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Reanalysis of occupant experiment in ZEB Living Lab

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Reanalysis of occupant experiment in ZEB Living Lab

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Abstract. In 2015-2016, a six-month long experiment was carried out in the ZEB Living Lab, one of the first houses in Norway planned to reach net zero emission throughout its lifetime. By means of qualitative experiments, social scientists evaluated how six groups of occupants impacted the zero emission building, and how the zero emission building impacted its occupants in different ways. Data were collected through direct observation, diaries and interviews before, during and after the stay. In this paper, we take a closer look at the sensor data from the detailed monitoring system, generated during each group's 25-day long residing's. We find that despite the experiment being a controlled environment with many shared household characteristics, occupancy is determined by diverse factors, and the users' preferences and attitudes influence energy consumption. All major household appliances were the same, but the time of use, frequency, duration and type of use differed. The study contributes to increasing understanding of user behaviour and energy use in low energy houses. Providing occupancy profiles is valuable, in light of the increasing amount of local renewable energy production. These datasets can be used as input in energy simulation and planning of zero-emission neighbourhoods.

1. Introduction

The experiment with six occupant groups in the ZEB Living Lab was conducted October 2015 – April 2016. Data were collected by mixed-methods through direct observation, diaries and interviews before, during and after the respective stays of 25 days. Sensor data from the detailed monitoring system (temperature, humidity, CO2 levels, light levels, motion, energy use, airing), was presented to the users in interviews but has thus far not been analysed further.

In this paper, we revisit the written logbooks and analyse the sensor data using statistical techniques in order to gain better understandings of two issues: 1) Whether the self-logged activities correspond to the highly-energy consuming activities, and 2) whether there are significant differences between groups concerning energy use and peak power consumption. This second endeavour could shed light on the role of occupant life phase, age, and family situation, on the design of zero-emission arrangements.

Other research from the experiment studies domestication of the zero emission technologies [1, 2], and how a sense of home was established in the Living Lab [3, 4]. Feedback from the occupants has also been used to explore the concept that people living in the house will act as both producers and consumers of energy [5]. In these studies, opportunities and limitations of the living lab setting are also addressed. The qualitative data from interviews and observations are at the centre of analysis, leading to insights on the expected and unexpected uses of the technologies, but without further quantitative



comparisons between groups. Some of the home living habits of the six groups concurred within the zero-emission ambitions, and some may lead to higher energy use than expected [2]. In this paper, we look into these previous findings by laying out the available sensor data.

However, the data gathered on energy use are not fully comparable between groups. Gaps frequently occur in the measurements, as indicated in the total equivalent days of 30-second monitoring data available per group (Table 1). The influence on heating need is not easily identified, as the outdoor temperature varies and the residencies are less than a month long. Moreover, the experiment was conducted right after construction. All technologies and sensors related to the heating system were not completely calibrated at the time of the experiment. Therefore, the analysis is limited to direct electricity use and domestic hot water use.

The six different user groups were composed as follows: two student groups, two families with small children and two elderly couples. Each group was asked to make the Living Lab their home, trying to use it as they would normally use their own houses. The average time spent at home differed between groups (and within the groups). Table 1 shows the average total hours per day (between Monday to Fridays) that no movement was detected in the house for an entire hour (see Figure 8).

Table 1. Overview of the resident groups, the data available for analysis and average time at home.

Group	Description	Analysis period	Unoccupied house
S1 Students	Male and female couple, 22 years old. Live in a 52 m ² student apartment	18.5 weekdays ^a	5 hours per weekday
S2 Students	Two female friends, 20 and 21 years old. Live in a shared apartment together with three other girls, built 1905	12.3 weekdays ^a	8 hours per weekday
F1 Family	Mother 31 years old and father 36. Son 6 years old and daughter 2. Live in a row house of 185m ² , built 2007	18.3 weekdays ^a	8 hours per weekday
F2 Family	Mother 31 years old and father 37. Two daughters of 3 and 2 years old. Live in a detached house of 135 m ²	15.5 weekdays ^a	7 hours per weekday
E1 Elderly	Husband 81 and wife 68. Live in a detached house of 170 m ²	14.5 weekdays ^a	3 hours per weekday
E2 Elderly	Husband 61 and wife 56. Live in a detached house of 120 m ²	17.5 weekdays ^a	6 hours per weekday

^a Total equivalent duration of monitoring data recorded at 30-second interval available for the analysis.

2. Method

The ZEB Living Lab is a single family house with a gross volume of approximately 500 m³ and a heated floor area of approximately 100 m². The monitoring system is designed based on the experimental data needed to characterise the energy and environmental performance of the building fully. A description of the test facility highlighting the architectural features and technological aspects, including the specification and quality aspects of the measurement system is published in [6].

