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# Looking beyond the hype: Conditions affecting the promise of behaviour change apps as social innovations for low-carbon transitions

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ABSTRACT

Digital tools, specifically smartphone apps, have emerged as enablers of social innovation for low-carbon transitions by using novel feedback to creatively engage people to act more sustainably, and thus capture the power of collective individual action. Such apps have increasingly been implemented in real-world experiments with positive results in the short-term. However critical reflection is required to look beyond this hype to understand the conditions for longer term impact, thus reaching a transformative social innovation potential. In this paper, we take two exemplary behaviour change apps and perform a cost-benefit analysis to assess the break-even point in number of users to achieve net-positive impact and discuss relevant technical, organisational, political and financial conditions that enable or impede this impact. We find that the required scale-up in users seems challenging, yet feasible. However, guaranteeing that the supportive conditions are available is necessary to warrant the focus on behaviour change apps by research and policy.

## 1. Introduction

Digital innovation has ubiquitously influenced the transition towards a more sustainable society in diverse sectors (Sareen and Haarstad, 2021). By capturing, analysing and communicating novel data, digital technologies have opened new approaches to tackle societal challenges, such as provision of health-care services, support to migrants, or tackling the climate crisis (Stokes et al., 2017). In this paper, we specifically focus on smartphone apps aimed at persuading behaviour change for a low-carbon transition in highly industrialised countries. Such apps support individuals to lower carbon emissions, thus addressing one of the five challenges that humanity needs to tackle within the overarching grand challenge of sustainability (Markard, Geels and Raven, 2020).

Policies and tools can support new ways of consuming and organising carbon-emitting goods and services; specifically behaviour change apps can shape collective energy-efficient and sufficient routines (Schot et al., 2016). This can occur through prompts to encourage a shift towards more sustainable choices using various persuasive feedback (e.g. personalised, real-time, entertaining,

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game-like, etc.) and ultimately can be cheaply disseminated for multiplying their transformative power (Froehlich et al., 2010; Spaiser et al., 2019). In the last decade, this type of "eco-feedback" (Sanguinetti et al., 2018) through apps has become widespread and a well-funded research area (Beck et al., 2019; Douglas and Brauer, 2021).

Recent reviews of app-based experimental interventions in the low-carbon domain have confirmed their promising behaviour change potential (Anagnostopoulou et al., 2018; Andersson et al., 2018; Chatzigeorgiou and Andreou, 2021; Douglas and Brauer, 2021; Hedin et al., 2019; Suruliraj et al., 2020). However, some scholars criticize the extent to which digitalisation improves the overall sustainability impact and carbon footprint of individuals (Andersen et al., 2021; Sareen and Haarstad, 2021). The ubiquitous use of apps may be seen as the first phase of a hype cycle, where promises and expectations create phases of societal attention and technological uptake (Van Lente et al., 2013).

In line with the broad conceptualisation by Pel et al. (2020) of social innovations, persuasive behaviour change apps can be enablers of new ways of doing, organising, framing, and knowing through changing social relations. Apps can offer ways to trigger collective impacts, if they provide app users with social interaction features favouring exchanges between each other and the creation of an active (virtual) community. Specifically, apps can be designed to initiate transformative social innovation processes (TSI), where "social innovation challenges, alters, or replaces dominant institutions in a specific social-material context" (Pel et al., 2020, p. 2), by enhancing the individual's capacity to contribute to climate emission reduction, which is reinforced by the effect of other users acting in the same manner. Therein, this approach challenges, and provides an alternative to, a persisting technology-centric narrative which has been insufficient in addressing the barriers to a low-carbon transition (Loorbach et al., 2020).

In this paper, we outline the conditions for behaviour change apps to be a TSI. Inspired by other work in the social innovation domain, such as the broad questions posed by Strand et al. (2021) to "balance experimentation with precaution" and the call for more critical review of digitalisation as a driver of transitions by Sareen and Haarstad (2021), we analyse the cases of two Swiss app-based intervention studies from app development to scale-up. We perform a cost-benefit analysis (CBA) of app use as an intervention measure to uncover the climate benefits in comparison to the development costs. And we examine how the apps interact with current institutional settings that support constructive learning to move into post-hype phases of effective use and scale-up (Geels et al., 2007).

Advancing understanding of such system conditions is relevant for applied research and policymaking. These contextual details are often lacking in reporting on intervention effectiveness, even when the experiment is well documented and scientific assessment procedures are followed. However, these details are critical to behaviour change apps' capability to trigger TSI processes, and thus cannot be backgrounded when discussing impact in comparison with other policy interventions. Particularly, a CBA is relevant for policymaking: if the benefits delivered by these apps are lower than the costs for development and maintenance over time, relying on them as tools to support a low-carbon transition would be at least questionable.

The paper is organised as follows: Section 2 details the TSI potential of persuasive apps, while Section 4 presents the app cases and analysis methodology. In Sections 5 and 5 we report the results of the CBA and the enabling and impeding conditions, respectively, and Section 6 concludes.

## 2. The transformative social innovation (TSI) potential of persuasive behaviour change apps

The use of persuasive behaviour change apps is one measure along a continuum of digital innovation which varies in transformative power depending on the extent to which the innovation challenges institutions and produces alternative structures (Gebken et al., 2021). Loorbach et al. (2020) specifically define TSI as being "socio-material, emergent and multi-actor phenomena" (p. 254). Herein, these purpose-built apps directly target substitution of carbon emitting practices of many people at once, and primarily support new ways of *framing* by helping people to reflect on the outcomes of their behaviour with impact-related data, and *knowing* through understanding their contribution to the solution, and potentially *organising* by connecting like-minded individuals for collective impact. Apps can act as a messenger or coach to encourage individual experimentation with different consumption patterns, so people can uncover where difficulties arise, stay motivated to overcome inconveniences, and get support from a wider community of peers and experts. Ultimately, this creates spaces for individuals to feel empowered towards changing their behaviour and at the same time supports development of shared identities, narratives, and visions of change.

Considering the propositions on TSI processes advanced by Pel et al. (2020), these apps "provide spaces to promote new or alternative values and align them with new knowledge or practices" (proposition 1, p. 7) and empower people in their efforts towards institutional change, by building on their "basic needs for relatedness, autonomy, and competence". This increases people's sense of impact, meaning, and resilience (proposition 3, p. 7) and favours the creation of trans-local networks (proposition 5). In doing so, apps contribute to reconfiguring the institutional logic in which dominant institutions are embedded (proposition 9). The resulting coordinated impact on resource consumption may challenge existing incumbent regimes (e.g. energy utilities may have to restructure their revenue model if energy consumption decreases) and the narratives of technology primacy in addressing climate problems. Despite many experimental studies assessing their behaviour change effectiveness, to our knowledge behaviour change apps have not been looked at through this TSI lens to acknowledge an app's interdependency with the incumbent innovation system, as well its actual role in challenging these structures.

