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Author(s):

Saner, Dominik; Heeren, Niko ; Jäggi, Boris; Waraich, Rashid A.; Hellweg, Stefanie

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Article

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Dominik Saner, Niko Heeren, Boris Jäggi, Rashid A Waraich, and Stefanie Hellweg

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*Dominik Saner^{a,1}, Niko Heeren^a, Boris Jäggi^b, Rashid A. Waraich^b
and Stefanie Hellweg^a*

^b Transport Planning Group, Institute for Transport Planning and Systems, ETH Zurich, Wolfgang-Pauli-Strasse 15, 8093 Zurich, Switzerland

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E-mail address: dominik.saner@ifu.baug.ethz.ch (D.Saner).

Abstract

Household consumption, apart from governmental consumption, is the main driver of worldwide economy. Attached to each household purchase are economic activities along the preceding supply chain, with the associated resource use and emissions. A method to capture and assess all these resource uses and emissions is life cycle assessment.

We developed a model for the life cycle assessment of housing and land-based mobility (excl. air travel) consumption of individual households a small village in Switzerland. Statistical census and dwelling register data are the foundations of the model. In a case study performed on a mid-sized community, we found a median value of greenhouse gas emissions of 3.12 t CO₂ eq. and a mean value of 4.30 t CO₂ eq. per capita and year for housing and mobility. 21% of the households in the investigated region were responsible for 50% of the total greenhouse gas emissions, meaning that if their emissions could be halved the total emissions of the community would be reduced by 25%. Furthermore, a cluster analysis revealed that driving factors for large environmental footprints are demands of large living area heated by fossil energy carriers as well as large demands of motorized private transportation.

Keywords: Household Environmental Impacts, Life Cycle Assessment, Housing, Mobility, Stochastic Modeling, Cluster Analysis

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1. Introduction

On average, 72% of greenhouse gas (GHG) emissions are directly or indirectly related to household consumption.¹ While discussions about greenhouse gas reductions often focus on industrial production and energy generation, the discussion about household demand is often left aside. For a serious debate about greenhouse gas emission reduction policies, it is crucial to analyze household consumption patterns, i.e. to quantify the individual demands and environmentally assess their supply.

Many municipalities aim for a rational use of energy, the decarbonization of their energy system, an amplified utilization of renewable energy carriers and hence a higher degree of self-sufficiency.^{2, 3} Thus, there is an interest in household environmental impact studies applicable and valid for specific geographical regions. In the last two decades several studies have tackled the issue of environmental impacts induced by household consumption. Hertwich provides a comprehensive overview.⁴ Commonly, three methodological approaches are applied to measure these impacts: environmentally extended input-output analysis (EEIOA), process-based life cycle assessment (LCA) and hybrid analysis. All three approaches are based on the same four elements: (a) final demand of households, (b) inter-sectorial (or inter-process) input-output relationships, (c) environmental interventions (i.e. emissions and resource use) per sector (or process), and (d) characterizations of environmental interventions.⁵

Many studies apply EEIOA.⁴ The final demands of households as well as inter-sectorial input-output tables (IOT) are provided by national statistical offices. IOT

59 hold information about aggregated financial transactions (or physical transactions
60 with associated prices) between the sectors of national economies. These financial
61 flows can be linked to environmental interventions (e.g. emissions or resource
62 use) per monetary unit of flow. Environmental interventions are available from
63 sectorial environmental accounts also compiled by national statistical offices. Thus,
64 financial expenditures of households for the output of a specific sector can be
65 environmentally assessed. However, the environmental assessment often covers
66 only national emissions and no upstream emissions due to the import of goods.^{1, 6, 7}
67 In a bid to overcome this shortcoming, there are trends towards multi-regional
68 EEIOA⁸ and small-scale analyses on municipal level.²

69 In hybrid analysis the final demand for domestic output is assessed with EEIOA
70 while upstream activities are assessed with LCA. Jungbluth et al., for example, have
71 performed a tiered hybrid analysis for Switzerland.⁹ They found that an average
72 inhabitant of Switzerland emits 12.5 tons of CO₂ equivalents (eq.) per year. In this
73 number they aggregated both domestic emissions (EEIOA) and foreign emissions
74 (LCA). The results yielded by the EEIOA part of the analysis are comprehensive in
75 scope, meaning that they cover all domestic sectorial outputs, for which there is a
76 final household demand. However, generally in hybrid analyses the segmentation
77 of the economy into different sectors is often coarse and the waste treatment
78 sector missing.⁵

79 LCA studies rely on life cycle inventories. They exist for a multitude of
80 consumption related activities and they include upstream processes and waste
81 treatment. Ecoinvent, a well renown life cycle inventory database, includes in its
82 latest version (v2.2) around 100 datasets for agricultural products, 50 datasets for

the generation of heat, and 40 datasets for different means of private transportation.¹⁰ These numbers will further increase in the future and also cover activities from other areas of consumption, which will allow detailed assessment of household consumption.