The analysis is concentrated on weekdays (Monday to Friday) to identify and classify variables related to occupancy profiles. Weekends are filtered out to look specifically at building occupancy and use patterns that emerge from daily activities. This choice also has a practical dimension as data acquisition losses occurred, most frequently on Fridays lasting until a restart on Monday mornings.

The variable categorisation that guides the analysis is taken from IEA EBC Annex 66 “Definition and Simulation of Occupant Behavior in Buildings” [7]. These reference procedures for obtaining occupancy profiles in residential buildings differentiates between variables that influence occupancy profiles such as socio-demographic driving-factors and variables influenced by occupancy impacting the use of equipment, building services and energy consumption [7].

First, data from the electricity meters are presented together with short descriptions from the diaries, outlining the routines in the house. We then investigate the variables influenced by occupancy and present them in two sections: The type of activity, the hours of presence in the different rooms. The use and description of lighting, appliances, cooking and demand for hot water.

3. Daily activities and energy use in the living lab

The occupants kept a logbook during their stay in order to get an overview of the routines in the house. From the logbooks, we recount (in Figure 2 – Figure 8) the type of activities undertaken, such as cooking, laundry, and dinners. The logged activities presented in the diagrams were selected to explain the events that can be seen in the hourly time of day electricity use. We found that occupants logged most activities, but not every single use such as dishwasher, or shower. In the figures below, some logbook entries are included of activities on days where there are gaps in the electricity measurements.

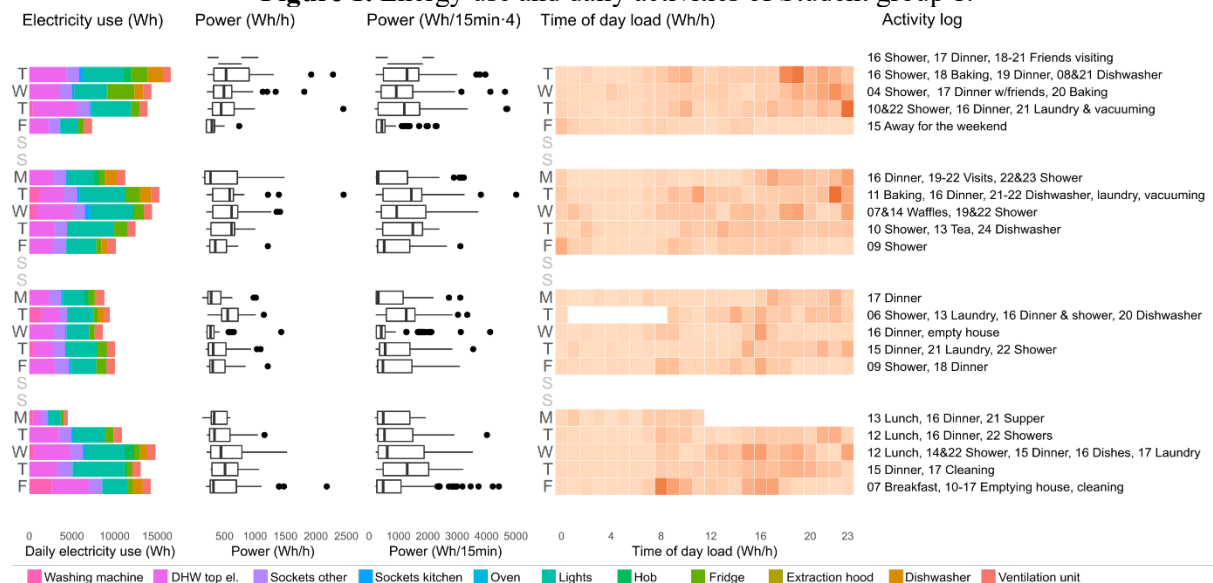
The guest visits occurred frequently among all the groups, and the time of day when the house was in use, cannot be presented here, but are discussed in the next section. During any given day, the number of visits and time of leaving, or home-comings of one or more building occupants, are too numerous to recount in these graphical representations.

On the left side a bar chart show the daily electricity consumption for different use. Then two rows show the hourly and 15-minute daily power load. Next to it is a heat map that show the hourly energy use horizontally day by day. A deep orange colour indicates higher energy consumption (>3 kWh/h). Finally, selected activities from the daily activity logs written by the occupants are listed to the left.

