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RESEARCH ARTICLE

The effects of teleworking on CO_2 emissions from commuting: baselining key data to investigate transformative change in living labs

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The quantitative monitoring of the greenhouse gas (GHG) mitigation potential of interventions is central to a living-lab approach and is a methodological challenge. Valid population data on consumption patterns and mobility behaviour are often scarce, especially when the living lab is initially set up (for example, the need for baseline data before an intervention). In the context of transportation studies, a cross-sectional survey was carried out to baseline key data on GHG emissions generated by commuting before implementing an intervention. Based on this information, the GHG emissions from commuting were calculated and analysed using a linear regression model. Results show the effects of different variables, such as the share of teleworking within a working week, the regular workplace location, and attitudes towards individual mobility and former relocation behaviour. An increase in teleworking of 10 per cent based on weekly working time leads to a reduction of approximately 60 kg of GHG (8 per cent) emissions a year. Our results serve as baseline key data to analyse upcoming (temporary) interventions (for example, new coworking spaces within our living lab). Hints for rebound effects, limitations of our study and future interventions are discussed.

Keywords living labs • teleworking • commuting • CO_2 emissions • rebound effects

Key messages

- Data to assess the effectiveness of interventions in living lab studies is scarce when a living lab is set up.
- Teleworking in a living lab can be seen as an intervention. Based on the key data generated, this intervention can be evaluated.
- Multivariate linear regression reveals that an increase in teleworking of 10 per cent leads to a reduction of 60 kg of CO_2 emissions a year.

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Introduction

In the context of the living lab (LL) methodology (Voytenko et al, 2016; Sahakian et al, 2021), transformative change needs to be monitored to measure the 'success' when means of (temporary) interventions are introduced. This is especially the case when the interventions are aiming for the reduction of greenhouse gas (GHG) emissions in line with the Paris Agreement. However, valid population data on relevant consumption patterns that need to be changed is often scarce. There is a lack of key figures that can be monitored over time in many initially set-up LLs. In the context of the SWEET SWICE project, we examine commuting-related GHG emissions in the transport sector before the start of a LL and an intervention (for example, providing a coworking space in the LL).

This is the starting point for the following research questions:

1. How can commuting-related GHG emissions before the start of a LL be examined?
2. What is the effect of teleworking in general on commuting-related GHG emissions (before the introduction of an intervention)?
3. Are there first hints of rebound effects?
4. How can such key figures serve as baseline data to introduce and evaluate future interventions within a LL?

These research questions will be investigated with data stemming from a LL that is situated in a suburban municipality in Switzerland. A quantitative cross-sectional study is carried out based on a standardised questionnaire that is statistically representative of the inhabitants of our LL (n=299, response rate 33 per cent). Based on the surveyed information, we derive GHG emission figures per person and year. Using the method of multivariate linear regression, GHG emissions for commutes are analysed according to various influencing factors, such as teleworking practices, socio-demographics, mobility tool ownership, attitudes towards mobility and socio-psychological self-assessment items.

The remainder of the article is structured as follows: first, we provide an overview of key trends in research to draw out the research gap in the context of teleworking, commuting-related GHG emissions and LL methodology. Second, the research method is described, and descriptive results and a multivariate regression model are presented and discussed considering our four research questions. Third, we discuss the limitations of the study. Finally, we present an outlook on future intervention design that aims to investigate transformative change within a LL that can benefit from our key findings.

Teleworking, decarbonisation and living lab intervention

Effects of teleworking on transportation

Since the late 1980s, new flexible forms of work, such as those provided in the home office, have been discussed in academic debates as a measure to reduce GHG emissions in the transport sector (Salomon, 1986; more recently Hook et al, 2020; Santos and Azhari, 2022). In this context, teleworking is understood as work activities outside the traditional workplace boundaries of an employer's office or production space (Morganson et al, 2010). Possible workplace locations that are covered by the term 'teleworking' are the private home (in a home office), on the move (in a medium of travel, for example, a train) and so-called third locations such as a coworking space or a café (Ravalet and Rérat, 2019: 584). These working practices can have an impact on transport demand. For Switzerland, Ohnmacht et al (2020a; 2020b) show the effects of the use of coworking spaces, as do Wöhner (2022) and Ravalet and Rérat (2019) for the use of home offices to reduce the distance travelled on the day of working from home.

However, research shows that it is simply not enough to consider work-related trips in isolation, ignoring trip chains and non-work-related trips that may even increase in frequency or length due to teleworking. Rebound effects must be considered, such as in the context of trip chaining. Trip chaining is the practice of combining multiple destinations or activities into a single journey to increase efficiency and save time. Trip chaining combines several stops on the way to a main destination (for example, working) to complete various tasks in between, such as shopping, running errands or taking children to school (Zhu and Guo, 2022). Since chaining trips are an important part of daily mobility for many people, the time 'saved' on teleworking days could be 'used up' on other forms of mobility. Thus, home offices may induce additional mobility, for example, for leisure or shopping purposes (complementary or rebound effect) (Salomon, 1986; Andreev et al, 2010). Additional mobility may include trips in trip chaining that have to be done despite teleworking (for example, taking children to kindergarten) or new trips made possible with teleworking (for example, leisure at the end of the afternoon) which is different from trip chaining.

Regarding long-term effects, it is found that telework does not only have an impact on daily mobility practices but also residential choices. Possible rebound effects may also include employees' increased tolerance to long-distance commuting. As residential choices are complex there is no clear evidence regarding causality in previous research on whether telework directly impacts the residential location. Nevertheless, Zhu (2013) illustrates how teleworking often resulted in increased household commuting distances, emphasising the substantial influence of telework on shaping commuting behaviours in combination with the residential location. Similarly, Ravalet and Rérat (2019) show that despite reducing the number of commuting trips, the distance travelled over the working week may still be greater due to the larger spatial distance between the home and the workplace. It thus depends further on the frequency of needing to commute to work or not.

