis of this use case shows that a promising $CO_{2eq}$ saving potential exists in the heating optimisation sector in non-energetically renovated multifamily houses in Switzerland. The amount of savings is dependent on the energy carrier used for heating or the other way around, as the cleaner the used energy is in terms of $CO_{2eq}$ emissions, the smaller the savings are. Further, it is possible to reduce the heating energy consumption of historical buildings or buildings close to their end of life without any expensive or inappropriate renovation work. If a closer look is taken at the savings month by month, it can be seen that the savings in general are higher in the transitional periods between autumn and winter and winter and spring. This result may be interesting if climate change is taken into consideration and possible strong weather changes within a few days.

# 7 Use case 4: Heating optimisation based on predictive calculated weather data

In this use case, the focus was on possible $CO_{2eq}$ savings due to reduced heating energy, such as oil or gas, during the heating period (Oct year A - May year B). The investigated building was an office building located in the city of Brugg. The building had an energy reference area of approximately 1000 $m^2$, and the optimised system went into operation on 16 September 2016. The pre installation energy consumption was 74 kWh/$m^2$, whereas the post installation energy consumption was 61 kWh/$m^2$. The reduction of heating energy was achieved due to the installation of temperature sensors on the heating water return and flow pipe and the replacement of the external temperature sensor by simulated weather forecast data. After reconditioning all sensor information, the existing heating system was controlled with these values. No other energy-related refurbishment took place, and therefore the savings can be attributed only to the optimised heating system. The system is connected by internet or mobile network to the main server of the providing company and can be monitored and controlled by an online dashboard. Thanks to such improvements being implemented, malfunctions can be detected as soon as they occur, and most importantly, the system is self-learning, calibrating heating to achieve optimal efficiency. In this use case, pre and post installation data on the fuel consumption of the heating system were compared to calculate the savings. The pre installation data comprised eight random readings of energy consumption data starting in 2012. The post installation data were more or less monthly readings starting on 30 September 2016 and ending on 30 June 2017. To account for different weather conditions, all data were weather-adjusted with the following formula (see Table 24), often used in Switzerland, according to E.A. Müller et al. Often, the value of 0.75 is used for α. This means that 75% of the energy used for heating is dependent on the weather condition, while 25% is independent (for example, warm water, user behaviour). In this study the value 1 was taken for α because the weather independent energy was estimated based on the SIA 380/1 norm of the year 1999 [41] (5.7 kWh/m2 and year, sums up to 500 kWh/month) and subtracted from the heating energy before weather adjustment. The weather data were taken from [34] for Buchs-Suhr, and the long-term mean values were extracted from [36] for Zürich, the closest available data. To enable a month-wise pre and post comparison, the consumption values had to be adapted to full months. This was achieved by distributing the read energy values over the months on the basis of the percentage monthly heating degree days.

## 7.1 Gross $CO_{2eq}$ savings

After monthly heating energy use was adapted, the percentage change between pre and post installation data were calculated month by month between 2012/2016, 2013/2016, 2014/2016, 2015/2016 and 2012/2017, 2013/2017, 2014/2017, 2015/2017 and 2016/2017 (see Table 26). The weighting was then performed in the same way as in section 6.1. To calculate gross $CO_{2eq}$ savings, the $CO_{2eq}$ emissions of the oil and gas energy carriers, the most common fuels for heating in Switzerland [35], [36], [37], were assessed. The specific emissions per kWh of these energy carriers are shown in Table 28. With these values and the average used amount of heating energy in the heating periods 2012 until 2016 and 2016 until 2017, the gross $CO_{2eq}$ savings were calculated using the formula in Table 39. In Table 40, the main results regarding gross $CO_{2eq}$ savings are shown.