3.1. Students S1 & S2

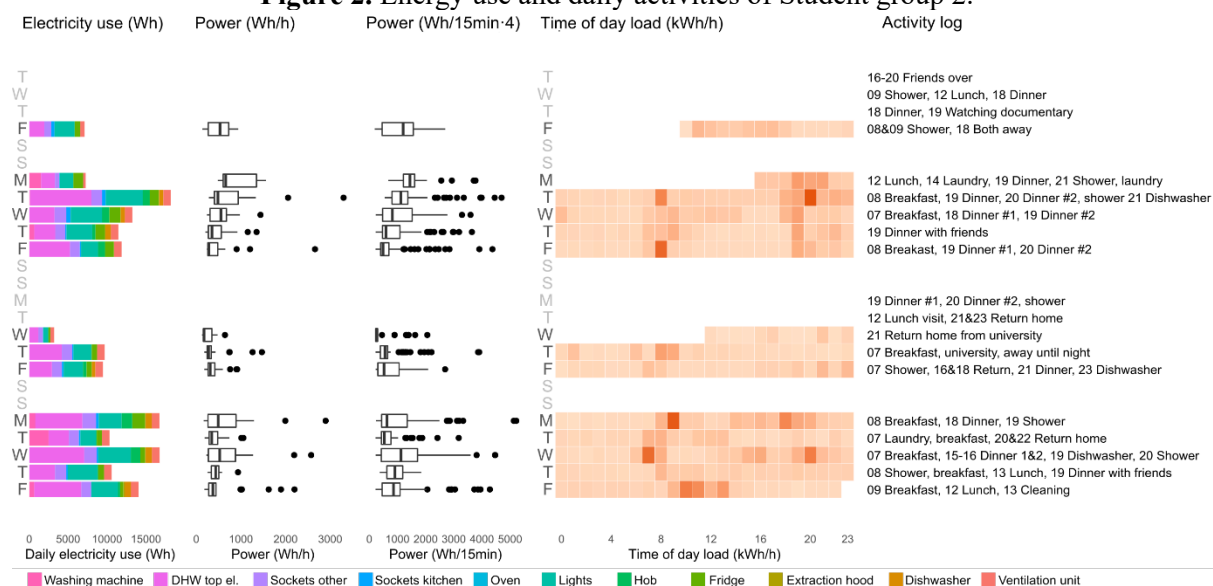
Both student groups studied close by, on the same campus. The students found that the location of the living lab, on campus, altered how and where they spent their day. Both group S1 and S2 often ate lunch in the house, and S1 would spend more time at home than usual (19 hours per day on average). The activity diary and electricity use that occurs in the daytime show the variation between days. Friends would also come over frequently. S1 brought a vacuum cleaner and its energy use is visible on the time of use (Figure 1). The other groups used a smaller chargeable vacuum cleaner that was provided.

Figure 1. Energy use and daily activities of Student group 1.



S2 Spent most of the daytime away from the house (8 hours unoccupied on average), but would sometimes come back for lunch or spend half the morning or afternoon there. The two students had some shared and many separate routines, such as eating and food preparation in the kitchen. Figure 2 shows the main energy use and power on an hourly basis to originate from showering. Unfortunately, many days are missing metering data, but the log provides an indication of the use on days without data.

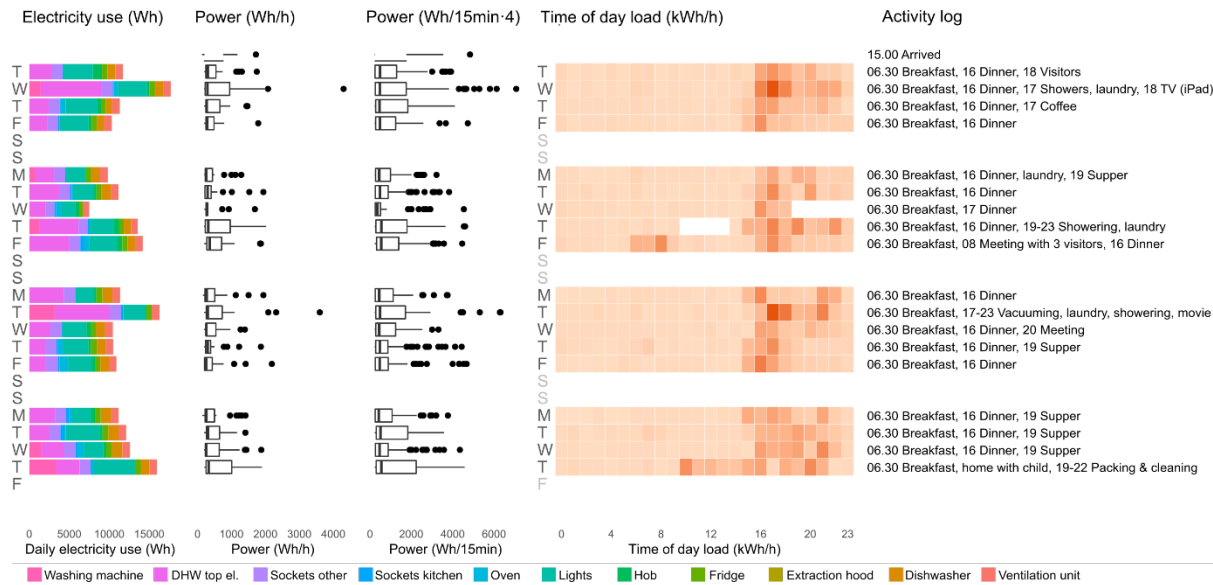
Figure 2. Energy use and daily activities of Student group 2.