A process-LCA based analysis is able to differentiate various household consumptions, but the final demands of households have to be determined first before they can then be environmentally assessed. Girod and de Haan extracted the individual final demands of households from the Swiss household income and expenditure survey.¹¹ The study resulted in a status quo LCA of the individual yearly consumption of approximately 14,300 households. However, the use of a national sample does not allow for analyzing household consumption on municipal level, which was the aim of this study. Furthermore, we suggest the assessment of environmental impacts of household consumption by modeling individual final demands of households based on register and census data available for all municipalities in Switzerland and employing LCA for the environmental assessment. A modeling approach has the advantages of conducting analyses for any given geographical region in Switzerland as well as of performing improvement studies, for instance, for finding the optimal housing energy supply under regional supply constraints.¹²

Tukker and Jansen claim in their review study that housing, mobility and food are responsible for 70% of the consumption impacts for most environmental impact categories (the rest being mainly clothing, healthcare, education, communication, recreation, and miscellaneous consumption areas).⁷ This figure varies depending on the applied environmental indicator, but holds in general, and has also been

confirmed by Jungbluth et al.⁹ We included two of these three areas of consumption, namely housing and land-based mobility, in our household consumption assessment. The third was included as well in a recent study.¹³

The goals of this paper are: (i) to assess the environmental impacts of all individual households on municipal level, (ii) to reveal the distribution of environmental impacts within the community, (iii) to compare the carbon footprint of households against a prospective societal goal of a 1 t CO₂ society formulated by Bébié et al.¹⁴ and in line with the IPCC,¹⁵ and (iv) to characterize different household consumption patterns that lead to low, medium and high environmental footprints.

2. Materials and Methods

2.1. Modeling of final demands of households for life cycle assessment

Life cycle assessment is a method to calculate and assess all emissions and resource uses along the supply, use and disposal chains of a product or a service. The computational structure of life cycle assessment is described in the literature as:⁵

$$\mathbf{h} = \mathbf{QBA}^{-1}\mathbf{f} \tag{1}$$

Where $\mathbf{h}$ is the impact result, $\mathbf{Q}$ is the characterization matrix, $\mathbf{B}$ is the intervention matrix, $\mathbf{A}$ is the technology matrix, and $\mathbf{f}$ is the final demand vector.¹⁶ We used this equation to assess the environmental impacts of households. But instead of analyzing the final demand vector $\mathbf{f}$ of an average household, we assessed the final demand vectors $\mathbf{f}_i$ for individual households i . The final

demands can therefore be expressed as matrix $\mathbf{F}=(\mathbf{f}_1|\dots|\mathbf{f}_i|\dots|\mathbf{f}_N)$ for all N households of a region under investigation.

Within the consumption area of housing we focused on energy demand for space heating, hot water and electricity as well as demand for building infrastructure. This relates to the United Nations Classification of Individual Consumption According to Purpose (COICOP¹⁷) groups 4.3 and 4.5 and is consistent with other studies that use also this classification system.^{4, 7} The modeling of land-based mobility consumption covered private traffic demand for leisure and shopping purposes as well as for commuting (COICOP group 7.3), but no air travel. Traffic generated by people at work, for instance by a truck driver, was excluded from the analysis. However, this traffic demand was covered in the background system of the LCA (e.g. the truck transport of light fuel oil from refinery to regional storage).

The analysis considers all households resident within the spatial boundaries of any selected Swiss municipality. This spatial scope was chosen because in Switzerland municipalities are the smallest autonomous entity and usually consist of between 1,000-10,000 households. The temporal scope was the year 2010. The temporal resolution of the model was on an hourly basis. This gave us the flexibility to aggregate data over any discretionary timeframe (e.g. days, months, seasons, year, or also March 20, 12 PM to June 21, 12 PM).

2.1.1. Housing demand

We used hourly outdoor temperature (T_a) as well as direct horizontal, and diffuse horizontal radiation as inputs for the calculation of space heat demand in buildings. Climatic data was generated with meteonorm v7.¹⁸ All residential

