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RESEARCH ARTICLE

Solar panels – is more always better?: Assessing the carbon footprint of communities

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Abstract • Are more solar panels always better in terms of carbon impact for a local energy community, and what is the influence of energy sufficiency? The answer is simple when the national electrical grid is taken as an infinite source of storage. However, this answer becomes uncertain if we consider that exporting power at the national scale is not a desired option. Although this is a conservative hypothesis, it is considered for technical and social reasons. In doing so, load profiles become a key to evaluating the carbon impact of hybrid systems with solar panels plus storage units. To summarize the impact of any load profiles on the optimal sizing of solar panels, we propose a novel index denoted 'natural self-sufficiency'. Our results show that not only reducing energy demand but also being more flexible significantly affects the carbon emissions related to solar panels.

Sind mehr Solarmodule immer besser?:
Bewertung des kommunalen Kohlenstoffausstoßes

Zusammenfassung • *Sind mehr Solarmodule immer besser, wenn es um die Kohlenstoffbelastung einer lokalen Energiegemeinschaft geht? Und welchen Einfluss hat die Energiesuffizienz? Die Antwort ist einfach, wenn ein lokales Stromnetz als unendlicher Speicher betrachtet wird. Die Antwort wird jedoch schwieriger, wenn man davon ausgeht, dass die Einspeisung von Strom in ein größeres Netz auf nationaler Ebene nicht die gewünschte Option ist. Obwohl dies eine konservative Hypothese ist, wird sie aus technischen und sozialen Gründen in Betracht gezogen. Unter dieser vorsichtigeren Annahme werden Belastungsprofile zu einem Schlüssel für die Bewertung der Kohlenstoffauswirkungen von Hybridsystemen mit Solarmodulen und Speichereinheiten. Um die Auswirkungen beliebiger Profile auf die optimale Dimensionierung von Solarmodulen zusammenzufassen, schlagen wir einen neuartigen Index vor, der als ‚natürliche Autarkie' bezeichnet wird. Unsere Ergebnisse zeigen, dass nicht nur die Verringerung des Energiebedarfs, sondern auch eine größere Flexibilität die Kohlenstoffemissionen im Zusammenhang mit Solarmodulen erheblich beeinflusst.*

Keywords • *self-sufficiency, energy communities, energy sufficiency, optimal sizing, greenhouse gas emissions*

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Introduction

Starting with a question on solar panels might be unexpected when energy sufficiency (Zell-Ziegler 2021) is the topic of interest. Although both renewable energy production and energy sufficiency are separate topics, they share a common goal and synergies. Both load shaping and shifting are critical to renewable energy integration but also related to energy sufficiency as they bring lifestyle changes (e.g., charging electric vehicles on sunny days). Our objective is to study the influence of energy sufficiency on greenhouse gas (GHG) emissions induced by solar plus storage systems.

At first sight, yes, more solar panels always reduce GHG emissions. At least, this is the answer from a simple back-of-the-envelope calculation. On the one hand, manufacturing and retiring solar panels have an average GHG cost of 1040 $kgCO_2eq$/kWp (ADEME 2021). On the other hand, producing electricity from a 1 kWp solar panel avoids on average 266 $kgCO_2eq$ per year in Germany and 69 $kgCO_2eq$ per year in France (elec-

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tricityMap 2022; Huld et al. 2012). It follows that after four years in Germany or 15 years in France, a solar panel has virtually reimbursed its carbon impact. If we assume that the lifetime of a solar panel is longer than 20 years, we can conclude that more solar panels always reduce GHG emissions.

However, this brief calculation makes the hypothesis that the electrical grid acts as infinite and ideal storage. In other words, it is always possible to import or export from or to the grid.

Let's consider the hypothesis where power injection into the upstream grid is possible but no longer desired. In such a scenario, more solar panels are not always better in terms of GHG emissions. It depends on the proportion of solar energy that can be absorbed locally. With that hypothesis, only the energy production that overlaps with local consumption is accounted to reimburse the initial carbon cost of solar panels.

From a greenhouse gas emission's perspective, what is the right number of solar panels and size of batteries, if exporting power is not a desired option?