Teleworking interventions in living labs

A LL introduces (a temporary) transformative change in a real-world setting (Voytenko et al, 2016). It aims to foster people's engagement through a participatory environment involving the co-design of interventions (Sahakian et al, 2021: 3). In a LL, interventions are developed in a participatory manner by using the so-called '4P' approach, which stands for a Public-Private-People-Partnership (Ruijsink and Smith, 2016; Lawrence et al, 2022). Here, various scientific disciplines, such as spatial planning, sociology, psychology, architecture, economics and engineering, work together to understand, promote and shape processes of social change on different geographical scales, such as local neighbourhoods in rural, suburban or urban areas. These academic disciplines collaborate with companies, public bodies, employees and the inhabitants which are based in the LL (Engels et al, 2019; Rose et al, 2019; Compagnucci et al, 2021).

Yet, the link between decarbonisation and the intervention of teleworking has been thematised in only a few studies on LLs. Vaddadi et al (2020) show in their conceptual framework that working from a local coworking space has direct and indirect environmental effects. They tested it on a LL in Stockholm and showed how operating the coworking space can counterbalance commute-related energy savings. Regarding rebound effects, their related empirical study summarises that teleworking increases energy requirements for non-travel activities (Bieser et al, 2021).

Learnings, ambiguities and research gaps

To conclude from our literature review on telework and the impact on GHG emissions, we see that a multitude of studies do quantify this relationship.

However, studies on the interrelationship between decarbonisation and teleworking in the context of a LL intervention are limited; so far, to the best of our knowledge, there are only the studies of Vaddadi et al (2020) and Bieser et al (2021).

A further research gap is to tackle possible rebound effects due to teleworking (Hostettler Macias et al, 2022). Rebound effects can mean that the effects of new forms of working on transportation may not be as positive as expected and may even be negative. Teleworking may incorporate many ambiguities, such as more leisure travel on teleworking days, increases in individual living space due to separate rooms being used for home offices or even growing single-trip commuting distances due to freedom in residential choices. These ambiguities may have a neutral effect on transport demand (zero effect in terms of the number of trips, but also distances) (Andreev et al, 2010).

This article adds to the stream of literature by filling the research gap on the relation between telework and GHG emissions in the context of LL research. The following section will provide empirical insights based on a population sample stemming from inhabitants of a LL.

Data and methods

Living lab setting

Our data was generated within a LL setting based on a 4P approach to foster transformative change by collaboratively developed interventions. The suburban site where a LL is started is called 'Suurstoffi' and is part of the municipality of Risch-Rotkreuz in Switzerland. The LL has 1,500 residents and 2,500 workplaces and accommodates a university with 2,600 students. The area is near a railway station and is well connected to the national road network. Here, public bodies on the municipality and governmental level, a real estate company, partners from industry and a railway company work together with inhabitants and employees to introduce interventions mainly to influence peak-hour travel. A coworking space on the site to encourage flexible forms of work is regarded as a promising intervention.

To start the work in the LL in September 2022, a common aim was to collect baseline data from the residents regarding travel behaviour that should be changed sustainably in the LL. A methodological design was developed in a collaborative workshop with several actors in the LL aiming to collect key information on commuting behaviour in the LL. Several members of the LL served as sounding boards for the content of our study and the survey design. Thanks to the LL setting, the public bodies of the municipality of the LL provide all the addresses of inhabitants aged 18 years and older in the context of this participatory approach for an empirical research study.

Content of the study

The questionnaire focuses on household characteristics and includes questions about individual mobility behaviour, level of employment, the location of the regular workplace and the main means of transportation used to get to work. In addition, questions were asked about teleworking activities (home office, coworking). Furthermore, attitudes towards mobility and socio-psychological self-assessment items were assessed. In detail, the transtheoretical model of Bamberg (2013) was applied; this is a concept for describing, explaining, predicting and influencing intentional behavioural changes. It assumes that change processes go through several qualitatively different and successive phases (see the Appendix).

Field organisation of the study

The residents received a letter of invitation with a paper-pencil survey and a stamped return envelope in October 2022. In parallel, an online survey in German or English was made accessible via a scannable QR code on the invitation letter. After handing in the response, the participants received an incentive in the form of a voucher worth 10 Swiss Francs from a bakery in the LL. At the end of October 2022, a reminder based on response control was sent out for those who had not replied yet. The research team provided a telephone hotline and email support for the LL inhabitants.

Response rate

Overall, the response rate was satisfactory at 33 per cent. This percentage can be interpreted as a comparatively high willingness to participate (Table 1).

Descriptives of the sample

Please also see Table 5 for descriptives of the sample. Half the people who completed the survey are women. The average age is 41 years. On average, there are 2.4 people per household. Thirty-eight per cent of the respondents live in a couple household, 32 per cent in a family household and 20 per cent in a single household. The average gross income per household is 10,149 Swiss Francs, calculated based on the

Table 1: Response rate and final sample size

	n	%	%
Gross sample	922		
Sample-neutral drop-outs (relocations, and so on)	7		
Net sample	915	**100**	
Response after data-cleansing, of which are filled out via:	299	33	**100**
physical questionnaire	125		42
online survey in German	127		43
online survey in English	47		15

Table 2: General descriptives on work-life and commutes

	n	Sample	Switzerland
Employment rate	245	83.9%	67.1%
Workload (on average of percent employment)	237	90.4%	75.0%
Share of people who telework (home office, coworking or third places)	144	60.8%	37.1%
Share of people who have a room available at home for a home office	142	59.9%	n.a.
Main mode of transport (MoT) for commuting is:			
car/motorbike	113	46.9%	54.2%
public transport	85	35.3%	27.3%
bike	11	4.6%	7.0%
walking	32	13.3%	9.4%
Commuting distance per day and one-way (mean values)	242	26.9 km	13.6 km
Teleworkers only	97	31.0 km	n.a.
Non-teleworkers only	145	20.7 km	n.a.