Thus, the TSI potential of behaviour change apps is not always realised: behaviour change for resource efficiency has been criticised in being, at best, not radical enough to reach the climate goals, or, at worst, re-enforcing consumption patterns and path dependencies of resource extraction, use, and disposal (Shove, 2018). If apps do not manage to realise the expected transformative potential, they remain stuck in the first phase of the "hype cycle" (Fenn and Raskino, 2008; Van Lente et al., 2013). The three-stage hype cycle states that, after an initial rapid increase in societal attention and expectations about a technology, disillusionment may occur, which is only sometimes followed by enlightenment if the innovation's value can be captured and diffused (Dedehayir and Steinert, 2016; Kester

**Table 1**
Key characteristics of the two app cases and the related processes and stakeholders.

| | enerjoy: $CO_2$ footprint of food and mobility choices | Social Power: At-home electricity savings |
|---|---|---|
| Development | 2017 | 2015 |
| Availability | 2018 – ongoing (October 2022); German language. | March 2016 – February 2017: German and Italian languages. |
| App's features | Users enter their food and mobility choices and receive feedback on their $CO_2$ footprint, which is compared to the individual footprint for a 1.5°C global warming target. The app also proposes challenges to reduce one's footprint and features information on sustainability topics. | Users get feedback on the household's hourly electricity consumption through a direct interface between the app and the household's smart meter.<br>The app supports saving electricity over a three-month period with weekly household electricity savings challenges (e.g., washing clothes or cooking) and provides step-by-step suggestions and tips. |
| Additional connections | No specific technology or infrastructure is needed since users self-track their consumption data. | The app receives the household's smart meter data from the electricity utility. |
| Project initiation and app development | Initiated and developed by a state-owned energy utility in Switzerland as an internal innovation project. A small design team at the utility worked with external developers to develop the app, and a small team of external researchers joined as part of a funded research project to evaluate the app. The designer team was funded by the utility. | Initiated within a research project funded by a private Swiss foundation.<br>The research team designed the key persuasive features. The technical development was performed by an external professional software company. Two utility companies provided the connection with smart meter data and later supported the app's field testing. |
| App implementation and behaviour change intervention | The app was tested over a six-week period in Fall 2020 with approx. 450 participants in the German-speaking part of Switzerland, who were voluntarily recruited by the research team. The research team managed communications and troubleshooting with the participants, and the development team provided additional support for technical issues. | A three-month intervention in Spring 2016 involved 100 households in the districts of two utilities in the German and Italian-speaking part of Switzerland. The utilities guaranteed smart meter connection and managed communication campaigns to recruit app users among their customers. Despite most of the app features being automated, trained staff were needed to recruit participants and create teams. |
| Long term maintenance and continued implementation | After the field test, the app continued to be developed and remained available in Switzerland. To support further development, the utility is still financing the design team, who are testing self-sustaining business models. As of October 2022, the business model involved a subscription model of the app, to access more tracking categories, costing 60 Swiss Francs (57 EUR, 67 USD) per year. The research team is not involved in any further developments due to lack of funding. | At the conclusion of the research project, the utilities confirmed their general interest in the app, but were not able to support its long-term maintenance. The software company who developed the app explored further project opportunities with other utilities, however, were unsuccessful due to cost and lack of strategic interest. Thus, the app was only available for a few months after the end of the research project. The future of the app lies with the research team and ultimately the interest of funding institutions. |
| Interest of key stakeholders | The utility sees itself as an efficient service provider for renewable energies, with the goal of providing a climate-friendly energy supply to its customers. An app that helps users to reduce their $CO_2$ footprint complements this overarching aim.<br>The utility is an independent but state-owned public enterprise in an area with powerful Green and Social-Democratic parties and an electorate that puts a relatively strong emphasis on environmental topics. Taking steps to help people reduce their carbon footprint is in line with local political goals. | The app was developed for research purposes to support evidence-based policymaking for the Swiss energy and climate transition. The interest by the utility companies was driven by the opportunity to differentiate themselves from potential competitors, in anticipation of the liberalisation of the electricity market for household customers, which for Switzerland is expected to come in the next years (currently utilities are monopoly providers to household customers in a region). The utilities regarded Social Power as a potential piece of their future loyalty strategy for households. |
| Additional literature | Grieder & Wemyss, 2021, www.enerjoy.ch | Wemyss et al. 2018, 2019, www.socialpower.ch |

et al., 2020; Kriechbaum et al., 2021; Ruef and Markard, 2010; Van Lente et al., 2013). Indeed, the rapid uptake of apps may be a hype that does not fulfil expectations, and if not addressed can lead to premature rejection of the technology.

## 3. Methodology

We adopt mixed-methods to analyse the two Swiss low-carbon behaviour change apps, "enerjoy" and "Social Power", and look beyond the hype of their immediate effects, identifying what can reduce costs, increase benefits, and improve apps as policy measures. To identify the contextual enabling and impeding conditions for impact, we qualitatively explore the financial, technical, organisational, and political conditions that affect each project stage, from the app's initiation to its long-term maintenance. Additionally, we perform an approximative quantitative CBA to estimate the apps' cost-benefit break-even point, corresponding to the minimum number of users required by each app for a positive net impact.

### 3.1. *The behaviour change app cases*

Both cases considered involve field research in Switzerland between 2015 – 2020, where real-life interventions were conducted to determine causal effects of the apps. Key characteristics and contexts of the two apps are summarised in Table 1. The *enerjoy* app aims at reducing individuals' consumption-related $CO_2$ emissions in a simple way. Users can manually record their daily food and mobility choices and the app calculates their $CO_2$ footprint and suggests lower-carbon alternatives. The *Social Power* app aims at reducing electricity consumption in households using in-app teams of households to collectively save electricity over a period of three months. The aim of our analysis is not to systematically compare the two cases, but rather to learn from both. Their differences allow us to uncover a more nuanced picture that could be relevant for future projects of behaviour change apps.

Social Power and enerjoy were identified as ideal case studies for several reasons. First, they were both developed and tested in a country where institutional and political framework conditions are highly supportive of the transition towards a low-carbon society, thus there were no explicit systemic barriers to the behaviour change interventions.[1] Therefore, impeding conditions emerging from the analyses specifically refer to the apps and their respective contexts (e.g. who had decision-making power in the project, how did the financing impact project implementation, etc.). The differing behaviours which the two apps focus on (i.e., more sustainable mobility, nutrition, and household electricity consumption) are exemplary of the cross-over between national climate-related policy and societal interest in Switzerland. Moreover, these are critical areas for greenhouse gas reduction for any signing parties of the Paris Agreement treaty on climate change (United Nations Framework Convention on Climate Change Secretariat, 2021).