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4 151 buildings situated within the borders of the spatial selection were considered for
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6 152 housing demand modeling. The data describing the buildings was extracted from
7
8 153 the Federal Register of Buildings and Dwellings (FRBD).¹⁹ The FRBD contains up-
9
10 154 to-date data of all buildings and dwellings in Switzerland. The data we used were
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12 155 geographic references (i.e. longitude and latitude, altitude above sea level),
13
14 156 building characteristics (i.e. year of construction, number of stories, number of
15
16 157 apartments, energy source used for space heating and hot water supply), and
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18 158 characteristics of the building's apartments (i.e. total floor area, number of rooms).
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22 159 We calculated the heating energy demand (Q_h) for each building based on its
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24 160 hourly heat flux balance. Thus, in order to determine Q_h we subtracted thermal
25
26 161 gains from the losses. As thermal gains we counted solar gains (Q_s) via windows
27
28 162 and internal gains due to occupancy (Q_{iP}) and electricity use (Q_{iEl}). Thermal losses
29
30 163 were losses due to thermal transmission through the building envelope (Q_T) and
31
32 164 losses due to ventilation (Q_V). This approach is in accordance with the Swiss
33
34 165 standard SIA 380/1²⁰ for thermal energy calculations in buildings published by the
35
36 166 Swiss Society of Engineers and Architects (SIA) and is formulated in eq 2.
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$$Q_h = \sum_{t=t_{begin}}^{t_{end}} (Q_{T,t} + Q_{V,t}) - \eta_g \cdot (Q_{s,t} + Q_{iP,t} + Q_{iEl,t}) \quad (2)$$

45
46

47 168 Herein t denotes the hour, t_{begin} and t_{end} are the boundaries for the analyzed period
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49 169 and η_g is the degree of utilization for heat gains, which depends on the thermal
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51 170 storage capacity of the building mass (cf. Supporting Information). For each
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53 171 building we then allocated the heat demand for the whole building to its
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55 172 apartments based on the apartment size. The modeled specific space heat demands
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of buildings were compared with average values for different construction periods found in literature. This validation can be found in the Supporting Information.

Transmission losses per hour were calculated by means of eq 3:

$$Q_{T,t} = \begin{cases} \sum_{j=1}^n (T_{i,t} - T_{a,t}) \cdot A_j \cdot U_j \\ 0 & \text{if } (T_{i,t} - T_{a,t}) \leq 0 \end{cases} \quad (3)$$

Where T_i is the ambient room temperature (e.g. 20°C), A_j is the area and U_j is the heat transfer coefficient of building component j . The U-values were taken from Wallbaum et al.,²¹ who reported heat transfer coefficients for four different building components (roof, wall, floor and windows) and distinguished their U-values according to year of construction of the building and year of renovation of the specific building component. The areas of the four components were calculated from the area of the building surface. The FRBD does not contain information on the shape of the buildings. Hence, each building was simply modeled as a cube with a square base. The base as well as the top area was assumed to be the aggregated apartment area divided by the number of stories. The building surface area was calculated by multiplying the aggregated apartment area with a correction factor and a so-called building envelope factor,²² which describes the relationship between total floor area and surface area. Base and top areas were subtracted from the surface area to get the facade area.²¹ The facade was then divided into windows and wall surface by assuming a share of window area of 18%.²³

The ventilation heat losses per hour were calculated with eq 4.

$$Q_{V,t} = \begin{cases} (T_{i,t} - T_{a,t}) \cdot \dot{V} \cdot \rho_a \cdot c_a \\ 0 & \text{if } (T_{i,t} - T_{a,t}) \leq 0 \end{cases} \quad (4)$$

$\dot{V}$ is the hourly air exchange ρ_a is the density of air and c_a is the specific heat capacity of air. For buildings with mechanical ventilation, $\dot{V}$ was reduced by a factor describing the efficiency of the heat recovery.

The solar gains were calculated with eq 5:

$$Q_{s,t} = \sum_{j=1}^n G_{s,j,t} \cdot A_{w,j} \cdot f_{s,j} \cdot 0.9 \cdot g_{\perp} \cdot f_F \quad (5)$$

Where $G_{s,j}$ is the global solar radiation, distinguished for the different facades j of a building (i.e. north, west, south, east, and top), $A_{w,j}$ is the window area, and $f_{s,j}$, f_F and $g_{\perp}$ are reduction factors for shading of nearby buildings, window frame and glass properties.

$$Q_{i,t} = Q_{iP,t} + Q_{iEl,t} \quad (6)$$

For the modeling of internal gains $Q_{i,t}$ we based our calculations on specific values provided by the SIA 380/1 standard.²⁰ Electricity demand Q_{El} was assumed to be 100 MJ/m²·year for multi-family dwellings and 75 MJ/m²·year for single family dwellings.²⁰ $Q_{iEl,t}$, the hourly internal gains from electricity use, was calculated in eq 7 as:

$$Q_{iEl,t} = Q_{El} \cdot f_{El} \cdot A_E / 8760 \text{ h/yr} \quad (7)$$

f_{El} is a reduction factor that considers the share of electricity that is useful for heating purposes. A_E is the heated floor area of the building.

212 $Q_{iP,t}$ was 0.252 MJ/hour·and person (i.e. 70 W/person).²⁰ This is the thermal
213 power people generate on average when being in a building. The average time
214 people spend in their home is 12 hours per day²⁰.