Source: Own calculations based on own data; FSO (2021); n.a. = not available.

averages per income category (2,000 Swiss Francs, 6,500 Swiss Francs, 10,500 Swiss Francs and 14,500 Swiss Francs). Twenty-three per cent of households are car-free. Fifty-three per cent of households have one car, and 24 per cent have two or more cars. Eighty-six per cent of the respondents own a season ticket for public transport. Seventy-one per cent of the respondents own the Swiss half-fare card (50 per cent reduction on all public transportation fares).

In line with the study objectives, Table 2 describes some general characteristics concerning the work status and the preferred vehicle used for commuting. The average employment rate is 84 per cent, of whom 75 per cent of the participants work full-time. Sixty-per cent of respondents do teleworking, which includes using a home office and third places, including coworking. Furthermore, the table shows that 60 per cent of people have a room available at home for a home office. Additionally, Table 2 shows that the majority of people travel to work by car or public transport. Forty-six per cent of the respondents get to their regular workplace by car or motorbike, 35 per cent by public transport, and 18 per cent on foot or by bicycle.

Overall, the sample descriptives reflect comparable shares to the population of the LL.

Enrichment of the data set with CO_2 equivalent figures for commutes

To operationalise GHG emissions we applied the measure of carbon dioxide equivalents – CO_2 eq for short. CO_2 eq standardises the climate impact of various greenhouse gases, including methane and nitrous oxide, beyond carbon dioxide, the primary greenhouse gas. The consumption of CO_2 eq from commuting in kilograms is needed for statistical analysis and as a key figure for the future evaluation of interventions in the LL.

The study participants report their number of working days per week, the share of teleworking within a working week and the postcode of the regular workplace location, as well as the main mode of transport for the commute. The steps to compute the CO_2 eq figures based on this information are as follows.

First, the data set is matched with the traffic zones of the National Passenger Transport Model (NPVM) of the Swiss Federal Department of the Environment, Transport, Energy and Communications (ARE, 2019). In the model, Switzerland is divided into around 8,000 territorial units or so-called traffic zones. These territorial units can be assigned to the postcode that is available in the survey data. Based on this information, all the workplaces and living locations of the LL residents were assigned to a traffic zone.

Second, this assignment forms the basis for supplementing the data set with further information on distance travelled depending on the main mode of transport, be it on rail or street network. A matrix was used containing the distances and travel times for all connections between the different traffic zones linked to postal codes, one each for public transport and private transport.

Third, a commuting distance was computed for each resident. The new variables for the commuting distance form the basis for calculating the CO_2 eq consumption from commuting based on Mobitool (2023), which are the commonly used CO_2 eq factors in Switzerland (see Table 3). The factors include the grey energy for the creation of the mode of transport, the operation and the infrastructure involved.

Fourth, since the survey collects the information for one exemplary working week, the yearly consumption is computed by multiplying the weekly figure by the average number of working weeks per year in Switzerland (FSO, 2022b). The factor is 46.9 (total calendar weeks minus the average days of holiday per year). The commuting distances are then doubled, with the assumption that a working day includes two trips. This calculation resulted in the figures for CO_2 eq emissions from commuter traffic shown in Table 4.

This approach is inspired by the Swiss census on commuter mobility. Within the Swiss Population Census both place of residence and place of work are surveyed, as well as the main mode of transport (MoT) for the commute. This is a convention

Table 3: CO_2 equivalent factors per passenger kilometre

Mode of transport	CO_2 eq factors[grams]
Passenger car, diesel, gasoline (fleet average)	186.4
Passenger car, battery electric (fleet average)	89.8
Bicycle	5.6
Train, regional transport, s-rail	8.2
By foot	0.0

Source: Mobitool v3.0 (Mobitool, 2023).

Table 4: CO_2 equivalent emissions from commuting in a year (mean values)

	CO_2 eq(in kilograms)
Switzerland	761
Own survey	742
Differentiated by main mode of transport (MoT)**	
Car	1,538
Public transport	77
Bike	28
Walking	0
Teleworking*	
Yes	622
No	819

Notes: n = 235, bivariate test statistics: ** = The difference is significant at the 0.01 level (p<.01, 2-sided), ANOVA; * = The difference is significant at the 0.05 level (p<.05, 2-sided), two-sample t-test.

and represents the standard procedure (FSO, 2021). Moreover, Switzerland's national transport model is very reliable in providing distances and times between transport zones (ARE, 2019). This procedure is a good alternative to individual estimates that could be surveyed within a questionnaire. The literature shows that such individual distance and time estimates are prone to error (Ohnmacht and Kowald, 2014).

We have not applied a mobility survey that gathers trip chains for regular working days that measures the sequences of other trip purposes before, or after, the commute (for example, shopping, accompanying others, and so on). It must be pointed out that this gives us only an indication of CO_2 eq for commutes; one that neglects trip chaining. However, this method provides a metric-dependent variable for our multivariate modelling. This (admittedly simplistic) method implies the advantage that we have the opportunity for a comparison with the Swiss official figures (see Table 2).

The sample mean for the study is 742 kg CO_2 eq emissions from commuting per year. For Switzerland in general, in 2021 almost 14 million tons of CO_2 eq are consumed in transport (FOEN, 2023). Since 28 per cent of all journeys are made for work and there are five million employees in Switzerland (FSO, 2022a), the Swiss average consumption of CO_2 eq is therefore 761 kg per capita per year. Therefore, as can be seen in Table 4, the sample mean is almost as high as the Swiss mean.

Modelling approach

Multivariate linear regression is applied to analyse various influencing factors (independent variables) on CO_2 eq emissions from commuting in kilograms per year (dependent variable). Regarding multicollinearity in the model, all independent variables are below the critical value of 10, based on the variance inflation factor (VIF) (see Belsley et al, 1980). The error terms of the models were checked to fulfil the assumption of homoscedasticity.