Why would we consider this more conservative hypothesis? We propose two reasons, first from a technical point of view, and second from a more social or energy sufficiency-oriented perspective. In reality, the electrical grid is far from an infinite storage, and exporting solar power also has a carbon cost. For instance, solar power does not replace the stability brought by large rotating machines (i.e., spinning reserve for frequency regulation), nor does it change the number of thermal power plants required to meet the electricity demand at night in winter. In some cases, it actually calls for more thermal power plants to increase 'ramp up' capacities when evening consumptions increase as the sun sets (Calero 2022). Exporting more solar power may also imply additional grid reinforcements and emissions from unintentional start-up and shutdown sequences of conventional thermal units.

The second reason to consider the hypothesis of constrained grid exports is of social nature. We believe that there is a trade-off to consider between the different scales of the grid, in particular between the national scale and the scale of local energy communities. A trade-off between efficiency gains from large-scale infrastructures, versus what the proximity to a limited production can bring in terms of energy sufficiency (Illich 1974). We do not advocate for grid-independent energy communities. However, we consider grid-dependent communities that chose to situate their actions for the energy transition at a local scale, rather than at a national scale. Then the question is: From a GHG emission's perspective, what is the right number of solar panels and size of batteries, if exporting power is not a desired option?

To answer this question, we formulate an optimization problem. However, minimizing GHG emissions by installing solar panels and storage systems is highly dependent on the load profiles that shall be met by both local assets and imports from the main grid. Indeed, some load profiles are naturally more inclined to absorb – i.e., self-consume – solar production when associated together. For instance, an office building with greater consumption during daytime is naturally better equipped to consume solar generation, than a residential building with an 8 pm peak demand. Unfortunately, real-world consumption profiles are scarce resources, especially when looking for a variety of consumer types. The existence of open-source databases is one solution to studying the effect of various load profiles on the optimal sizing of solar panels and storage capacities (Quoilin et al. 2016). However, this only provides discrete answers, without offering a continuous analysis for degrees of 'alignment' between load profiles and solar production.

In order to quantify this concept of 'alignment', but also to study the sensitivity of GHG emissions to this concept, we propose a novel approach, where 'alignment' is measured as a novel index denoted as natural self-sufficiency (NSS), and load profiles can be modified to match a given NSS. This approach appears as a relevant solution to provide lower and upper bounds on GHG costs, which is potentially faster than running large Monte-Carlo simulations.

Our contribution in this publication is to:

- inform the GHG cost of solar panels and storage systems when considering that exporting power is not the desired option,
- provide a method for estimating the impact of load profiles on lower and upper bounds of GHG emissions,
- explore the effects of energy sufficiency on resulting GHG emissions.
- All the data, models, and results developed in this paper are made available in open access online (see research data, s.n.).

Defining natural self-sufficiency

Motivations and definition

Our objective is to develop a metric that quantifies the relative ability of a load profile to overlap with solar production. We aim for a relative metric, as we expect to compare different load profiles at the same location but with unequal energy demands.

To build such a metric, we rely on the well-established self-sufficiency metric (Luthander et al. 2015) which represents

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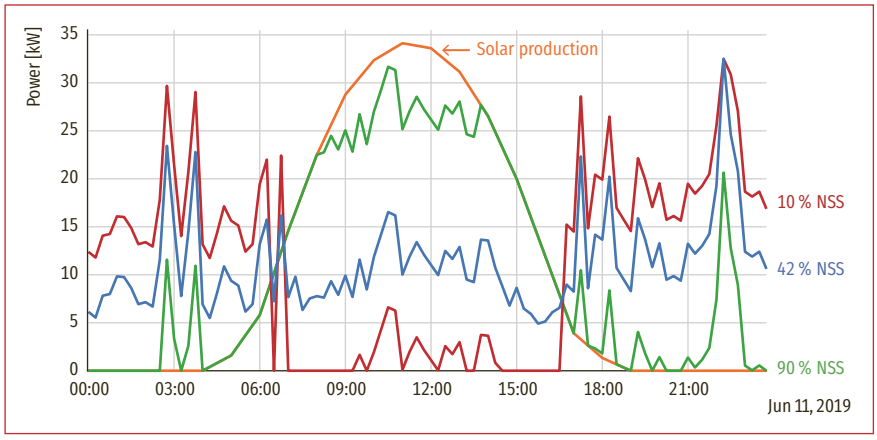