Additionally, the two cases have some intrinsic differences (e.g., Social Power was initiated for research, whereas enerjoy was developed for commercial purposes). The method for collecting consumption data differs for each app, but was an intentional design feature from the respective development teams. In enerjoy the designers wanted to encourage reflection and engagement with the app while reporting daily food and mobility choices. While self-reporting in other domains can induce "cheating" in order to provide a more socially-desirable report, it is unclear how this impacts environmental behaviours (Vesely and Klöckner, 2020). Furthermore, enerjoy encourages experimenting with tracking different choices so the user can learn what is the impact of alternative behaviours. In contrast, Social Power wanted to provide accurate hourly electricity consumption data, which would be cumbersome to self-report (i.e. read off the electricity meter), and is relatively consistent over time. Thus, the users were encouraged to monitor outcomes of behaviour changes which were taught within the app. Differences in the apps' setup could lead to differing effectiveness and shed light on unique impeding and enabling conditions.

Finally, information on the two cases is reasonably accessible to the authors. We were involved in the project consortia who managed the app's development (Social Power) and / or in their real-world testing (Social Power and enerjoy) and therefore have additional data concerning contexts, budgets, and stakeholders involved. Our analyses are derived from two sources of data. First, quantitative and qualitative data come from non-confidential internal project reports, documentation (such as the project website), and our own experience within the two projects. We complemented this documentation with one-hour semi-structured interviews with an app developer from each app in 2020. The interviews focused on how the app was used for behaviour change and the challenges they faced in creating an impact with the app, and a directed content analysis approach was used on the transcribed interviews.

### 3.2. Cost-benefit analysis (CBA)

The goal of the CBA is to better understand the magnitude of costs and benefits of the cases, and to roughly gauge how many additional app users would be necessary to balance the climate benefits created by the apps with the resources invested in their development and maintenance. As for any such analysis, considerable uncertainty and commensurability issues exists when estimating and translating costs and benefits from different domains into a common metric and comparing them. Thus, the precision of the results is necessarily limited, and we take care to highlight key assumptions.

To find the number of users that each app requires so that their climate benefits equal their costs, i.e., to estimate their "break-even point", we compare the climate benefit, i.e., the savings in $CO_2$ equivalent ($CO_{2eq}$) average emissions per user due to behavioural changes induced by the app, to the total cost of developing and running the app. The underlying assumption of this approach is that, even though every ton of $CO_{2eq}$ emissions saved is a success for trying to prevent climate change, given the scarcity of resources and the multitude of possible interventions, it is crucial to focus on measures that trigger the largest climate benefits relative to the cost incurred for their implementation.

The project managers estimated the apps' development and running costs based on project team efforts. The climate benefits are estimated based on the publicly available outcomes of the real-world experiments with the apps (Grieder and Wemyss, 2021; Wemyss et al., 2019). Further assumptions on the evolution of the benefits and the costs over time are based on the same sources. All assumptions and data used are presented in Section 5 and the Appendix.

Importantly, based on the experimental evaluations, we only consider direct behavioural effects of app use that are quantifiable in terms of $CO_{2eq}$ emissions. The $CO_{2eq}$ metric provides us with a relevant measure that is frequently used in similar CBAs (e.g. Ghesla et al., 2020; Sidhu et al., 2018) and for which there exist numerous studies quantifying its impacts in terms of climate change and the associated social cost (the "social cost of carbon" - SCC, see for instance Howard and Sterner 2017; Nordhaus 2017; Pindyck 2019; Ricke et al. 2018; Rode et al. 2021).

The behavioural changes triggered by the two apps also have indirect environmental (and other) benefits. For instance, Grieder and Wemyss (2021) found that enerjoy significantly increased app users' knowledge about the relative carbon footprint of different foods and mobility options, as well as increased app users' perceived responsibility for climate change and personal norm for changing one's behaviour (see Steg et al. 2005; Stern et al. 1999 for the relevance of these concepts). Similarly, Wemyss et al. (2018) found that Social

[1] With its Energy Strategy 2050, Switzerland is striving for a low-carbon society. In the past two decades, the country has been active both at the strategic level, for instance by creating the inspirational concept of the 2000 Watt$^{-1}$ ton Society (Stulz et al., 2011), and at the practical level, for instance by delivering generous incentives for energy refurbishment of buildings (Wiencke, 2013) and promoting energy efficiency in households through the EnergieSchweiz programme (Sager et al., 2014).

**Table 2**
Guiding questions to identify the enabling and impeding conditions for impact.

| | | Project phases<br>Project initiation and app development | App implementation and evaluation | Long term maintenance and scale-up |
|---|---|---|---|---|
| Conditions | Technical | What are the technical prerequisites that are needed to make a project feasible? | What are technical opportunities and limitations that impact implementation?<br>What are socio-technical factors that are relevant for project acceptance and uptake? | How can the technology evolve to address challenges in the implementation? |
| | Organisational | What actors are necessary for project acquisition? Who is involved in the app development?<br>How do these actors reinforce certain limitations or provide opportunities? | What intermediary actors are necessary for marketing and recruitment (secondary roles, trouble shooting, etc.)? | Who needs to be involved in long term maintenance of apps/ interventions? |
| | Political | What regulatory conditions enable or impede project development? | How do current political conditions impact implementation? | What are intended and unintended effects of policy (e.g., for facilitating scale-up)?<br>Where is there misalignment of interests between business and policy? |
| | Financial | What financing conditions enable or impede project acquisition? | What foreseen and unforeseen costs are associated with implementation? | What are viable long term business models to ensure scale-up? |

Power increased the self-reported prevalence of various additional pro-environmental behaviours and tended to have a positive effect on perceived injunctive social norms about expected pro-environmental behaviour. These effects of app use are likely to trigger further indirect climate benefits, which may be just as important as the direct effects that we consider. However, since they cannot be easily quantified, indirect effects are not included and in our CBA: we take a conservative approach for estimating the apps' climate benefits by only considering quantifiable direct behavioural effects of app use. Our results should therefore be interpreted as capturing only a *lower bound* of the climate benefits of the two apps.

However, we are aware that behaviour change apps, and social innovation in general, can have adverse effects. Mildenberger et al. (2020) compiled a literature review on the effects of social innovation on society and found several unfavourable effects, such as unequal opportunities and exaggerated confidence in its potential, causing opportunity costs (see, e.g., Brandsen et al., 2016; Fougère and Meriläinen, 2021). As these effects are hard to quantify, we also abstain from integrating them into our CBA.