3.2. Families with young children F1 & F2

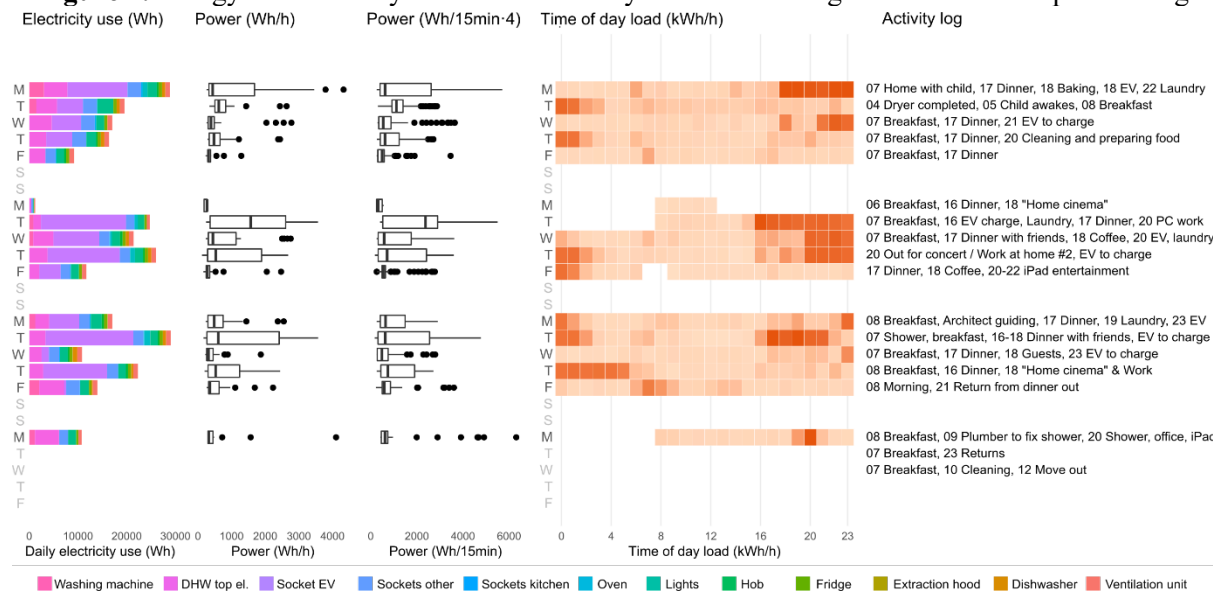
The two families have the most pronounced occupancy patterns, clearly indicating the time away to approximately 8 hours per work day and the electricity use for dinner preparation in the afternoons. Both families experienced sickness during their stay, which can be seen from the electricity use heat map. The first family F1 brought a portable electric radiator (1 kW), but for the sake of comparison with other groups, electricity consumed by this heater is subtracted from the data presented in Figure 4.

Figure 3. Energy use and daily activities of Family 1.



The second family, F2, had an electric car. The electric vehicle (EV) charger is connected to a metered socket in the technical room, drawing 2.15 kW in typical charging cycles lasting 6 hours. The car was left to charge after returning from work, or in the late evening (Figure 5). The bar chart in Figure 5, shows what the daily energy use for the electric car amounts to kWh/day and the box plots show loads.

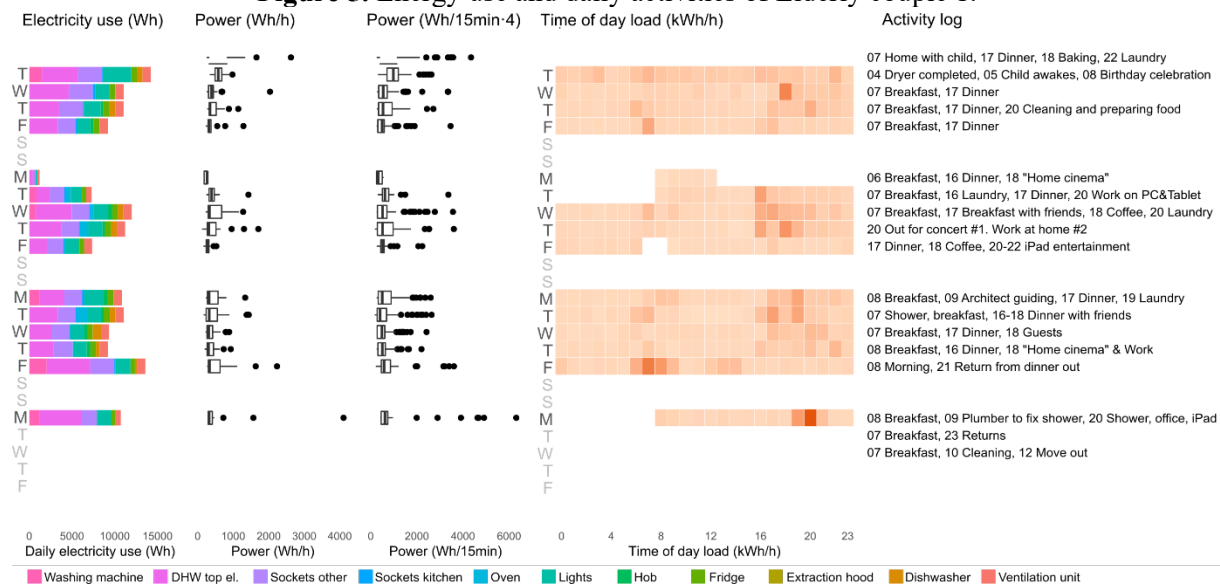
Figure 4. Energy use and daily activities of Family 2 with EV-charger. Notice the bar plot scaling.