Descriptives and bivariate statistics

To provide some oversight of our modelling data, descriptions, averages and percentages are presented in Table 5.

Table 5: Summary of variables for modelling

Independent variables		
Variable	**Descriptives and measurement**	**Data source**
Share of teleworking within a working week	Share of teleworking at different work locations per week Metric (as a percentage) *Mean: 29%*	Own survey data
Workload	Information on part-time or full-time working Binominal *part-time: 23.8% (no)* *full-time: 76.2% (yes)*	
Apartment ownership	Information if owner or tenant Binominal *owner: 17.8%* *tenant: 82.2%*	
Length of residence	Length, calculated by years since moving in Metric (as years) *Mean: 4.2*	
Public transportation subscription	Information if the individual has a public transport subscription (not Swiss half-fare travelcards) Binominal *users: 30.1%* *no users: 69.9%*	
Cars in household	*Number of car(s) in household* *Metric (number of cars)* *Mean: 1.1* *(diesel/gasoline: 0.91* *hybrid/battery: 0.09* *electric: 0.12)*	
Bikes in household	Number of bike(s) in household Metric (number of bikes) *mean: 1.7* *(bike: 1.4* *electric bike: 0.3* *electric cargo bike: 0.07)*	
MaaS use in a year	Mobility as a Service (MaaS) usage per year (all modes) Metric (times of use per year of users) *Mean: 16.3*	
Regular workplace location	Information if regular workplace location is suburban, urban or rural Nominal *suburban: 13.7%* *urban: 83.2%* *rural: 3.1%*	Swiss Federal Office of Statistics (FSO, 2023)
Phase model of action (PMA)	Self-assessment item for five phases (see Appendix): Nominal *Phase 1: No car-use reduction planned (29.1%)* *Phase 2: Reduction considered, but impossible (14.9%)* *Phase 3: Reduction planned, first attempts (9.3%)* *Phase 4: Is reducing, wants more reduction (22.8%)* *Phase 5: No car is used at all (23.9%)*	Own survey data

(*Continued*)

Table 5: Continued

Independent variables		
Variable	**Descriptives and measurement**	**Data source**
Residential location choice, closeness to: highway public transportation workplace	Information on reason for choosing Suurstoffi as a place of residence based on a dichotomised 5-point Likert scale, reduced to no (1–3) to yes (4–5) Nominal highway: 50.2% (yes, was important) public transportation: 73.2% (yes, was important) workplace: 49.2% (yes, was important)	
Travelling by modes of transport other than a private car is practicable for me	Information based on a dichotomised 5-point Likert scale, reduced to no (1–3) to yes (4–5) Binominal *yes: 55.2%* *no: 44.8%*	
Gender	Information on sexes Binominal *Male: 50.2%* *Female: 49.8%*	
Age	Age in years Metric (in years) *Mean: 41.1 years*	
Gross household income	Metricised based on category means: *ordinal (five categories, Swiss Francs, CHF)* *below 4,000 CHF (4.3%)* *4,001–9,000 CHF (27.8%)* *9,001–12,000 CHF (18.7%)* *over 12,001 CHF (28.4%)* *category average (3,000, 6,500, 10,500, 13,500): 10,149 Swiss Francs*	
Household size	Number of persons in the household *Metric (number of people)* *Mean: 2.4 persons*	
Expats	The survey language (German or English) serves as proxy-variable for indicating the status of expats (yes, no) Binominal *English surveys: 15.7% (yes)* *German surveys: 84.3% (no)*	
Dependent variable		
CO_2 emissions form commuting (kg per year)	CO_2 emissions of the routing distance to the main office per year depending on the trips per week to the main office, the means of transport and the corresponding CO_2 emissions factors Metric *Mean: 741.85 kg*	Own data multiplied with Mobitool factors v3.0 (2023)

Modelling results

The model for predicting the CO_2 eq emissions from commuting in kg per year is presented in Table 6. Overall, the model predicts 49 per cent of the variance of CO_2 eq emissions from commuting.

Table 6: Linear regression model for explaining the CO_2 equivalent emissions to commute in kilograms per year

		CO_2 emissions to commute (kg per year)				Sig.
Independent variables		**b**	**SE**	**t-values**	**Pr (>ltl)**	
Intercept	measurement	1680.93	556.42	3.02	0.003	**
Share of teleworking within a working week	percent	–5.86	2.38	–2.46	0.015	*
Workload	full-time (ref.: part-time)	341.43	162.82	2.10	0.038	*
Apartment ownership	owner (ref.: tenant)	–49.65	192.99	–0.26	0.797	
Length of residence	years	33.20	21.75	1.53	0.129	
Public transport subscription	yes (ref.: no)	–270.84	168.97	–1.60	0.111	
Cars in household	metric	–55.72	241.14	–0.23	0.818	
Bikes in household	metric	165.18	175.95	0.94	0.349	
MaaS use in a year	metric	–3.24	6.67	–0.49	0.628	
Regular workplace location	suburban urban (ref.: rural)	110.69 –944.72	395.51 366.25	–0.28 –2.58	0.780 0.011	 *
Phase model of action (PMA)	Phase 2 Phase 3 Phase 4 Phase 5 (ref.: Phase 1)	546.52 17.90 –55.40 –247.74	188.30 238.00 188.06 265.51	2.90 0.08 –0.30 –0.93	0.004 0.940 0.769 0.352	**
Residential location choice	Close to: highway public transport workplace	 61.98 –272.62 –332.56	 158.54 159.18 129.28	 0.39 –1.71 –2.57	 0.696 0.089 0.011	 . *
Travelling by MoT other than private car is practicable for me	yes (ref.: no)	–316.16	157.58	–2.01	0.047	*
Gender	male (ref.: female)	108.04	133.27	0.81	0.419	
Age	years	–4.86	6.55	–0.74	0.459	
Gross household income	Swiss Francs	0.02	0.02	0.80	0.428	
Household size	Metric	19.93	65.72	0.30	0.762	
Expats (proxy: English survey)	yes (ref.: no)	–244.65	245.48	–1.00	0.321	
n = 235						
Explained Variance = 49%, adjusted-R^2= 49%						
F-statistic				6.097	0.000	*

Notes: ** p<0.01, * p<0.05, . p<0.1, Ref. = reference category, b = beta coefficient, SE standard error, Sig. = Significance.