Ultimately, the CBA we conduct needs to be interpreted bearing in mind the issue of commensurability. Measuring socio-cultural, environmental, and economic impacts using a uniform metric is a complicated task (see Andersson and Lundberg (2013) for an example of a method to reach commensurability for a tourism project). However, trying to reach full commensurability would be exceeding our aim of an illustrative CBA for this analysis.

### 3.3. Enabling and impeding conditions for impact

The implementation contexts for behaviour change apps can differ greatly considering pressures, dependencies, opportunities, and risks related to the development teams, users, and technologies involved, which may play out at both local and regional levels (van den Heiligenberg et al., 2022). Thus, context influences success of the intervention and the benefits delivered by app use, particularly when trying to address the acknowledged limitations of this approach. Thus to understand where limitations exist, we take a TSI lens (Avelino et al., 2019) to identify interrelated enabling and impeding conditions. Inspired by the concept of harbours from van den Heiligenberg et al. (2022) "as a combination of local and regional context conditions enabling the transfer of sustainability innovations to and from other locations" (p. 375), we look at four conditions defining context: technical, organisational, political, and financial. This lens is applied at the project level, as well as the level of dominant institutions locally and regionally.

Firstly, *technical* opportunities and limitations intrinsically influence the potential of a digital tool, such as a smartphone app. The opportunities may range from data collection, consolidation, and display, to novel forms of reminders, gamification, community building, and social innovation (De Rosa, 2017; Morton et al., 2019). Additionally, we acknowledge socio-technical conditions related to the user's experience and subsequent behavioural change. In particular, efficiency gaps, that is the difference between the theoretical efficiency and what is actually achieved, can stem from poor estimation of acceptance, trust, and ease of use of a technology (Eon et al., 2018; Venkatesh and Bala, 2008).

Considering the multi-disciplinary teams required to run a behavioural intervention using a smartphone app, the *organisational* context of actor networks, and their power interdependencies, are relevant (Avelino et al., 2019). For example, Schwanen (2015b) points out the relevance of autonomy of cities in bringing about a sustainable mobility transition, and Parag and Janda (2014) introduce the crucial functions of intermediary actors to advance local sustainability transitions. These examples highlight the need to look beyond app development teams and users to identify actors that influence the transformative potential of the app.

Related to the organisational conditions, the *political* will to directly address climate issues can change the pace of transitions, by, for example, re-assigning funds into transition research on behavioural interventions (Kern and Rogge, 2016). Further, policy signals change citizens' attitudes, for example towards uptake of renewable energy, and thus impact the acceptance of an intervention (Kotilainen and Saari, 2018). Particularly for public energy utilities, policy can impose requirements for more demand-side management which supports collaboration with behaviour change designers (Hobbs and Centolella, 1995). Both the opportunities and limitations of political leanings, and the subsequent impact on the relevant actors, need to be considered.

Finally, persuasive app interventions are heavily dependent on initial *financing* to reach a development maturity which can be easily disseminated, thus exploiting the intrinsic value of digital tools for scale-up. Depending on the type of tool developed, i.e. an independent smartphone app vs. a web app accessible through a smartphone, the costs of both development and maintenance can substantially vary (Dalmasso et al., 2013).

Such conditions play different roles depending on the phase of a project's lifecycle. The first phase starts with the initiation of a behaviour change app project and includes all activities involved in developing the digital tool (e.g., design of persuasive app features; software coding; connection between app servers and other technologies; testing and bug fixing), up until the app is tested in the real world. The second phase covers the implementation and evaluation of the app in a behaviour change intervention with users. If such an assessment provides encouraging results, the third phase starts, which corresponds to the app's long-term maintenance and scale-up to further users. To guide our analysis of the enabling and impeding conditions, we identified questions for each condition and each project phase based on the prominent aspects highlighted in the literature (Table 2).

The questions aim to reveal the nuanced contexts which improve (or not) the potential of behaviour change apps to achieve a net positive impact. Viewing the apps from this external lens situates them within the dominant structures, stakeholders, and processes which can have intended and unintended consequences on their potential. To explore the context and identify the enabling and impeding conditions for impact, we rely on the content analysis of the interviews with the app developers, as well as on our own direct experience as members of the project teams.

## 4. Costs, benefits, and number of app users for break-even

Regarding the costs, for both apps we divide the total cost into development and maintenance costs. The estimated development costs were quite different for the two apps. For Social Power, the estimate provided by the developers was 99,000 US Dollar, whereas for enerjoy, which was developed in a commercial context, it was 825,000 US Dollar. The estimate for Social Power might be lower because the app was developed within an academic research project, thus potentially not all costs are accounted for. For the CBA, we assess the cost estimates provided by the respective developers and also assume higher development costs for Social Power. Based on estimates from the developers, running costs are estimated at 44,000 US Dollar on average per year per app.[2]

Regarding the benefits, we first identify climate-relevant behaviour changes triggered by app use, then we estimate their monetary value. For Social Power, Wemyss et al. (2018, 2019) tested the effect of the app compared to a control group in the short term (directly after three months intensively using the app) and the long term (12 months using the app; $N = 82$). They found that the app users consumed roughly 8% less electricity per household in the short term and roughly 5% less in the long term compared to their baseline before the intervention; however, compared to the control group only the short-term difference is statistically significant (Wemyss et al., 2018). However, both the short-term and the long-term effect are of similar magnitude compared to other similar experiments in industrialized countries (e.g. Allcott 2011; Allcott and Mullainathan 2010; Andor et al. 2020; Delmas et al. 2013; Ghesla et al. 2020; Iweka et al. 2019). We therefore use these point estimates as the best available evidence for the effect of Social Power for triggering electricity consumption reductions.

As the data by Wemyss et al. (2019) indicate, the savings effect decreases over time. We thus assume that the app triggers an 8% reduction in electricity consumption in the first 6 months of app use, a 5% reduction for months 7-12, and a 2% reduction for months 13-18. In the spirit of conservative estimates of the apps' climate benefits, we assume that there are no lasting effects of the app after 18 months. This is a conservative assumption: it is likely that at least some users would still use the app and some savings might persist longer into the future. However, a decrease in effectiveness usually comes from "relapse" effects (Ohnmacht et al., 2017; Prochaska and Velicer, 1997). To overcome relapse, post-action or maintenance activities are usually needed, which consolidate a given effect and maintain it in the long-term, however these were not specifically designed into Social Power. If in-app prompts had been implemented, the savings observed during months 7-12 might have been maintained for longer, as was seen by Schleich et al. (2017) using web-portals and written reports for electricity consumption feedback, or by Anderson et al. (2017), who used email to provide smart metering feedback – and this in both cases where devices only delivered consumption feedback without additional motivational features.