215 Apart from heating and electricity demand, we also calculated the energy demand
216 for the supply of hot water Q_{ww} for each household. Hereby again, we relied on
217 standard values²⁰ (i.e. 75 MJ/m²·year for multi-family dwellings and 50
218 MJ/m²·year for single family dwellings). The total space heating, hot water and
219 electricity demand was then broken down according to the floor area into demand
220 per apartment.

221 Although FRBD is rather comprehensive, some data such as the renovation year of
222 specific building parts, roof inclination, or specific heat supply technology was not
223 available. We therefore assumed that the unknown parameters were stochastic. All
224 of them along with their distribution and uncertainty parameters are stated in the
225 Supporting Information. One of these unknown parameters was the applied heat
226 supply technology for a specific building. The FRBD, however, holds information
227 on the energy source used for space heating and hot water production. It
228 distinguishes between oil, coal, natural gas, electricity, wood, heat pump, solar
229 collectors, and heat from a district network. Wood, for instance, can be further
230 differentiated into heat from logs, chips or pellet incinerating systems. Therefore,
231 we applied stochastic modeling to determine the detailed heating supply
232 technology. From statistical data about wood energy use in Switzerland we derived
233 discrete shares $p(x_i): \square \rightarrow [0,1]$ of log, chips or pellet furnace technologies
234 $x_i = \{1, 2, 3\}$. We assigned a random number $Y: \square \rightarrow [0,1]$ to each building. These

235 random numbers were uniformly distributed among all buildings. Based on Y we
236 determined the furnace technology x of the specific building with:

237
$$Y = P(x) = \sum_{x_i \leq x} p(x_i) \tag{8}$$

239 We used the database ecoinvent¹⁰ for the life cycle inventory data. Life cycle
240 inventories describe all inputs to and outputs from an economic process. The
241 inputs can be products from other economic processes or resources from the
242 environment. The outputs are direct emissions to environmental compartments
243 and economic goods. Ecoinvent provides datasets covering various supply
244 technologies for each of the aforementioned energy sources. Thus, we extracted
245 the shares of the technologies for a specific energy source from statistics²⁴⁻²⁶ and
246 distributed the technologies stochastically among all buildings using this source.
247 We did that for all energy sources. Then, we linked the space heating and hot water
248 demands per apartment with the respective reference flows of the supplying
249 technology in the technology matrix A . Additionally to the datasets from
250 ecoinvent, we also established new datasets that we included in the technology
251 matrix. The life cycle inventory of heat from brine-water heat pump, was taken
252 from Saner et al.²⁷ Regionalized electricity supply datasets were modeled
253 according to the respective declaration by the local electricity utility and linked to
254 the household's direct electricity demand and the heating technology's electricity
255 demand.

256 2.1.2. Land-based mobility demand

257 Land-based mobility demand was calculated based on the output from an agent-
258 based transport simulation called MATSim.²⁸ An agent-based model was employed
259 because it is able to model individual demands for a specific geographic region.
260 MATSim is a modeling environment, which allows for simultaneously simulating
261 land-based mobility patterns of millions of so-called agents. Agents represent
262 inhabitants of a municipality, region or country. MATSim has been implemented
263 and validated for Switzerland and is able to model traffic behavior of Swiss
264 inhabitants for an average workday.^{29, 30} At the moment no weekend or intra-week
265 model for Switzerland is implemented in MATSim. Therefore, we approximated
266 yearly mobility patterns with 365 workdays. As the average travel distance for
267 weekends equals the average travel distance for work days this assumption is
268 justifiable.³¹

269 MATSim simulates the agents' workday mobility patterns based on the agents'
270 daily plans. These plans are defined by the locations where agents live, work, and
271 spend time for shopping and leisure. Swiss National Census 2000³² and micro
272 census 2005³³ (micro census is a census about the land-based mobility behavior of
273 people) data are the statistical basis for the generation of a synthetic population of
274 agents and their daily activity plans. Agents have characteristics like age, gender,
275 and education and are grouped together in households with specific household
276 characteristics like income, geographic location and types of fuel (i.e. petrol, diesel
277 or other), which are derived from the Swiss National Census 2000³². The daily
278 activities of agents are defined by the agents' characteristics, census data about
279 their place of work as well as spatial information about schools and shopping

280 opportunities in their vicinity. For an in-depth description of the MATSim
281 modeling framework and its application to Switzerland we refer to the work of
282 Balmer et al.²⁸

283 MATSim uses an iterative approach, which is based on a co-evolutionary
284 algorithm.³⁴ This means, after one traffic simulation for a day, the performance of
285 each agent is scored using a utility function, e.g. lower travel time resulting in
286 higher score. For the next iteration the current plan can be adapted or a previously
287 executed plan reselected for execution. Only a limited set of plans is kept within
288 the memory of the agent, from which plans with higher score have a higher chance
289 of reselection, while bad plans are deleted over time (see Supporting Information).
290 This corresponds to the survival of the fittest in a co-evolutionary algorithm. As the
291 iterations continue, the process approaches equilibrium. This means, at this point
292 the utilities of agents only change marginally between iterations. The output data
293 from a MATSim simulation contains the details of selected plans together with
294 detailed output of the traffic simulation for each agent. These plans state when
295 agents left a specific location, for how long and how far they drove and what traffic
296 mode they used.