The model shows which variables have an influence on the explanation for CO_2 eq consumption from commuting in kg per year. The following figures show the significant effects of the linear influence of the significant independent variables on CO_2 eq emissions from commuting in kg per year by the use of probability plots.

Probability plots for significant effects

Figure 1 shows that CO_2 eq emissions from commuting in kg per year in Switzerland are 761 kg, and in the 'Suurstoffi' LL they are 742 kg. An increase in teleworking of 10 per cent on a person's overall working time leads to a reduction of approximately 60 kg of CO_2 eq per year. A person who works 50 per cent in teleworking consumes approximately 500 kg of CO_2 eq per year. The findings of the study can be explained using the linear regression formula, which in this case finds a linear significant relationship between a 10 per cent increase in telecommuting and an 8 per cent reduction in commuting-related emissions.

Figure 2 illustrates the leverage of the different groups of people who have their regular workplaces in rural areas and those who have them in urban areas, assuming all other influencing factors are kept constant in the model. There is a significant difference between the location of the regular workplace in a rural area (1,295 kg) and a city (351 kg). The CO_2 eq emissions are higher if the workplace is in a rural area compared to a workplace in the city, possibly due to more car use and longer distances.

There is a significant difference between those who stated that closeness to public transport was a reason for choosing Suurstoffi as a place of residence (436 kg) and those who did not (709 kg) (Figure 3).

Figure 4 shows the leverage of the different groups of people who stated that closeness to work was a reason for choosing Suurstoffi as their place of residence and those who did not when all other influencing factors are kept constant in the model. There is a significant difference between those who stated that closeness to

Figure 1: CO_2 equivalent emissions to commute by the share of teleworking within a working week

Figure 2: CO_2 equivalent emissions from commuting by the share of teleworking within a working week

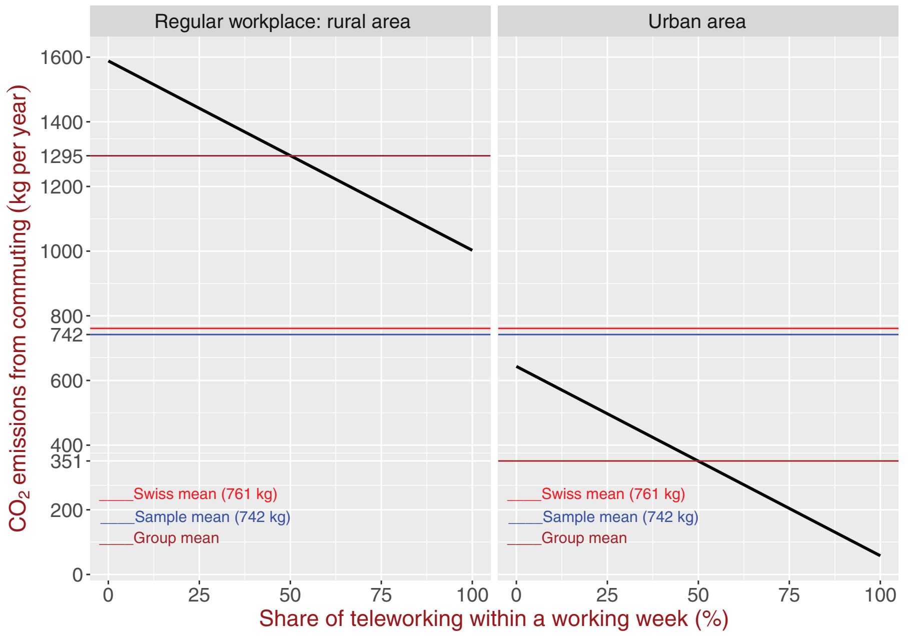


Figure 3: CO_2 equivalent emissions from commuting depending on the reason for moving: 'closeness to Public Transport (PT)'

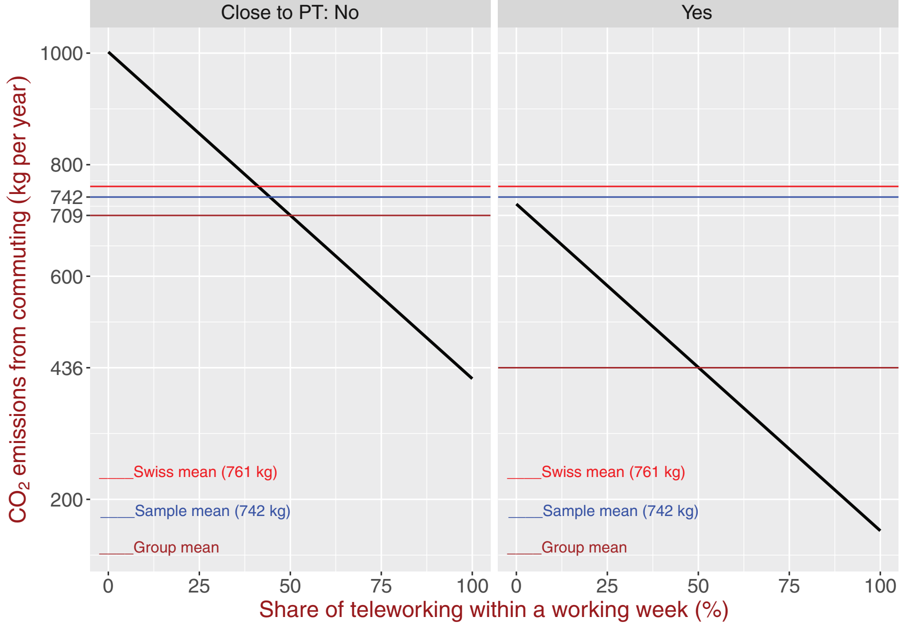


Figure 4: CO_2 equivalent emissions from commuting depending on the reason for moving: 'closeness to work'

public transport was a reason for choosing Suurstoffi as a place of residence (340 kg) and those who did not (673 kg).