3.3. Elderly couples E1 & E2

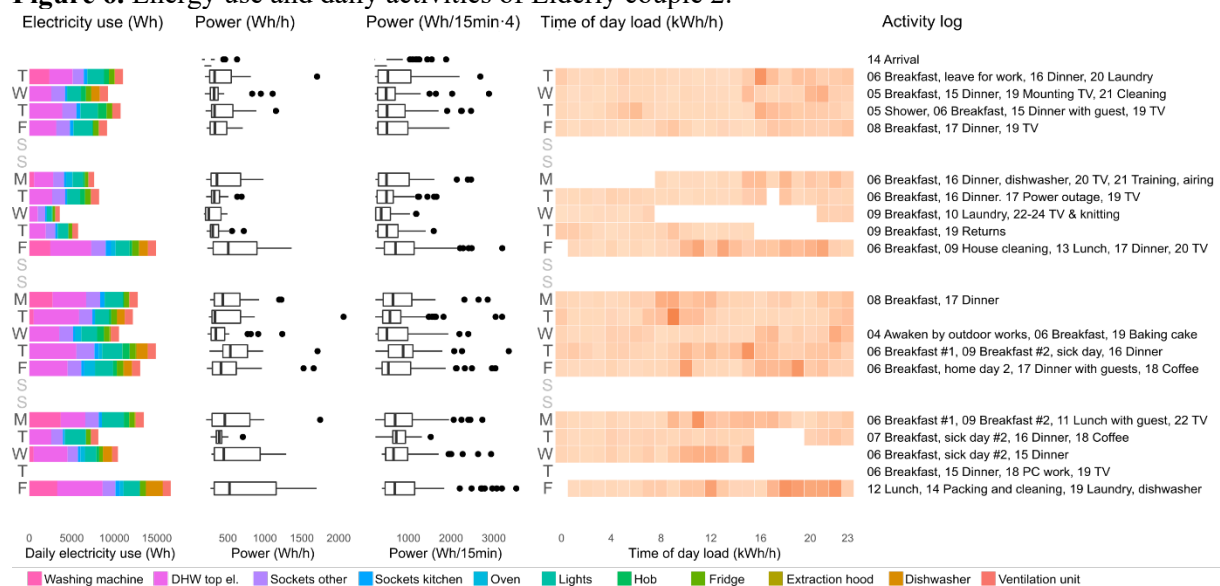
The two older couples both held high levels of activity with many guests and family visits. One can see more electricity use in the daytime than for the families with children. E1 would bake frequently and spend more time in the kitchen. During their time in the living lab, the house was vacant approximately 3 hours per day on average, according to the presence detection sensors. Unfortunately, most of the data of week 4 is missing. Periods of the highest energy use originate from the kitchen.

Figure 5. Energy use and daily activities of Elderly couple 1.



The other couple (E2) was away from the house about 6 hours on an average day. Some data are missing, including a one-hour power outage on Tuesday week 2. E2 was the only group to bring a TV.

Figure 6. Energy use and daily activities of Elderly couple 2.



4. Amenities in the living lab

4.1. Electrical equipment

Participants were asked to bring with them what they regarded as necessary to create a home. This included electrical equipment. As larger appliances were in place (Table 3, Appendix), participants brought various smaller electric equipment from home, like a coffee grinder, kitchen machine, electric kettle, toaster, blender, waffle maker, stereo, hairdryer and chargers for tablets and phones. Simple plug-in energy meters revealed how much some of these devices were in use over the total stay (Table 5, Appendix). Sockets were also monitored on room level. The peak power registered for plug loads in

each room, presented in Table 2, can largely be explained by the following observations. S1 brought a vacuum cleaner (moved around between sockets), F1 brought a radiator heater (moved between living S and living N sockets), F2 brought an iMac (on “Living N sockets” in Table 2), and E2 brought their TV (living N socket). The various kitchen equipment brought by the group all produces maximum loads of around 0.7 kW over 15 minutes or less over a full hour. The hourly peak value on each meter is well below 1 kW.