For enerjoy, Grieder and Wemyss (2021) conducted a field experiment (N=473) testing the impacts of app use after two and five weeks.[3] They found a significant effect on participants' food choices. Specifically, app users reduced dairy consumption by around 1.5 meals per week compared to the control group, corresponding to a consumption reduction of 5.4%. As we cannot estimate the decay (or persistence) of the effect over time from the enerjoy study, for simplicity and comparability, we use the same decay rates as for Social Power. According to these assumptions, the reduction in dairy consumption triggered by enerjoy is a 5.4% reduction for the first 6 months, dropping to a 3.3% reduction for months 7-12, and a 1.3% reduction from months 13-18. We again assume no lasting behavioural effects of app use after 18 months.

Since the low-carbon behaviour changes manifest in reduced dairy and electricity consumption respectively, it is necessary to

[2] Note that we do not consider the energy consumption caused by the app usage as this is difficult to estimate but likely very small (see, e.g., Yan et al. 2019 for such estimates).

[3] Appendix A1 provides more detailed information on the design, implementation, and sample characteristics of the field studies we rely on to estimate app benefits.

**Table 3**
Cost-benefit analysis (CBA): Summary of results.

| | enerjoy (1) | Social Power (2) CH | (3) GER | (4) CH | (5) GER |
|---|---|---|---|---|---|
| Development cost (USD) | 825,000 | 99,000 | 99,000 | 825,000 | 825,000 |
| Running cost per year (USD) | 44,000 | 44,000 | 44,000 | 44,000 | 44,000 |
| Total climate benefit per user (USD) | 6.16 | 2.13 | 6.10 | 2.13 | 6.10 |
| Number of users necessary to reach break-even point | 144,233 | 36,043 | 13,866 | 190,749 | 73,381 |

*Notes:* All cost estimates were provided in Swiss Francs and converted to US Dollars at an exchange rate from early 2022 of 1.10 USD/CHF. The time horizon of the analysis is 18 months, i.e., no costs or benefits are assumed to occur after that. Discount rate of 3%. See text and Tables A1 and A2 in the Appendix for further assumptions.

convert this impact of the two apps into $CO_{2eq}$. To do so, we multiply the average consumption reduction (in percent) per app user with the average consumption (in kWh of electricity per household for Social Power and in kg of dairy per capita for enerjoy) and the carbon intensity per unit of consumption to get $CO_{2eq}$ saved. The corresponding numbers and assumptions for the two apps are summarized in Tables A2 and A3 in Appendix A2.

### *4.1. Social cost of carbon (SCC) and break-even points*

In a next step, we multiply the estimated $CO_{2eq}$ savings with the social cost of carbon (SCC) to get the (undiscounted) total climate benefit of using the app for 18 months. SCC attempts to measure the societal cost of emitting one ton of $CO_{2eq}$ in the atmosphere (considering all possible impacts on the environment, the economy, human health, etc.). Thus, the role of SCC for commensurability is central, since it translates $CO_{2eq}$ savings into monetary units that are comparable to the costs of developing and running the apps. It is important to keep in mind that the concept of SCC itself is somewhat elusive and the value of the SCC is passionately debated (Pezzey, 2019). Various approaches such as integrated assessment models (Metcalf and Stock, 2020) or expert-knowledge elicitation (Pindyck, 2019) are being used to estimate its value, with each having major deficiencies. We employ a value of 175 USD per ton of $CO_{2eq}$, which is within the currently most frequently used estimates according to the expert survey by Pindyck (2019), at the lower end given results of Ricket et al. (2018), but close to the most recent estimates by Rennert et al. (2022) (for further estimates see Howard and Sterner 2017; Nordhaus 2017).

Finally, despite the short time horizon we consider (i.e., there are no costs or benefits of the apps after 18 months), we apply a discount rate of 3% to all costs or benefits that accrue in this period, as it is common in environmental cost-benefit evaluations (see, e. g., Atkinson and Mourato 2008 for a discussion). We chose this discount rate since it is within the range of most social CBAs in industrialized countries (Zhuang et al., 2007) and also in the calculation of the SCC (e.g. Ricke et al. 2018; Rode et al. 2021). However, the importance of the discount rate for our results is limited due to the short time frame considered.

Table 3 provides a summary of the results of our CBA. Column (1) presents the results for enerjoy, columns (2)–(5) for Social Power. For Social Power, we provide different variants. Columns (2) and (3) use development costs estimated by the Social Power developers. As discussed above, this estimate may be too low, because of the research context wherein Social Power was developed. Therefore, in columns (4) and (5) we provide the analyses using the considerably higher development cost estimate from enerjoy. Moreover, as the $CO_2$-intensity of the Swiss electricity mix is very low (because domestic electricity production is almost 100% hydro and nuclear power), in columns (3) and (5) we run the analysis using the 2021 $CO_2$-intensity of the German electricity mix, which is more $CO_2$-intensive, thus resulting in higher environmental benefits of the savings triggered by the app per user.

The last row in Table 3 provides the estimated break-even point, that is the number of app users that are necessary for the direct climate benefits of app use (in terms of reduced $CO_{2eq}$-emissions valued at the SCC) to outweigh the development and maintenance costs. For enerjoy, we find that roughly 140,000 users are necessary to reach a net positive impact. This equals to roughly 300 times more users than involved in the intervention. For Social Power, the necessary number of users varies between 14,000 and 190,000 depending on the assumed development cost and $CO_2$-intensity of the electricity saved. This equals to 140 – 1,900 times more users than during the intervention.

These break-even numbers of users necessitate very significant scale-up efforts, which come at a cost not included in our analysis. However, achieving such total user numbers appears feasible, as several similar apps were able to achieve considerable app downloads in a rather short period of time. For instance, GoodGuide, an app providing environmental and ethical information on household products, had over 400,000 downloads in its first year (Schwartz, 2010). And the H2020 project ENCHANT is working on behaviour change interventions, potentially involving smartphone apps, targeting up to 10 million households in six countries (Carrus et al., 2021).

Considering that the apps could be launched in all German-speaking countries with no additional translation cost, it seems that the threshold for successful sustainable behaviour change apps to be viable is not trivial but in principle possible to reach. There are around 7.9 million smartphone users in Switzerland, 74.8 million in Germany, and 7.5 million in Austria (estimates for 2021 from O'Dea (2020)), thus reaching 140,000 users would mean capturing 0.16% of the user base. Of course, the actual target group willing to download and use such apps is limited, nevertheless the scale-up possibilities are potentially large. However, it is important to consider the actual benefits that app use can trigger and to focus on contexts where such apps can have the largest climate impact, to ensure the benefits will eventually outweigh the development and maintenance costs.