297 The micro census, the statistical basis of MATSim, only covers land-based
298 transportation modes. Thus, only land-based mobility patterns can be simulated by
299 MATSim. MATSim distinguishes the following four travel modes: car, public
300 transport, bicycle, and walk. Motorcycles are subsumed under the category car.
301 Hence, we calculated the mobility demand (in terms of travelled kilometers) of
302 each agent and each traffic mode and aggregated the traffic demand on household
303 level.

Household data from the Swiss National Census 2000³² is subject to data protection thus its geographic reference does exactly coincide with the geographic reference of building in the FBDR. However, the geographic reference of households is accurate within a 100×100 m grid resolution. Thus, each household was assigned to the nearest building and within the building to an appropriate apartment, i.e. an apartment with enough rooms to hold all members of the household. If an apartment was already occupied by another household then our model looked for another available apartment. Hereby, double occupancy was avoided. After this step, we knew for each household i the housing and land-based mobility demand. This was then compiled in a final demand vector $\mathbf{f}_i$. The non-zero values of the vector represented the demand for a reference product supplied by a process stored in the technology matrix $\mathbf{A}$. Final household demand vectors were merged into the final demand matrix $\mathbf{F}$ and impact results $\mathbf{h}$ calculated with eq 1.

2.2. Uncertainty analysis

The FRBD and MATSim did not provide all information needed for the modeling. For instance, we had no information if the windows in a certain building had already been replaced since the time of construction. However, we had the data on the probability that windows had been replaced and the according U- and g-values of the replaced windows. Thus to compensate for missing information in the data sources like the exact assignment of households to apartments we employed stochastic modeling. A comprehensive list of uncertain model parameters can be found in the Supporting Information. Uncertainty analysis was performed by employing Monte Carlo simulation. The simulation was run 1,000 times. This

means that impact results from housing and mobility were calculated each time with different input values. Sample values for the Monte Carlo simulation were obtained with the Latin hypercube sampling method.³⁵ After the simulation there were 1,000 samples of impact results for each of the analyzed households. Household impact results within one sample were not independent from each other due to various modeling constraints. For example, two households could not share the same apartment. We tested, whether the 1,000 samples of household impact results were samples of the same statistical population by means of the Kruskal-Wallis-test.³⁶ We calculated the median impact result for each sample and then calculated the median, the 2.5th and 97.5th percentiles of these 1,000 median values. This led to the median sample and the samples representing the 2.5th and 97.5th percentiles that are presented in Supporting Information.

2.3. Cluster analysis

The modeling resulted in impact results for several thousand households of a region. According to their environmental footprints we categorized the households in four groups. Cluster analysis (CA) for each group of households then allowed for further data reduction without losing information on differences in the households' environmental footprints. We used hierarchical clustering applying Ward's method as linkage criterion.³⁷ The cluster analysis started by treating individual households as single clusters. Then, always two clusters were merged into one bigger cluster based on the smallest proximity measure. This procedure was performed until only 3 to 4 clusters per group remained. As proximity metric we used the squared Euclidean distance, which is the sum of the square differences between the elements of two vectors.³⁷ The shorter this distance the closer two

clusters are. The two clusters with the shortest distance were then merged. As parameters for the cluster analysis we used aside from life cycle impact results the following household characteristics:

- Size: Number of household members.
- Income: Household income per month. Income is categorized into 10 categories. 1 equals 0-1,999 CHF/month, 2 equals 2000-2,999 CHF/month and so forth. 10 equals 10,000 CHF /month and more.
- Age of the oldest household member.
- Age of the youngest household member.
- Highest education: The highest educational level that was achieved by one of the household members. Education is categorized in 10 categories. The categories range from no education (1) to university degree (10).

Additionally, average apartment area per person, and average number of apartments per building were calculated per cluster.

2.4. Case study

To illustrate the application of the household consumption LCA, we performed a case study for Wattwil, a municipality located in the eastern part of Switzerland in the canton of St. Gallen. Wattwil has around 8,000 inhabitants living in 3,238 households and is the capital of the Toggenburg district.

The environmental impacts of each household were assessed on a yearly basis. Life cycle greenhouse gas emissions³⁸ were used as the main environmental indicator.