The major household appliances were all the same, selected to be energy efficient (Table 3, Appendix). In this case, the peak power between groups is similar. Except, the fridge has a rapid freeze cycle function likely used by the student groups (bringing maximum power to 2 kW over 15 minutes). It also appears the students did not use the oven on the weekdays. The induction hob has a rated power of 7.4 kW max, 2.3 kW per heating zone and 3.2 kW in boost mode (Table 3, Appendix). Table 2, show that over an hour, the peak power of the induction oven was well below 1 kW.

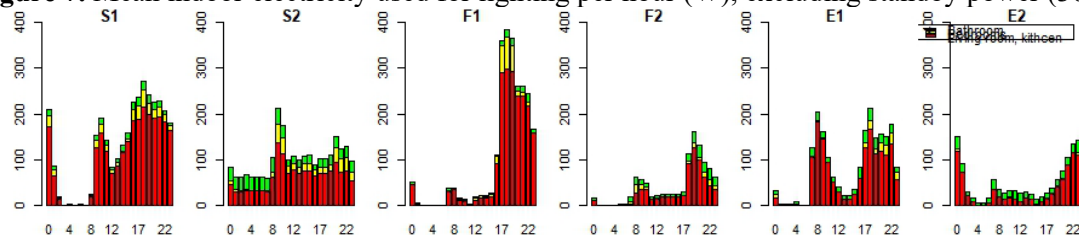
Table 2. Maximum peak power (kW) per 15 minutes and per hour on weekdays.

	Maximum power load in kW (kWh per 15 min · 4 / kWh per 1 hour)					
	S1	S2	F1	F2	E1	E2
Kitchen sockets	0.7 / 0.6	0.7 / 0.3	0.6 / 0.2	0.5 / 0.2	0.7 / 0.4	0.7 / 0.4
Living S sockets	0.6 / 0.1	0.1 / 0.1	1.4 / 1.0	0 / 0	0.9 / 0.3	0.8 / 0.2
Living N sockets	0.5 / 0.2	0 / 0	0.8 / 0.4	0.2 / 0.2	0.1 / 0.1	0.1 / 0.1
Bedrooms sockets	0.1 / 0	0.1 / 0.1	0.1 / 0.1	0 / 0	0.5 / 1	0 / 0
Bathroom sockets	0.2 / 0	0.3 / 0.1	0 / 0.1	0.2 / 0	0.7 / 0	0.2 / 0
EV-charge socket	-	-	-	2.2 / 2.1	-	-
Washer & dryer	2.1 / 1.2	2.0 / 0.6	2.1 / 1.4	2.1 / 0.9	1.7 / 0.6	2.1 / 1.4
Fridge & freezer	2.0 / 0.9	1.8 / 0.7	0.1 / 0.1	0.1 / 0.1	0.1 / 0.1	0.1 / 0.1
Induction hob	1.3 / 0.6	1.6 / 1.0	1.7 / 0.6	1.0 / 0.4	2.4 / 1.1	1.7 / 0.9
Oven	0 / 0	0 / 0	1.8 / 0.8	1.7 / 0.8	2.2 / 1.1	1.7 / 0.7
Dishwasher	1.7 / 0.8	1.6 / 0.6	2.1 / 1.1	1.7 / 0.6	2.1 / 0.6	1.9 / 0.7
Extraction hood	0.1 / 0.1	0.1 / 0	0.1 / 0.1	0.1 / 0	0.1 / 0	0.1 / 0.1
Indoor lighting	0.8 / 0.8	0.8 / 0.7	0.8 / 0.8	0.7 / 0.7	0.5 / 0.4	0.5 / 0.5

4.2. Electricity use for lighting

Earlier studies have not found clear correlations between daylight availability, control of shading devices and the artificial lighting [8, 9]. The LED lighting system has an installed power of 912 W, or 742 W installed indoor, 137 W outdoor and 33 W transformer loss (Table 4, Appendix). Figure 7 shows the average indoor lighting use per hour of the day. The profiles are affected by daily routines, time at home, dimming preferences, and reflect that occupants stayed in the house between October to April. Red coloured bars are main areas (living rooms, entryway & kitchen), yellow bedrooms, and green bathroom.

Figure 7. Mean indoor electricity used for lighting per hour (W), excluding standby power (30 W).