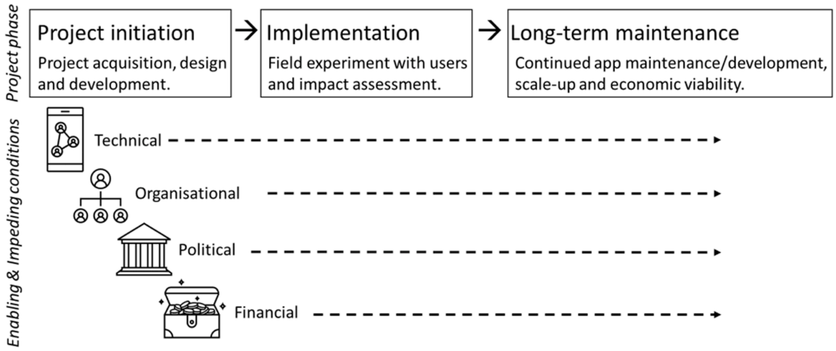


**Fig. 1.** Overview of enabling and impeding conditions impacting each project phase.

## 5. Enabling and impeding conditions during project lifecycle

Significantly more users are required to obtain net climate benefits from the apps, thus conditions to decrease costs or increase benefits are critical to examine. We highlight the conditions during the project lifecycle (as visualised in Fig. 1) for Social Power and enerjoy which have either enabled or impeded their potential impact. Note these conditions are not mutually exclusive and thus their interconnectivity is relevant within and between phases.

### *5.1. Project initiation and app development*

At this phase, project financing and involved partners strongly define the direction the app develops. Project initiation, in both cases, came from an external impulse: either a public research grant or internal funding by the local utility. Thus, alignment of the (sometimes implicit) objectives between the funders and project team may limit app impact, despite both funding sources being motivated by political decarbonisation goals. The enerjoy developer noted "We have a new energy law that is really strict … and we have to react to [it] ... we have to react on what people and the government want", highlighting the tension between working within the constraints of their funder, the local utility, while trying to capture the potential for app scale-up following the interests of the users.

Considering the systemic nature of long-term mitigation and adaptation to climate change, political action is a necessary component. The interplay between political (in)action and individual behaviour directly impacts engagement and the effectiveness of interventions. Importantly, political interest can open funding opportunities, encourage (or enforce) different actors to work together, or increase public acceptance and willingness to participate (Becker and Naumann, 2017; Purtik and Arenas, 2019; Sung and Park, 2018). As Swiss energy utilities are publicly owned, and Swiss citizens have direct influence on politics through the direct democracy system, local attitudes and political interest can lower barriers to develop such projects. Political support can help to amplify the diffusion of app-based tools, favouring their uptake and sustained use over time by a larger and more diverse audience, and thus support the creation of wide-scale benefits. However, when poorly implemented or when power dynamics are not addressed, participation can alienate or deter communities and reduce acceptance (Macdonald et al., 2017).

Political influences can enable or impede project initiation but are also relevant for continuity of an app into the future. This is the case particularly for enerjoy, where the involvement of the local energy utility brings complexity: the app exists due to internal financing which provides security, however this also creates a power dynamic wherein an economic bottom line and company's goals impose pressure which may not always align with the desired impact by the project team. For Social Power, the struggle was in finding partners willing to take advantage of the already installed smart meters to capture added-value of their data.

A behaviour change intervention occurs within a network of actors and intermediaries who can hold different roles in enabling or impeding the success of the intervention (Parag and Janda, 2014). Beyond the focal actors, such as the research team and app developers, additional businesses (e.g., restaurants, electricians), formal and informal social groups (e.g., church communities, university students, local associations and NGOs), the public administration (e.g., department of transportation, commission for research funding), and policymakers are relevant actors for project initiation, participant recruitment, implementation success, and long-term continuity. It is crucial to find ways to balance engagement and input from these actors and rapid development of the app (see, e.g., Abrahamsson et al., 2002). Furthermore, app-based behaviour change interventions should extend their collaborator networks to capture more partner and user buy-in, as well as ease processes and ensure sufficient resources to grow beyond the test phase, guaranteeing viability for long-term implementation.

### *5.2. App implementation and evaluation*

Both apps were developed and tested in real-world settings using control groups, to determine causal effects of the apps. While this approach is scientifically rigorous, for enerjoy the need for a control group meant that only part of the recruited study participants could receive the app to use. Recruiting enough participants to be able to make statistically robust inferences and draw meaningful conclusions about the impact of the tested app is an important step, and if not successful can generate additional recruitment costs or yield inconclusive results.

Participant management during registration and app familiarization was carried out by the project teams during the experiments. Most of this process was automated through an online registration tool, however there remained many individual cases that had to be managed, particularly in the case of Social Power where additional set-up was necessary to connect to household smart meters. Considering the need for scale-up, the personnel costs for participant management would be too large without further automation of this stage. Trust plays a role in app uptake and use, and an existing relationship was found to be supportive. For Social Power, initial communication to the household came from their energy provider, and the longer-term customer relationship legitimized the project.

Additionally, the automatically collected data or relevant databases presented to the user, such as the $CO_2$ footprinting data used in enerjoy, need to be reliable and transparent, as this form of behavioural intervention centres around meaningful and trustworthy personalized information feedback. From the technical perspective, designing automated or user-provided data collection presents a trade-off that needs to be carefully assessed depending on the user's willingness to engage in each data-centric application (Lidwell et al., 2010). Automated collection may provide a certain insight, accuracy, and novelty into more unknown areas of consumption, like energy (Hargreaves et al., 2010). However, automation allows for distance between individuals and the impact of their consumption practices, making it easier to forget once the novelty has worn off (Hargreaves et al., 2013).

For Social Power, several challenges arose with the transfer of the electricity consumption data to the app. Due to data protection laws, household electricity consumption data are considered to be sensitive personal data and thus it is only possible to access the smart meter data once per day, despite the consumption data being produced every 15 min. In addition, there was a physical limitation on the amount of transmitted data, thus some users had gaps in the data displayed in the app. This is not what participants expected from a proposed "real-time" electricity consumption solution.