This method was chosen as it enables the comparison with other studies.³⁹

Although we are presenting the results only in CO₂ equivalent (eq.) emissions, our

375 model is capable of applying all common life cycle impact assessment methods
376 provided by ecoinvent¹⁰ (e.g. ReCiPe⁴⁰ midpoint indicators) to calculate various
377 environmental impacts of households.

378 3. Results and Discussion

379 The life cycle assessment of households' consumption was performed for the
380 reference year 2010. Figure 1a shows the median life cycle greenhouse gas (GHG)
381 emissions in metric tons for housing and land-based mobility consumption of
382 3,238 individual households. The results were normalized by the number of
383 household members. We found by applying the Kruskal-Wallis-test that there was
384 no significant difference between the 1,000 different samples calculated with
385 Monte Carlo simulation (see Supporting Information). Thus, the results of the
386 median sample are representative and suitable for further discussion. The blue
387 bars in Figure 1a represent GHG emissions induced due to commuting, shopping
388 and leisure purposes by different means of land-based traffic modes and the use of
389 their infrastructure. GHG emissions induced by space heating, hot water, electricity
390 consumption and building infrastructure are depicted in yellow. The resulting GHG
391 emissions are normalized by the number of people living in the household and
392 ranked from the lowest to the highest emitters. Impact results for ReCiPe⁴⁰
393 midpoint categories and Ecological Scarcity⁴¹ are reported in the Supporting
394 Information.

Figure 1. Life cycle greenhouse gas emissions of individual households in Wattwil (CH) in the year 2010 induced by housing and mobility (a) and housing (b) and mobility (c) alone. The impact results per household have been normalized by the respective number of household members and ranked from smallest to largest value. The included map shows the size of Wattwil and its location within Switzerland (map data: BFS GEOSTAT / swisstopo).

The median value for life cycle GHG emissions over all 3,238 households was calculated as 3.12 t CO₂ eq. per person and year. Hence, 50% of households emit less and the other 50% emit more than this value. The mean value is 4.30 t CO₂ eq. per person, which is 10% lower than the Swiss average for housing and land-based mobility consumption in 2005 (4.76 t CO₂ eq. per person).³⁹ The distribution of environmental impacts in the municipality is skewed to the right. Thus, more households generate less GHG emissions than the mean value. A Gini inequality

index⁴² G of 0.44 was calculated for Wattwil. A G of 1 would mean total inequality and a G of 0 would mean total equality among the impact results of the different households. For calculation of G see the Supporting Information. The findings suggest that GHGs are not emitted equally and that a small share of households in Wattwil is responsible for a large amount of GHG. This is supported by the cumulative relative impact results also presented in Figure 1a, for which it is shown that at the lower end 50% of the households are responsible for only around one fifth of the housing and mobility impacts, but that the 20% of the households with the largest impacts emit 50% of GHGs. The results in Figure 1a also indicate that already around 12.4% of Wattwil inhabitants (311 households) comply with a 1 t CO₂ eq. per capita goal so far. However, if we added more consumption categories, the number of inhabitants complying with the goal would of course decrease.

Figure 1b and c show the ranked household impacts differentiated for housing and mobility. The impacts for the two consumption areas are further distinguished into housing operation (space heating, hot water, and electricity) and building infrastructure, and motorized private, non-motorized private and public transportation, respectively. Building infrastructure amounts on average only to 5.8% of total housing impacts. This means that the building stock in Wattwil is rather old, as for new buildings the impacts of infrastructure can strongly influence the housing impacts.⁴³ The Gini coefficients are 0.49 for housing and 0.64 for mobility. This means that housing impacts are more equally distributed among households than mobility impacts. Housing is the main driver for the carbon-intensity of households. Another thing that can be observed is that by aggregating

the impacts of both consumption categories we find a more equal impact distribution among the low-emitting households.

As the geographical references of the households are known, we are able to present the magnitude of household-specific consumption impacts at the place of residence of the respective households (see Figure 2). Thereby, it is possible to identify areas of a municipality, where high-impacting households reside. The maps were rasterized with a cell size of 100×100 m and the environmental impacts within one raster cell were averaged for the reason of data privacy protection. The map on the left hand side shows the spatial distribution of life cycle GHG emissions induced by housing, the map on the right hand side shows the same for mobility. The results are graduated into four classes, meaning that the raster cells are categorized into four groups according to their average impact per raster cell. The groups were derived by investigating the impact result distribution depicted in Figure 1a. The groups consist of households that are below 1 ton CO₂ eq. per capita and year, households that emit less than the median value (i.e. 50th percentile or 20% of cumulative emissions), households that contribute between 20% and 50% and households that contribute more than 50% to the cumulative impact result (i.e. the 80th percentile).