Phase 1 of the transtheoretical model by Bamberg (2013) is associated with 428 kg and phase 2 with 974 kg (Figure 5). Self-assessment statements, such as the orientation towards the ability to use means of transport other than the car, also make a difference in the level of CO_2 eq emissions from commuting. Commuters in phase 2, who state that they want to reduce their current car use (but currently it is impossible to do so), have higher CO_2 eq emissions in comparison to the group in phase 1, who see no reason to reduce their car use. Generally, this indicates that more consumption is associated with more willingness to change.

Figure 6 shows that there is a significant difference between those who stated in the mobility attitudes that travelling by means other than car is practicable for them (368 kg) and those for whom it is not practicable (684 kg) when all other influencing factors are kept constant in the model.

Figure 7 shows the significant difference between those who indicated that they work part-time (249 kg) and those who work full-time (591 kg) when all other influencing factors are kept constant in the model.

First hints of rebound effects

The first rebound effect relates to relocation and anchoring in the residential environment: teleworkers tend to live further away from their workplaces than non-teleworkers. For this analysis, the commutes of teleworkers can be considered, as information on the distances travelled to commute was provided. Table 2 shows that

Figure 5: CO_2 equivalent emissions from commuting depend on self-attributed phase affiliation

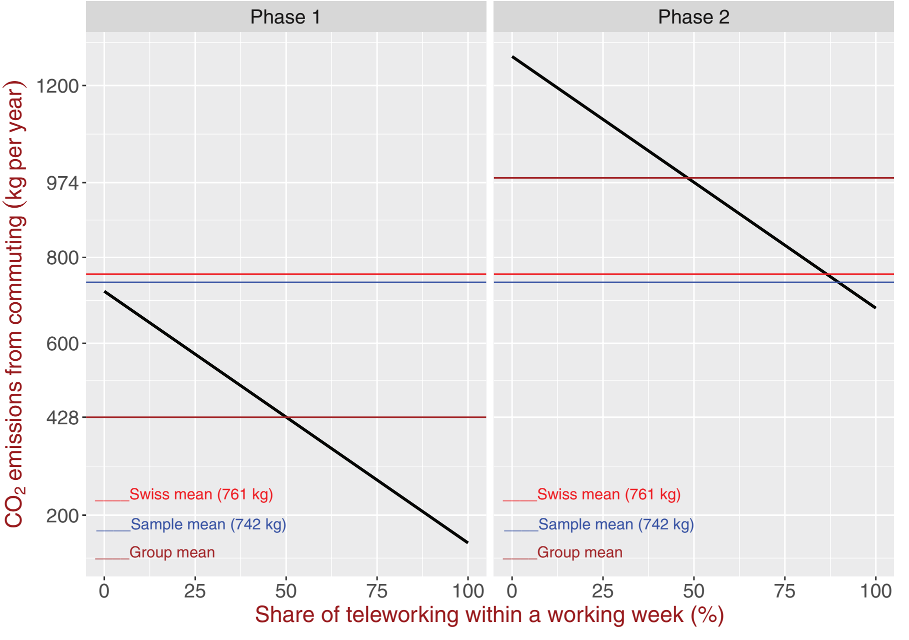


Figure 6: CO_2 equivalent emissions from commuting depend on the practicability of alternatives to a car