Enerjoy presented a different data management case, as all the user data in the app was provided by users themselves and connected to an extensive database to calculate the $CO_2$ footprint. Providing one's own data affords some experimentation with alternative, yet fake, inputs, such as for instance exploring the footprint of eating meat, if one is vegan, or vice-versa. Misusing the app in this way is not necessarily problematic, as it is meant to allow the user to explore new behaviours and not as a controlling tool. Here the challenge is to encourage participants to provide their consumption data, as the app has no automatic data collection. High dropouts were expected by the enerjoy app developers, thus continuous communication was provided during the experiment which helped keep participant attrition at acceptable levels, however this involved additional work for the project team.

Also, data provided by users when tracking their own behaviours (e.g., what they eat or how they use electrical appliances) can offer particularly unique design opportunities for behaviours which have no or insufficient automated collection. This may be relevant when addressing behaviours in more complex practice settings which are impacted by social, economic, and structural conditions (Shove and Walker, 2014).

As data protection awareness of the users increases, as seen with the introduction of the EU General Regulations on Data Protection (GDPR) in 2018 (Kovacs, 2019), users are nonetheless purpose-driven and many may disregard the data management policy in order to skip to their primary use (Sandovar et al., 2016; Shklovski et al., 2014). Further, as data management becomes more regulated, efforts for compliance need to be anticipated in future data-driven behaviour change apps. While the data transmission issues experienced in Social Power can likely be overcome, the data protection laws continue to restrict the added value of the highly granular electricity data that is possible with smart meters. Considering that the Swiss smart meter roll-out is a political mandate, this contradiction with the access to the data requires attention. Thus, the future of data-driven behaviour change will evolve within a socio-technical-political landscape.

## 6. Long term maintenance and scale-up

Despite Social Power being initiated as a research project, and enerjoy being tested within one, both apps were conceptualized to be used beyond their study period to achieve the growth that appears easy through accessibility of an app store. In both cases, however, the jump from a project into a self-sustaining business is yet to be achieved (see Table 1 for further details). The Social Power developer, having experience in both commercial and research projects, acknowledged the opportunity for apps, but also the challenge to develop a business case: "*Developing an application is a very risky business, if you expect to make your money out of the market. There are hundreds of applications competing for the same users, the very same money, and just one or two can make money and the other thousand would be just there*". Even in the smaller domain of climate-related behaviour change apps, strong competition exists, and user uptake will depend on more than functionality, but on transparency, privacy, trust, and cost (Brauer et al., 2016).

In general, consumers' willingness to pay for apps is low (Niemand et al., 2019), and this may be even more the case for societal and environmental topics which have less direct intrinsic value, in comparison to self-improvement apps, such as fitness trackers. Thus climate-related apps may be difficult to finance over the traditional methods of subscription fee, advertising, or affiliate sales, and thus need to look for a multi-dimensional value capture considering the additional social and environmental benefits (Gregori and Holzmann, 2020).

Furthermore, as app development is dependent on a supporting technological ecosystem, it is not possible to plan for consistency over the long-term, and requires the necessary financial planning to continue to update the app: "*I think that nobody in the mobile industry makes [a multi-year] forecast for an application because nobody knows what the market will be like in five years… The technology you are using, the version of your tool chain compilers, and tools, become obsolete in such a long timeframe. Probably in an academic project, it could be acceptable to be on the market with something that is not absolutely cutting edge in terms of technology, in terms of design… If you plan an application, especially for mobile devices, you have to think about a very fast development cycle*" (Social Power developer). While apps are

**Table A1**
Characteristics of field studies.

| | Social Power | | enerjoy | |
|---|---|---|---|---|
| Study period | Oct 2015 – May 2017 | | Oct 2020–Dec 2020 | |
| Unit of analysis | Household | | Individual | |
| Main data used to evaluate app impact | Smart meter data on electricity consumption | | Self-reported food consumption and mobility behaviour | |
| | *Treatment* | *Control* | *Treatment* | *Control* |
| Final # observations | 42 | 40 | 341 | 132 |
| Assignment to group | Voluntary sign-up for study | Matched control households (unaware of study) | Random | Random |
| Demographics | Single house/h: 63% | 59% | Mean age: 25.3 | 25.3 |
| | Family house/h: 37% | 41% | Females: 69% | 64% |
| | Apartments: 72% | 72% | Males: 31% | 36% |
| | Houses: 28% | 28% | Students: 96% | 95% |
| | | | Employed (fully or partly): 62% | 67% |

**Table A2**
Assumptions used for calculating the climate benefits of Social Power in terms of $CO_{2eq}$ savings.

| | Switzerland | Germany |
|---|---|---|
| Average yearly electricity consumption per capita | 1,300 kWh (Swiss Federal Office of Energy, 2016) | 1,300 kWh (German Association of Energy Industries & Water, 2021) |
| Average household size | 2.2 (Swiss Federal Office of Statistics, 2021) | 2.0 (German Federal Institute for Population Research, 2021) |
| $CO_{2eq}$ emissions per kWh electricity | 128g (Krebs & Frischknecht, 2018) | 366g (German Environment Agency, 2021) |
| *Assumed consumption reduction (based on Wemyss et al., 2018):* | | |
| 1-6 months (after app-use) | 8% | |
| 7-12 months | 5% | |
| 13-18 months | 2% | |
| >18 months | 0% | |

**Table A3**
Assumptions used for calculating the climate benefits of enerjoy in terms of $CO_{2eq}$ savings.

| | |
|---|---|
| Average yearly dairy consumption per capita in Switzerland | 299.1 kg (Swiss Federal Office of Agriculture, 2021)[a] |
| $CO_{2eq}$ emissions per kg of milk | 2,400g (FAO, 2010) |
| *Assumed consumption reduction (Wemyss & Grieder, 2021):* | |
| 1-6 months (after app-use) | 5.4% |
| 7-12 months | 3.3% |
| 13-18 months | 1.3% |
| >18 months | 0% |

[a] Note that the dairy consumption in these sources is measured in whole milk equivalents which means that we are using the $CO_2$ emissions for milk and not dairy in our calculations.

ubiquitous, Google and Apple control the availability of apps to smartphone users, with only minor exceptions (e.g., F-droid), and thus all innovation possibilities are limited by these platforms. Correspondingly, maintaining functionalities of apps through the frequent iOS and Android operating systems updates can be cost-intensive and may remove functionalities overnight (Yang et al., 2018).

For Social Power, further implementation is dependent on research funding, and thus the project team had only minimal resources to promote the app. Additionally, the current market conditions in Switzerland, with utilities acting as monopoly providers to household customers within their region (Mühlemeier, 2019), do not incentivise utilities to implement innovative customer-oriented products. The support for enerjoy from the local utility is an exception in this regard. With the planned liberalisation of the household electricity market in Switzerland (Swiss Federal Office of Energy, 2020) or an increased policy focus on a low-carbon society, an approach like Social Power or enerjoy may become more attractive to engage consumers.