Wattwil is a center for the surrounding rural region.⁴⁴ This is also reflected in the spatial distribution of households, which shows that most households are situated along a main street crossing from North to South.

Figure 2. Rasterized maps of Wattwil (map data: BFS GEOSTAT / swisstopo) showing averaged life cycle GHG emissions per hectare graduated into four classes. Blue and pink circles indicate areas, where housing and mobility impacts are significantly different. Green circle indicate areas, where housing and mobility impacts are both on a similar level.

The spatial distribution of impacts shows that for some areas in the municipality we find differences between the impacts of housing and land-based mobility. One of these areas is marked by a bright blue circle. Here we find households that belong mainly to the 3rd and 4th group in terms of GHG emissions from housing, but to 1st and 2nd group in terms of mobility. The finding suggests that these households live either in poorly insulated buildings and/or use fossil fuels for space heating. However, they generate a smaller demand of motorized individual transportation than other households. This might be explained by the fact that we find these households located in the old town near the train station. The inverted phenomenon is marked by a pink circle, where households are located which have high mobility impacts, but low impacts from housing. These two examples support findings of other authors who state that environmental impacts of households are often subject to trade-offs between the different consumption categories.^{11, 45} But

we also find households whose environmental performances are similar for both areas of consumption. One such example is marked with a green circle. These households are below the 1 t CO₂ eq. goal in both consumption categories. Possible trade-offs were not further investigated.

The question about the reliability of the aforementioned findings is of utmost importance. As we performed stochastic modeling of the household demands we were able to identify the median as well as the 95%-confidence interval of impact results. We found that the distributions of impact results among the households stay constant over the whole range of uncertainty samples (see Supporting Information).

We used the aforementioned grouping of households for subsequent cluster analyses. Here the groups are denoted as A, B, C, and D. Applying cluster analyses we were able to reduce several hundred individual households to 3-4 clusters per group. The results of the CA are presented in Table 1. We find three meaningful clusters in group A, four clusters in group B, four in group C, and three clusters in group D.

Table 1. Clusters of similar households with their respective household characteristics, greenhouse gas emissions per capita and year induced by housing and land-based mobility as well as the distance to city center. Values are presented as average values of cluster.

Cluster name	Cluster size [No. of household]	No. of persons per household	Household income category	Max. Age of the oldest person in the household	Min. Age of the youngest person in the household	Highest education level achieved by a household member	Housing operation impacts [t CO ₂ eq. per person and year]	Building infrastructure impacts [kg CO ₂ eq. per person and year]	Mobility impacts [t CO ₂ eq. per person and year]	Apart-ment area [m ² per person]	No. of apart-ments per building	Distance to city center [km]
A1	110	1.5	3	70	66	3	0.4	92	0.2	82	3	1.13
A2	122	4.6	5	46	10	5	0.2	22	0.5	23	3	1.36
A3	79	3.5	5	38	14	3	0.5	32	0.2	36	8	1.39
B1	172	1.6	4	55	51	4	0.5	93	1.3	78	3	1.25
B2	365	3.3	3	40	14	4	1.3	34	0.7	34	7	1.33

B3	347	4.6	7	45	10	5	0.7	25	1.2	24	6	1.37
B4	424	2.0	5	67	57	4	1.7	46	0.4	46	9	1.06
C1	143	2.0	6	56	46	6	3.0	53	1.1	60	8	1.06
C2	297	1.4	3	73	71	3	3.5	71	0.7	75	8	1.11
C3	295	3.5	5	46	19	5	1.2	31	3.0	34	7	1.31
C4	216	1.3	3	40	38	4	3.1	116	1.1	91	7	1.12
D1	305	1.2	3	62	61	3	5.6	101	3.2	111	9	1.17
D2	181	3.1	6	49	24	5	2.6	44	6.4	50	9	1.20
D3	182	1.3	3	34	31	4	6.2	79	8.1	100	7	1.07

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492 The clusters are ranked in ascending order according to their total impacts (i.e. the

493 sum of housing operation, building infrastructure and mobility impacts). The

494 cluster sizes range between 79 and 424. For each cluster we also calculated the

495 average of the distance between each household of the cluster and city center.

496 The first group (A) of clusters represents 9.5% of all households in Wattwil and

497 comprises households that emit below 1 ton of GHGs per person and year for land-

498 based mobility and housing. Cluster A1 consists of small households of elderly

499 people and clusters A2 and A3 are formed by families with children. The

500 apartment area per person is rather small (average for group A is 47 m² per

501 person) and the buildings are, judged by the low infrastructure emissions (i.e.