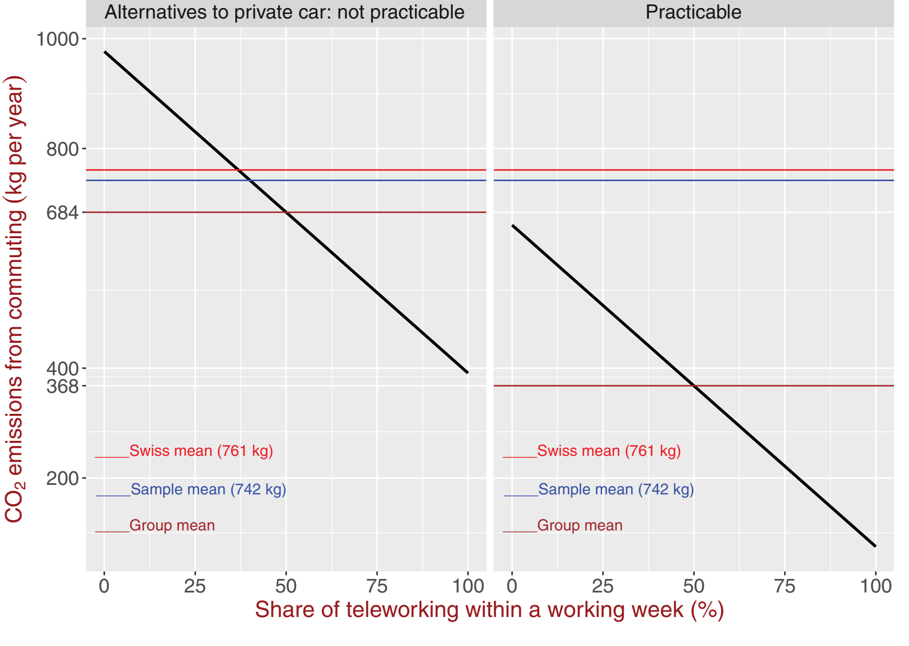
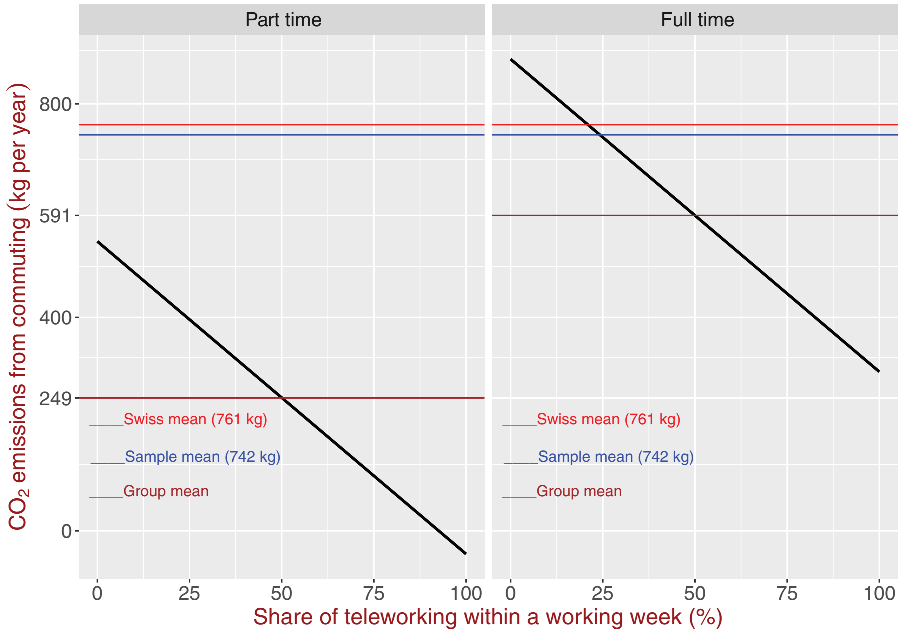


Figure 7: CO_2 equivalent emissions from commuting depend on workload



the average commuting distance is 31 kilometres for teleworkers and 21 kilometres for non-teleworkers. This could be interpreted as an increased tolerance to long-distance commuting due to teleworking and thus a possible rebound effect. Whether teleworking is the facilitator to live farther away from work or telework is necessary because of the longer distance, cannot be concluded by our data, as we do not have any information on the mobility biographies of the participants in our survey. However, overall, teleworkers seem to commute less per year and thus have lower CO_2 emissions from commuting (see Table 4; 622 versus 819 kg for non-teleworkers). The option of teleworking thus reduces commuting distances per year.

The second rebound effect relates to non-work trips made on teleworking days. Table 7 shows which transport purpose people are following when they work at their regular workplace compared with when they telework. Table 7 shows that, on a working day at the regular workplace location, 52 per cent of mentions are for shopping, 29 per cent for leisure activities and 19 per cent for dropping off and picking up children, for example. On a teleworking day, 38 per cent of the mentions are for shopping, 36

Table 7: Other transport purposes on a normal working day, differentiated by work mode

Working	Shopping (for example, errands, going to the pharmacy)	Leisure (for example, sports, visiting friends)	Bringing and picking up (for example, children to music lessons, grandparents to the doctor)	Total
At the regular workplace (n=244)	51.6%	29.1%	19.3%	100%
During teleworking days (n=302)	38.1%	36.1%	25.8%	100%

Note: Multiple answers possible.

Table 8: Teleworking and availability of a separate room being used for home office at place of residence

	Separate room being used for home office at place of residence is available:		Total
Teleworker	**No(n=95)**	**Yes(n=142)**	
Yes (n=144)	27.8%	72.2%	100%
No (n=93)	59.1%	40.9%	100%

Note: The chi-square statistic is significant at the 0.05 level.

per cent for leisure activities and 26 per cent for dropping off and picking up children. Working during teleworking days therefore leads to lower shares of shopping as a reason for transport and higher shares for leisure and accompanying others. Table 7 only shows relative shares, but absolute trips could explain more about the impact of teleworking. Trips were not surveyed. However, more responses were given for the multiple answer sets in the category 'during teleworking days' than 'at the regular workplace'. Table 7 thus gives a hint that other activity forms may increase during teleworking days.

The third rebound effect relates to the availability of a separate room being used for a home office at the place of residence. Table 8 shows that 72 per cent of teleworkers have a spare room in their homes being used as a home office, and non-teleworkers only 41 per cent.

Discussion

We aim to have a measure at the starting point of a LL that indicates GHG emissions stemming from the commute. We examine how it is affected by teleworking before an intervention has been introduced within a LL setting. Thus, we have first computed a baseline figure for GHG emissions for commuting based on inhabitants. Second, we modelled the effects of teleworking on mobility regarding GHG emissions.

According to our results, GHG emissions from commuting are influenced by the share of teleworking within a working week, the workload, the regular workplace location (rural versus urban), residential location choices (for example, closeness to public transportation, workplace), the transtheoretical model towards car use, and mobility orientations (for example, whether alternatives to private-car use are practicable or not).

In fact, an increase in teleworking of 10 per cent based on weekly working time leads to a reduction of approximately 60 kg of CO_2 eq emissions a year. Thus, increasing teleworking opportunities within a LL can be seen (on first sight) as a promising intervention.

Regarding the issue of accessibility, our findings show that those whose residential choice was based on public transportation infrastructure emit much less GHG (340 kg versus 673 kg). This illustrates the importance of providing housing where low-carbon modes are attractive. Our LL provides easy access to public transportation infrastructure.