A significant financial base is critical for app development, whether it be in the private sector or research. As is seen in both cases, the initial sunk costs for development were financed outside of a viable business model, which is a necessary starting point. Considering both the time required to change behaviour, as well as the scale of climate change challenges, either intervention financing or another revenue stream should support the maintenance of the desired behaviour for multiple years and allow for scale-up to more users (Ohnmacht et al., 2017; Wilhite et al., 2006). This tension has already emerged as “typical” within social innovation in the energy domain, particularly community-based renewable energy projects (Bere et al., 2017; Branker et al., 2011). In theory, repeated implementation of an app should see a rapid decrease in the running cost per user, as onboarding and management can become more automated and simplified. While the support system for getting a project started and implemented exists, currently a viable business model is missing to secure continued implementation and relevant impact.

## 7. Conclusion

In this paper we have presented two cases of behaviour change apps, enerjoy and Social Power, and assessed their capability to foster TSI to support the transition to a low carbon society. This assessment adds a transitions system view to the calls for improved rigour in design, implementation, and evaluation of behaviour change apps, wherein critiques range from a lack of theory-informed practices hindering evaluation and reproducibility (Beck et al., 2019; Douglas and Brauer, 2021), to the short-term focus of most studies (Chatzigeorgiou and Andreou, 2021), or reflections on gamification and use of ICT in sustainability domains (Beck et al., 2019; Knowles et al., 2018; Morton et al., 2019), and the reductionist notion of smartphone apps (Schwanen, 2015a). We contribute to this discussion by looking beyond the direct behaviour change to address the conditions supporting long-term transformative impact, as well as the number of users required to reach a positive benefit.

We highlight several perspectives for capturing the transition relevance of behaviour change apps, mainly: understanding the advantages and constraints of implementing an app in a rapidly changing technological and data protection environment; aligning long-term goals between actors to secure political and financial support; and reflecting on the feasibility to scale-up users to an ambitious break-even point.

It is important to recognize that these two apps, while being concrete examples of social innovation in a low-carbon transition context, are not necessarily generalizable to all apps for sustainability or for contexts largely different than Switzerland. Specifically, these behaviour change apps have changed knowledge and practices of users, asked for reflection on the local utilities' business models, and ultimately questioned the prevailing narrative around "technology-first" approaches in Switzerland. In other countries, the institutional barriers are indisputably different, and yet are necessarily intrinsic to the success of this approach.

For future research, we recommend behaviour change initiators explore their intervention contexts, from the perspective of the prevailing technical, organisational, political, and financial conditions, by addressing the questions summarized in Table 2. Understanding which specific conditions can enable or impede the large-scale transformative potential of an app can support the decision about the development of tools, as well as help to innovate for the "long game" of behaviour change, in order to identify viable business models and obtain the suitable (government or other) support for the needed long-term scale-up.

Considering the urgency to address climate change, funding for behaviour change policy and initiatives should necessarily be directed to have long-term impact following on cost-effective choices for scale-up (Nielsen et al., 2021). The necessary number of users obtained from the CBA indicate that behaviour change apps are only a judicious option for research or policy if considered within a realistic long-term scale-up strategy.

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## Data availability

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

## CRediT authorship contribution statement

**D. Wemyss:** Methodology, Writing – original draft, Writing – review & editing. **F. Cellina:** Funding acquisition, Methodology, Writing – original draft, Writing – review & editing. **M. Grieder:** Methodology, Investigation, Writing – original draft, Writing – review & editing. **F. Schlüter:** Investigation, Writing – original draft.

## Declaration of Competing Interest

The authors declare that they have no known competing interests that could have appeared to influence the work reported in this paper.

## Data Availability

Data will be made available on request.

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## Appendix

### A1. Details of enerjoy and social power field experiments

Social Power and enerjoy were both tested in field studies in Switzerland to evaluate the effects of the app. Social Power was developed and tested in 2015-2017 (see Wemyss et al., 2018, 2019), enerjoy was developed and tested in 2019–2020 (see Grieder and Wemyss, 2021). The Social Power study did not have fully random assignment of participants to treatment and control groups, whereas the enerjoy study did. In the Social Power study, households who had expressed an interest in using the app were all assigned to a treatment group receiving one of the versions of the app and their electricity consumption was compared to a control group that was unaware of the study during the intervention period. The enerjoy study also relied on a self-selected sample (which seems appropriate given that the effectiveness of the apps was to be tested for the interested target group), yet it had full random assignment of participants to treatment group (with one of two versions of the app) and control group (without the app). Table A1 below summarizes some basic information on the design, implementation, and sample characteristics of the two studies. The original papers cited above provide full details.

### A2. Assumptions used for calculation of climate benefits of app use

To estimate the climate benefits of the two apps in terms of $CO_{2eq}$ reductions, we multiplied the consumption reduction (in percent) per app user obtained from the field studies by Wemyss et al. (2018, 2019) and Grieder and Wemyss (2021) with the average consumption (in kWh per household for electricity for Social Power and in kg per capita for dairy for enerjoy) and the carbon intensity per unit of consumption. In Switzerland, the average yearly per capita electricity consumption amounts to 1,300 kWh (Swiss Federal Office of Energy, 2016), which we multiplied by the average household-size of 2.2 (Swiss Federal Office of Statistics, 2021), to obtain a rough estimate of average consumption per household. The average per capita dairy consumption is 299.1 kg (Agristat, 2021). The amount of CO2eq emissions of 2.4 kg per kg of milk was obtained from a lifecycle assessment of greenhouse gas emissions from milk production provided by the United Nations (Food Agriculture Organization, 2010). The average emissions for the Swiss electricity mix of 128 g per kWh were taken from a study commissioned by the Swiss Federal Office of the Environment (Krebs and Frischknecht, 2018). As the Swiss electricity mix has relatively low $CO_{2eq}$ emissions (because domestic electricity production is almost 100% hydro and nuclear power), we also provide results using data from Germany, where the current electricity mix is more $CO_2$-intensive. As for Switzerland, we multiplied average electricity consumption per capita of 1,300 kWh per year (German Association of Energy Industries and Water, 2021) with the average household-size of 2 (German Federal Institute for Population Research, 2021), to obtain average consumption per household. For the CO2-intensity, we used the value of 366 g per kWh from the German Environmental Department (German Environment Agency, 2021).

Tables A2 (Social Power) and A3 (enerjoy) provide an overview of the assumptions used in the calculation of the climate benefits ($CO_{2eq}$ savings) in the cost-benefit analysis reported in Section 4.

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