*Table 39: Formula to calculate $CO_{2eq}$ savings depending on the energy carrier*

$$CO_{2eqs} = \gamma_{ec} \times (E_{hp,pri} - E_{hp,post})$$

$CO_{2eqs}$ $= CO_{2eq}\ savings$

$\gamma_{ec}$ $= Emission\ parameter\ of\ energy\ carrier\ (oil\ or\ gas)$

$E_{hp,x}$ $= Energy\ consumption\ per\ heating\ period\ pre\ or\ post\ intstallation$

*Table 40: Main results of gross $CO_{2eq}$ savings*

| Variable | Result |
|---|---|
| Mean percentage reduction of heating energy | -18.2% |
| $CO_{2eq}$ savings per heating period oil | 4632 $kgCO_{2eq}$/y |
| $CO_{2eq}$ savings per heating period gas | 3790 $kgCO_{2eq}$/y |

## 7.2 $CO_{2eq}$ emissions of the installed system

To calculate the $CO_{2eq}$ emissions of the installed system, all additional components were treated as one single IoT sensor to enable an upscaling based on the data of the previous LCA study (see Table 41). Table 42 shows the main inputs for the up/down scaling, and Table 43 shows the $CO_{2eq}$ emissions of the installed system. To install and maintain the system, some service traffic was caused, so the resultant $CO_{2eq}$ emissions were taken into account as well. Because no heavy equipment for installation was needed, this calculation was done with the average $CO_{2eq}$ emissions of a Swiss passenger car.

*Table 41: Used values from existing LCA study for up/down scaling*

| Component | Weight [kg] | $CO_2$ emissions [$kgCO_2$/y] |
|---|---|---|
| Sensor housing | 0.23 | 0.46 |
| Sensor electronic | 0.05 | 2.72 |
| Sensor battery | 0.10 | 0.16 |
| | | |
| Life expectancy | 4.5 years | |

*Table 42: Used components, specifications and data sources for calculation*

| Component | Specification | Data source |
|---|---|---|
| Housing | 11.3 kg | Company X[1] |
| Electronic incl. sensors | 2.7 kg | |
| Battery | -- | |
| Life expectancy forecast receiver | 15 years | |
| Average $CO_{2eq}$ emissions/km CH car | 0.32 $kgCO_{2eq}$/km | [38] |
| Length of service tour/system life | 900 km | Company X |

*Table 43: Calculated $CO_2$ emissions of hardware and service/maintenance trips caused by the system*

| Component | $CO_{2eq}$-emissions per year [$kgCO_{2eq}$/y] | Calculation: |
|---|---|---|
| Housing | 6.9 | $\frac{kgCO_{2eq}(LCA) \times kg(this\ study)}{kg\ (LCA) \times LCF}$ |
| Electronic incl. sensors | 44.1 | |
| Battery | -- | |
| | | |
| Service/maintenance trips | 19 | |
| Total | **70** | |
| | | |
| Life correction factor forecast receiver(LCF) | | 3.33 |

## 7.3 Net $CO_{2eq}$ savings

The net $CO_{2eq}$ savings were then calculated according to the formula in Table 1. The results are shown in Table 44. Furthermore, the $CO_{2eq}$ break-even point was calculated. This is the point at which the $CO_{2eq}$ savings and the $CO_{2eq}$ emissions of the hardware are balanced – if more $CO_{2eq}$ is reduced, then the savings become positive. This was calculated by dividing the $CO_{2eq}$ emissions of the used IoT hardware by the $CO_{2eq}$ emissions of the energy carrier. The results shown in

Table 45 indicate that if roughly 22 litres of oil or 27 cubic metres of gas are spared, the system will work efficiently in terms of $CO_{2eq}$ savings.

[1] This company does not want to be named in this study.

*Table 44: Net $CO_{2eq}$ savings depending on energy carrier and energy reference area (era)*

| Variable | Result |
|---|---|
| Net $CO_{2eq}$ savings per heating period oil | 4562 $kgCO_{2eq}/y$ |
| Net $CO_{2eq}$ savings per energy reference area oil | 4 $kgCO_{2eq}/m^2era$ |
| Net $CO_{2eq}$ savings per heating period gas | 3720 $kgCO_{2eq}/y$ |
| Net $CO_2$ savings per energy reference area gas | 3 $kgCO_{2eq}/m^2era$ |

*Table 45: $CO_2$ break-even point per energy carrier*

| Variable | Result |
|---|---|
| $CO_{2eq}$ break-even point for oil per heating period | 221 kWh/y |
| $CO_{2eq}$ break-even point for gas per heating period | 270 kWh/y |

## 7.4 Upscaling for Switzerland

The estimation of how much $CO_{2eq}$ could be saved in Switzerland in 2020 by using this heating optimisation technology was completed in the same way as in *Use case 3: Heating optimisation based on weather forecast.* The difference in this use case is that a pre-installation energy use of 74 $kWh/m^2$ and 18.2% was used, and the number for the energy reference area of service buildings was calculated instead of that for habitual space in 2020 (see Table 46) [40]. The estimated net $CO_{2eq}$ savings in 2020 are shown in Table 47.