Regarding the issue of mixed-use urban development, we can confirm that the planning of the location and distribution of job opportunities is of special importance. Our results show that there are great differences among the LL residents depending on the urban and rural locations of their workplaces and their related mode choices for commutes. Those who work in city centres emit much less GHG than those working in rural areas (351 kg versus 1,295 kg). The geography of teleworking and regular working spaces therefore seems to have an important influence on GHG emissions. Besides these promising findings, however, we have shown the first hints of rebound effects. There may be an overcompensating effect, when people reduce their commutes, it frees up time and resources for other types of 'mobilities' (leisure trips on teleworking days or other days). Additionally, telework may result in increased square metres of private living space to use as a home office.

Given these findings that support the effect of teleworking on reducing GHG emissions and querying the results at the same time, we come to the following conclusion: for the future design of LLs, we recommend considering the rebound effects – especially in the transportation and building domain – in more detail. Thus, the design of the LL should incorporate different behavioural areas to identify rebound effects (for example, interrelations between living space and telework possibilities).

Limitations of the study

In the following, we mainly focus on our five limitations regarding:

1. the simplistic way we have measured commuting by using the main MoT and travel distances from home to work (in line with Swiss Population Census method for commuting matrices) which leads to neglecting the effects on 'trip chaining' for the commutes;
2. the variations for the use of modes of transport at different times of the year (seasonal);
3. modelling approach;
4. missing qualitative insights; and
5. generalisability of our study.

First, no trip chaining could be considered, since only the main means of transport to and from work were surveyed. Analysing trip chaining on regular working commutes could reveal more insights into the rebound effects. Employees may combine their commutes before and after with additional trips, for reasons such as taking their children to daycare or looking after family members, and so on. On the one hand, their travel habits might not see significant alterations due to teleworking. On the other, within a trip chain, the shortest part is likely to refer to care (for example, kindergarten, school) and the longest to work. Concentrating solely on commuting may result in an exaggerated view of the travel-related benefits offered by remote work.

Second, commuting behaviour may be highly seasonal (for example, due to changes in the weather). The timing of data collection is therefore of great importance. However, we cannot control for this in our survey, as it is a cross-sectional survey that was conducted in October. The most regular mode of transport for the commutes was surveyed in our study.

Third, our modelling approach is limited to a simple, multiple ordinary least square (OLS) linear regression model. The advantage is that the results in the probability plots are easy to communicate to the stakeholders of the LL. Our result is a linear significant relationship that shows that a 10 per cent increase in telecommuting results in an 8 per cent reduction in commuting-related emissions. This finding provides a simplistic understanding of this relationship. For future research, it would be helpful to apply non-linear models to the data. Non-linear regression models offer flexibility to represent more complex relationships between variables.

Fourth, for our LL it is essential to have quantitative data as a starting point to monitor transformative changes introduced by interventions. Our LL context aims at reducing GHG within the energy discourse. However, other approaches of the LL methodology are more process-driven and focus on qualitative research and put the socio-cultural animation at centre stage. Thus, certain LLs place a greater emphasis on qualitative data when assessing their 'success', and they have valid reasons for adopting this approach, such as including the variety of individual views based on qualitative research (see Engels and Rogge, 2018; Schäpke et al, 2018). Several other limitations of quantification merit a critical discussion, such as the complexity of human behaviour, and the temporal and spatial variability of key figures. A critical approach to quantification must therefore recognise these limitations and complement quantitative analyses with qualitative insights to gain a fuller understanding of the complexities involved in transformative change (mixed methods design).

Fifth, generalisability is limited. The results stem from a probabilistic population survey, which is representative of a specific area, but not for the Swiss population. The results are therefore representative of areas that have a similar household and income structure, nearby access to a train station and a mobility concept. In addition, the location of the area is rather suburban, but the transport connections have the attributes of an urban area. Comparisons with Switzerland and transferability to other local authorities must therefore always be taking into account the specific characteristics of our LL.

Outlook on intervention design and investigating transformative change within a living lab

Based on this research, the first key figures have been generated that can be monitored in the LL. The data is currently only available for the first wave of a time series analysis. Interventions can now be implemented (for example, the provision of a coworking space). Since our LL has been under research for six years, replication studies should be made after two and four years. Based on the assessment of effectiveness, the interventions can then be scaled up or transferred to other local or regional contexts. Research indicates that initial outcomes of interventions (such as training programmes for inhabitants or urban trials, for example, closing a road to traffic) may appear favourable in the short term. However, their long-term impacts can be less beneficial or even detrimental (Allcot and Rogers, 2014). This is particularly true in cases where routine behaviour will jeopardise health and environmental improvements in the long run (see Uttley and Lovelace, 2016 for the case of cycling promotion). Our results highlight the need to consider how the time saved by teleworking will be used in both the shorter and longer terms. It is therefore promising to assess the effects of teleworking by including trip chaining into the survey methodology and from an individual life-course perspective that could complement such quantitative approaches (see Scheiner and Rau, 2020) (for example, how it may change the location of home and/or work and increase the tolerance to longer commuting distance). Moreover, not only can the LL methodology accelerate such reductions introduced by the measure of teleworking, but there are additional measures on the structural level that can be supportive (for example, taxes, subsidies, structural changes) that need to be controlled in empirical research.

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Conflict of interest
The authors declare that there is no conflict of interest.

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Appendix: Transtheoretical model according to Bamberg (2013)

Phase	Self-assessment items
1	I currently use the car for most journeys. I am satisfied with my current car use and see no reason to reduce it.
2	At the moment I still use the car for most journeys. I would like to reduce my current car use, but at the moment I find it impossible to do so.
3	I currently use the car for most of my trips, but my goal is to reduce my current car use. I already know which journeys I will replace and which alternative modes of transport I will use, but I have not yet put this into practice.
4	As I am aware of the many problems associated with car use, I am already trying to switch to other modes of transport as much as possible. In the coming months, I will maintain or even reduce my already low car use.
5	As I don’t own a car or have access to one, reducing my car use is not an issue at the moment.