4.3. Domestic hot water use

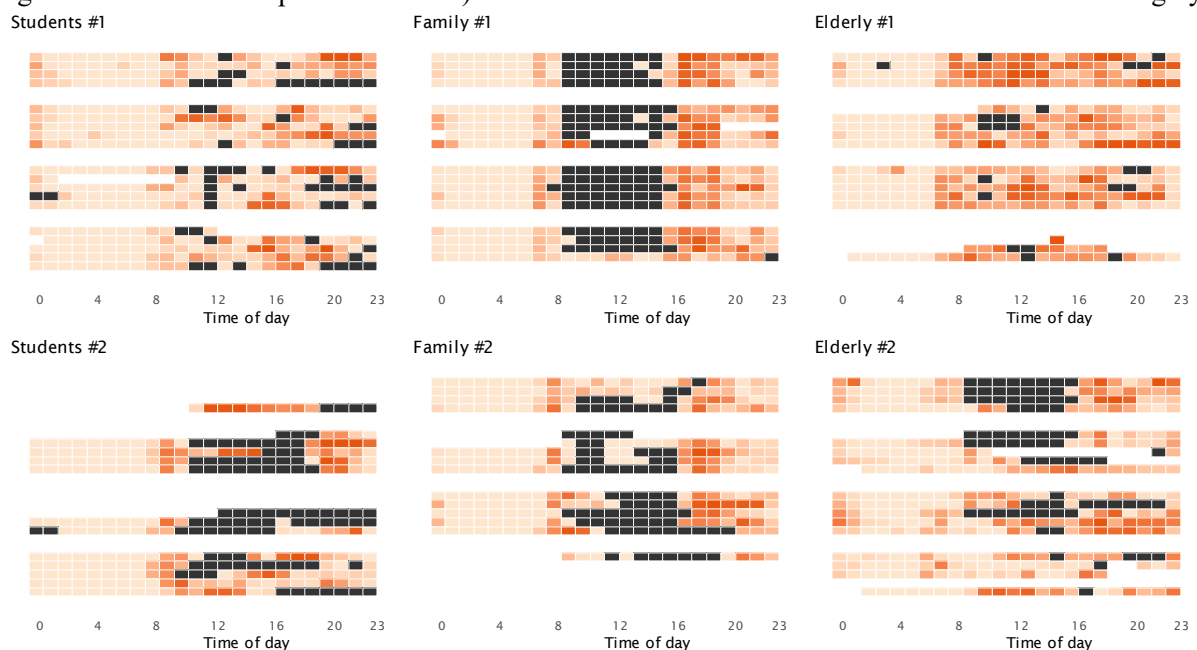
The hot water accumulation tank was heated by a direct electric resistance heater of 2.7 kW to 70 degrees, which is a typical configuration in Norway. This electric hot water heating was included in the analysis. Due to the design of the heating system in the Living Lab, the total energy use for DHW heating could not be easily identified at the time of the experiment. The incoming tap water was preheated through a coil in the space heating tank which held a tank temperature of 35 to 40 degrees. This space heating tank can be heated by low-temperature sources; solar thermal panels, a ground source heat pump or direct electricity. Without the preheating coil, the electric heater in the DHW accumulation tank would need to operate for a longer time to lift the temperature for DHW. Therefore, the total energy need for hot water is higher than the electricity reported in this study, but the 2.7 kW electric power is representative of hot water tanks heated directly by electricity.

A split between the DHW used for personal hygiene, showers, or other domestic uses has not been attempted from the existing monitoring data, but it is safe to assume that showering is the greatest cause of energy use for DHW heating. Several groups mentioned that they showered longer in the lab because the shower head was nice and comfortable, also they did not pay for electricity.

4.4. Cooking

Table 1 gave an overview of total hours per day where the living lab is unoccupied. Figure 9 shows the day to day hourly variations when no movement is detected overlaid in grey colour. The orange colour in the heat maps shows when there is someone present in the kitchen. Together these two variables, kitchen presence and building vacancy, were found to correlate to the hourly load patterns. On days when the house was not left vacant in the daytime or evenings, more meals would be cooked.

Figure 8. Kitchen occupancy hour by hour on weekdays (presence over an entire hour in dark orange, lighter colour if vacant part of the hour). Hours of in-house movement not detected is overlaid in grey.



5. Conclusion

The analysis proves that all major explanatory variables are logged in the lab, given that the monitoring system operates. By laying out sensor data descriptively and combining it with the daily activity-logs, we created a starting point for other studies, i.e. to estimate occupancy from CO₂-levels or occupant habit effects on heating need using system identification techniques. The dataset also has the potential for occupancy detection and modelling, for example by using Markov-Chain or other techniques [7].

Despite that the experiment is in a controlled environment with many shared household characteristics, diverse factors determine occupancy, and the users' preferences and attitudes influence energy consumption. All major household appliances were the same, but the time of use, frequency, duration and type of use differed. Excluding space heating from the analysis, the most energy consuming activities are related to showering, cooking and EV-charging. Kitchen presence and building vacancy were found to correlate with electricity use, translating into the time spent at home and the meals cooked there, both varying on a day to day basis. Of the self-logged activities, cleaning also to some extent were of the more energy consuming activities, be it a combination hot water draws for handwashing dishes, vacuum cleaning or use of the dishwasher, laundry machine that according with the logbook coincided with food preparation or cleaning in the kitchen. Some patterns were expected, – families with small children and seniors had more stable routines. These patterns may have been more clear over longer periods and could be used to plan new experiments.