502 average for the group is 49 kg CO₂ eq. per person and year), rather old. The

503 impacts from space heating, hot water and electricity consumption (i.e. housing

504 operation) are below 0.5 t CO₂ eq. This means that households of these clusters live

505 in more poorly insulated buildings than households of clusters from other groups

506 (building infrastructure emissions for group C 66 kg CO₂ eq. per person and year,

507 and group D 79 kg CO₂ eq. per person and year), but the apartments are heated by

508 low GHG emitting heating systems (share of wood heating system in group A is

509 57%, heat pumps 6%, and electricity 9%) and they only use a limited living area.

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4 510 Impacts from mobility are very low, due to low demand for motorized private
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6 511 transportation and only moderate demand for public and non-motorized private
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8 512 transportation. The group not only comprises households of elderly people, who
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10 513 tend to have lower demands of mobility, but also clusters of young families. This
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12 514 finding suggests that these households have either short or no commuting
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14 515 distances (e.g. farmers).

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18 516 Group B is formed by households that emit less GHGs than the median but more
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20 517 than 1 ton. Also here we find clusters of singles/couples and families. Each cluster
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22 518 is below 1 ton GHG emissions in one of the two consumption areas. This means
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24 519 that they either perform very well in housing (B1, B3) or mobility (B2, B4). The
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26 520 rather moderate emissions from housing stem from a higher share of wood and
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28 521 natural gas fueled (14% and 36%, respectively) heating systems and the small
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30 522 living area per person, which on average for the group is even slightly smaller
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32 523 (44m²) than for the clusters in group A. Most clusters have moderate demand for
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34 524 motorized private transportation or high demand for public transportation.
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36 525 Mobility impacts are highest for cluster B1. They are even higher as for three
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38 526 clusters of group C, and only cluster C3 has higher impacts for mobility.

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41 527 Group C consists of three clusters (C1, C2 and C4) with GHG emissions dominated
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43 528 by housing operation and one cluster (C3) with high impacts from mobility. The
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45 529 emissions of one category are often two to three times higher than the emissions of
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47 530 the other.

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50 531 Group D is formed by households that consume large amounts of fossil fuel for
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52 532 heating (share of oil heating approx. 66%) and transportation purposes. This
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54 533 group is responsible for 50% of the cumulative GHG emissions induced by
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households in the case study municipality, meaning that if their impacts could be halved, the cumulative impacts of Wattwil would be reduced by 25%. The households in group D have similar properties as the households in the other groups (i.e. single/couples and families with grown-up children). However, their emissions are high from housing and also from mobility. Clusters D1 and D3 have the highest emissions for space heating, hot water and electricity consumption, but also among the highest for building infrastructure, which suggests that the buildings inhabited by the people in these clusters are fairly well insulated. However, the emissions from housing are high, because the two clusters use large apartment areas (on average 92 m² per person) and heat with fossil fuels.

In our analyses we were only examining the life cycle GHG emissions induced by household consumptions. Thus, our conclusions are only valid for this impact category. However, under this constraint and for the situation in Wattwil, we can conclude for housing that we can only achieve low impacts by a combination of small demand and almost low-carbon supply (cf. group A and B of clusters). Therefore buildings should be refurbished and living area per capita should be kept small. Wood heating and heat pump systems should be installed. The disadvantage of the former is the high emission loads of particulate matter and that of the latter is the augmented use of electricity. These drawbacks could be mitigated by installing efficient, centralized systems connected to the buildings via district grid.⁴⁶ For today's land-based mobility we cannot switch immediately to a low-carbon supply. Alternatives to internal combustion engines like plug-in hybrid, battery electric or fuel cell cars are now made ready for the market, but still have deficiencies in range and necessary infrastructure. Thus so far, impacts from

mobility can only be significantly reduced by a reduction of motorized private transportation and a moderate use of public transport. However, this is often not possible due to long commuting distances. Hence, for a long-term GHG reduction strategy it is of great importance to bring living and working places closer together.

4. Outlook

There are also other factors than housing and mobility contributing to overall household environmental impacts. Food and clothing are the third and fourth most important consumption categories and further work should focus on implementing household demand models for them. Hence, this would lead to a more complete LCA-based picture of household environmental impacts.

More Swiss municipalities should be investigated in the way we demonstrated for Wattwil. This would allow comparing the different distribution profiles of household environmental impacts against each other. Low-impacting communities could be identified and factors like short commuting distances could be derived from the analysis of their community structure. The results should be used to establish long-term roadmaps that focus on promoting these factors.

The presented modeling approach can furthermore be used for scenario analysis of changes in housing and mobility demand (e.g. better insulation of buildings, introduction of electric cars, etc.) as well as for the optimization of mobility or housing supply under different regional supply constraints.¹²

579 5. Supporting Information Available

580 Details on uncertainty considerations and further impact assessment results can
581 be found in the Supporting Information. This information is available free of charge
582 via the Internet at <http://pubs.acs.org/>.

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