*Table 46: Energy reference area in total in 2020 and non-energetically renovated*

| Year | [$m^2$] | Source |
|---|---|---|
| 2020 | 166631000 | [40] |
| 2020 | 133304800 | non-renovated |

*Table 47: Estimated $CO_{2eq}$ savings in 2020 by a share of oil and gas in the heating sector as it was in 2016*

| Variable | [$MtCO_{2eq}/y$] |
|---|---|
| Net $CO_{2eq}$ savings per heating period in 2020 | 0.3 |

## 7.5 Conclusions

With the analysed technology described in this study, it is possible to reduce the $CO_{2eq}$ emissions of non-energetically renovated office buildings in Switzerland by a significant, promising amount. Thereby, the effective amount of savings is dependent on the energy carrier used for heating. For example, if oil is used, the savings are higher compared to natural gas because oil emits more $CO_{2eq}/kWh$ than natural gas. In other words, the savings are dependent on the $CO_{2eq}$ emission factor of the energy carrier. What makes this technology interesting is the fact that historically protected buildings can reduce their $CO_{2eq}$ emissions without any change in their physical appearance, inside and outside. Further, buildings close to their end of life can be equipped without huge investments and save some energy before they are dismantled. By looking closer at the month-by-month savings, it is clearly visible that the savings are the highest in the transition periods. This is not a surprising result because weather changes in these heating periods occur quickly, and conventional heating controllers have problems adapting because they do not consider the inertia of the building.

# 8 Closing remarks

Overall, there is evidence that every investigated use case yielded $CO_{2eq}$ savings; but in some cases, the savings were negligible. Further, the additional $CO_{2eq}$ emissions caused by the IoT devices were, in three out of four cases, negligible compared to the amount of saved $CO_{2eq}$. This suggests that from a $CO_{2eq}$ point of view, IoT is a technical solution for reducing $CO_{2eq}$ emissions in the investigated cases and therefore a possible contributor to the goals of the Energy Strategy 2050. Whether this is valid for other areas of IoT application must be investigated in future studies. Regarding the four use cases, it is important to state that the $CO_{2eq}$ savings for each were specific and cannot therefore be compared with each other in terms of which is the most promising. Even use cases three and four, which had some commonalities at some stages, are not comparable due to different starting positions. For example, one is a residential building, while the other is an office building. Further, the basic data needed different types of adaption to enable comparisons on a monthly level. If the outcomes of this study were to be compared to the savings values of the studies mentioned at the beginning of this report, it could be concluded that the effective savings are really dependent on the case. Therefore, it cannot be said that, for example, a savings of X percentage is certain in the heating optimisation sector. The only thing that is clear is that due to the small size of IoT sensors, a relatively small amount of $CO_{2eq}$ savings is needed to reach a trade-off in this respect. To generate more universal numbers and calculate future $CO_{2eq}$ saving potentials, the quantity of data needs to be increased, and more use cases similar to those in this study need to be investigated. Beside this, it is necessary to conduct a holistic overview of the used technologies that considers other parameters besides $CO_{2eq}$ – for example, the use of rare materials, potential problems in the production sector and economic efficiency. Therefore, if IoT technology is really to be used to enable a 'greener' environment, all other external factors and their $CO_{2eq}$ emissions must be considered as well. Otherwise, just the end of the pipe is 'clean', so to speak, resulting in many questionable side effects. To provide a holistic overview, further investigations are needed.