There are differences in energy use between the groups, but are they significant? The time of use on the course of the day differs significantly between the groups and from day to day, especially depending on whether someone is home in the daytime. This is an important consideration in the planning and operation of a ZEB building with solar PV aiming to optimize self-consumption, or a battery storage solution. The peak power per 15 minute or 1 hour; however, is not very different between groups, except in the case where additional space heaters, or electric cars are brought in. The magnitude of peaks, for most household appliances, are less than 1 kWh/h. Combined loads (represented by box plots) were below 4 kWh/h for all groups including EV charging and electric hot water heating (excluding space heating). Over an hour, this is also true for how the induction hob was used. Despite the rated maximum power of 7.4 kW, or 2.3 kW per heating zone, the highest load over an hour was 1.1 kWh/h. The study contributes to understanding user behaviour and energy use in low energy houses. In light of the increasing amount of local renewable energy production, providing occupancy profiles is valuable, to be used as input in energy simulation and planning of zero-emission neighbourhoods.

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(a) Appendix

Table 3. Overview of installed electrical appliances.

	Type of appliance	Energy label	Electrical power	Annual energy use ^a
Washing machine	Combined washing machine and dryer, 8 kg.	A+++ with heat pump	1000 W	177 kWh
Fridge / freezer	Combined fridge and freezer, 200/63 l.	A++	140 W	233 kWh
Hob	Induction top 4 zones, all with booster function	-	7.4 kW max, 2.3 kW per zone 3.2 kW boost	-
Oven	Combi-steam oven, 71 l.	A	3500 W	230 kWh
Dishwasher	Dishwasher, 60 cm.	A++	2200 W	241 kWh
Extr. hood	150-280 m ³ /h, 70-125 W	-	195 W incl. lights	-

^a Annual estimated energy use for appliances as specified by the manufacturer.

Table 4. Overview of installed LED lighting groups per room [9].

Location	Type of light	Electrical power	Dimming	Energy use per 1000h ^a
Technical room 5m ²	Transformers	33 W (standby)	-	33 kWh
Entryway 8m ²	Ceiling, Furniture	35+3 W	2 · 0-100	38 kWh
Living room S 25m ²	Ceiling, Furniture, Floor lamps	70+22+19 W	3 · 0-100	111 kWh
Kitchen 13m ²	Ceiling, Pendant lamp, Furniture	72+58+8 W	3 · 0-100	138 kWh
Living room N 20m ²	Ceiling, Furniture	97+32 W	2 · 0-100	129 kWh
Mezzanine 12m ²	Ceiling	44 W	1 · 0-100	44 kWh
Main bedroom E 16m ²	Ceiling, Desk, Cabinet, Bed-light	76+2+2+22 W	4 · 0-100	102 kWh
Bedroom W 12m ²	Ceiling, Desk, Cabinet, Bed-light	82+43+1+16 W	4 · 0-100	142 kWh
Bathroom 4.5m ²	Ceiling	38 W	1 · 0-100	38 kWh
Outdoors	External lighting	137 W	1 · 0-100	137 kWh

^a 1000 hours corresponds to about one year of usage according to EC consumer guidelines (EC, 2015).

Table 5. Observed plug loads and accumulated on plug-in el. meters (25-day periods incl. weekends).

	Students		Families		Elderly	
	S1	S2	F1	F2	E1	E2
Kitchen	Coffee grinder, el. kettle	El. Kettle: 3.6 kWh, blender & kitchen machine: 0.5 kWh	Blender, coffee maker, grinder, toaster: 5.6 kWh	Coffee maker with el. kettle: 3.4 kWh	Toaster: 2.7kWh, kitchen machine: 0.7kWh, waffle maker	Coffee maker, el. kettle, mixer & waffle maker: 7.5 kWh
Living S	Speaker	Stereo: 0.9 kWh	Additional space heater	0 kWh	Radio, tablet charger	Small heater, radio
Living N	Laptop, Tablet	Unknown	Battery radio, add. space heater	iMac: 32 kWh, chargers: 0.8 kWh	Unknown	TV, chargers for tablets & phones: 4.4 kWh
Bedrooms	Phone charger: 0.3 kWh	Unknown: 0.9 kWh	Tablet & chargers: 0.4 kWh	0 kWh	Unknown: 0.3 kWh	Unknown

Bathroom	Unknown: 0.1 kWh	Meter 2: 3.0 kWh	0 kWh	Hairdryer & shaver: 0.3 kWh	Unknown: 0.5 kWh	Hairdryer & shaver: 0.3 kWh
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