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# 10 Tables

# 11 Appendix

## 11.1 Appraisal of the final report:

### Analysis of potential for Internet of Things (IoT) to act as an enabler for climate protection and the energy Strategy 2050; Impacts of IoT on energy consumption and CO2eq emissions in specific use cases

**Reviewers:**

*Dr. Bernard Aebischer, senior expert and volunteer at WWF Switzerland*

*Dr. Patrick Hofstetter, director climate & energy, WWF Switzerland*

**Basis**

This appraisal is based on the final report, excel calculation sheets and a student thesis from B. Shala (29.9.2017). Other documents have not been consulted.

**Aim of the report and its corresponding results and conclusions**

The report looks into four use cases for IoT-technologies. The aim of the report was to investigate whether these use cases have the potential to result in net-greenhouse gas savings, to provide a calculation framework to do so and to provide an order of magnitude estimate of the yearly mitigation potential if applied within Switzerland in all instances and applications.

Based on the data used in the report, the provided calculations and the experience and plausibility checks by the reviewers we can confirm that all four use cases have the potential for net-greenhouse gas savings. We can also confirm that the mitigation potential varies a lot between the use cases. Further, the very limited empirical basis used for the use cases does indeed only allow to make an order of magnitude guess for a country-wide implementation. In this sense, the use case specific data would need to be re-calculated if other cities, PV installers or roll-out of building controls need to be assessed.

We did not check the unpublished source for the GHG-emissions for sensors and controls. However, the estimates given are plausible and mean that in all cases these pre-invested emissions are small or even negligible. However, system wide effects such as rebound effects or behavioral change was outside of the scope of the study. Some of these effects may reduce the system-wide net savings in GHG emissions. However, it is unlikely they would reverse the outcome.

**The real potential of the use cases**

The report is based on very limited empirical evidence with little reference to national or international data for similar applications. Also, the report did not have the intention to suggest improvements of the use cases or provide recommendations for the way a roll-out may indeed reach a 100% spread. In this respect the given potentials are not more than an indicator to show that building controls have certainly the largest potential while the optimization of waste collection are from a GHG-only perspective not the first place to start. Due to different population densities, climate and habits the net-savings of the four use cases may look different in other countries.

### Recommendations

To mitigate greenhouses gas emissions, the four use cases demonstrate useful applications of IoT technologies. If these use cases are turned into business cases we suggest planning for monitoring to get more reliable real data for gross and net reductions. This could also be used to validate the results presented in this study and further optimize the use cases itself.

Zürich, June 6, 2018

## 11.2 Interview guideline

| |
|---|
| ***Interview Leitfaden für die Evaluation von möglichen Use-Cases im IOT Bereich (Swisscom / ZHAW INE)***<br>*Ziel: Erkenntnisse gewinnen zu:*<br>● *Teilnahmebereitschaft der Industriepartner*<br>● *Einsetzbare Ressourcen*<br>● *Potential vorselektierter Use-Cases*<br>● *Datenlage aktuell und historisch*<br>● *Datenlage zu verwendeter Hardware* |
| *Interviewer:* |
| *Teilnehmer:* |
| *Unternehmen:* |
| *Zeit und Ort des Interviews:* |
| |
| *Kurze Einleitung zum Hintergrund dieser Fallstudie analog zu BFE Antrag* |
| |
| 1. *Wie sieht Ihr Use-Case genau aus?* |
| 2. *Wie sieht Ihre Teilnahmebereitschaft für diese Studie aus?* |
| 3. *Wie viele Ressourcen stehen von Ihrer Seite zur Verfügung?* |
| 4. *Können Sie intern eine Ansprechperson bereitstellen als Schnittstelle zwischen Ihrem Unternehmen und uns?* |
| 5. *Haben Sie historische Daten zu den zu untersuchenden Fällen (vor Implementierung von IOT Applikation, Fahrstrecken, Anzahl Servicefanfahrten, Länge der Anfahrten, Energieverbrauch etc.)?* |
| 6. *Haben Sie aktuelle Daten zu den zu untersuchenden Fällen?* |
| 7. *Haben Sie Daten zu den verwendeten Hardwarekomponenten (Sensoren, Anzeigen, etc.)?*<br>a. *Wenn ja: Bis auf welche Verarbeitungsstufe?*<br>b. *Wenn nein: Besteht die Möglichkeit diese Daten bei Ihren Zulieferern zu bekommen? (Bereitschaft der Zulieferer diese Daten zu liefern)* |
| 8. |