Fig. 1: Illustrative example of modifying the natural self-sufficiency of a load profile from 42 % (blue) to 10 % (red), and 90 % (green). *Source: authors' own compilation*

the percentage of consumption that is covered by local production within 15-minute intervals. However, to provide a metric relative to a load profile and a location, we calculate self-sufficiency for a solar panel capacity that generates the same amount of yearly energy as consumed by the load profile (i.e., a net-zero energy balance). Taking this solar capacity enables to theoretically reach a 100 % natural self-sufficiency for any load profile.

The resulting NSS metric provides a way to differentiate the load profiles' ability to absorb solar production. For instance, to differentiate a residential load profile from an office building load profile. The latter is more likely to have a higher NSS as most of its consumption occurs during daylight hours as opposed to a residential scenario.

Method to create load profiles with a specific natural self-sufficiency

In and of itself, NSS is interesting to differentiate load profiles. Characterizing NSS opens the door to a second phase where we can modify the load profiles to match a given NSS value. There are several reasons to create new load profiles with modified NSS. One reason is to provide lower and upper bounds with regard to variations in load profiles when optimally sizing solar panels.

Another reason, which we explore in this paper is to summarize the impact of any load profile (i.e., with different patterns, and energy demands) on the optimal sizing of solar panels with a single index. This is useful to exhaustively explore the impact of load profiles (from 0 to 100 % NSS) on GHG emissions. In a way, we estimate the minimum GHG emission for any load profile, and therefore for any local energy community (at a given location).

To generate new load profiles, we start from an original real-world load profile and implement an optimization-based approach. The objective of the optimization is to make as few changes as possible from the original profile (i.e., minimum mean square error as an objective) to match a certain NSS target. Further, we impose that the energy consumption remains unchanged and that the previous maximum power demand is not exceeded as additional constraints. The problem results in a mixed-integer quadratic programming problem, for the complete set of equations, we refer the reader to online supplementary materials.

Before closing this section, we illustrate both, the concept of NSS, and modifying load profiles. Fig. 1 shows a load profile with a 42 % NSS (in blue), which is then modified to either reach a 10 % NSS (in red) or a 90 % NSS (in green). The illustration is considered on a single day for simplicity. The 10 % NSS target results in little load demand during the day, whereas the 90 % target increases demand during daylight hours compared to the original load profile (in blue). For all the profiles, peak demand and overall energy consumption remain the same.

Natural self-sufficiency as a moderator

Motivations and methods

In the previous section, we have explained our methodology to construct load profiles from 0 % to 100 % NSS. In this section, we explore GHG emissions as a function of NSS (i.e., load profiles), but also as a function of a self-sufficiency target. Including self-sufficiency enables observing GHG emissions for local energy communities where GHG emissions are not the only sizing criteria (e.g., financial costs may lead to a different target in terms of self-sufficiency).

Intuitively, a community expecting to be fully self-sufficient with a NSS index close to zero will need large storage capacities leading to a high GHG impact due to carbon installation costs. On the contrary, achieving 30 % self-sufficiency for a community with an already high natural self-sufficiency of 50 % might avoid any storage, or oversized solar panels, and thus lead to a low GHG impact. This balance between self-sufficiency and GHG emissions is expressed in Fig. 2 for load profiles with different starting NSS.

Each data point in Fig. 2 is the result of an optimization problem that sizes solar panels, and storage to reach a given self-sufficiency with a minimum amount of carbon emissions. The emissions estimations account for the solar and storage manufacturing ('capital' emissions) as well as the emissions incurred by energy imports from the grid ('operational' emissions). This method to minimize GHG emissions while achieving a given self-sufficiency is described in (Hodencq et al. 2021). In a nutshell, this method mixes short-term constraints (e.g., on a 15 min basis) and long-term constraints (e.g., over 20 years). It covers short-term operations to meet self-sufficiency goals (e.g.,

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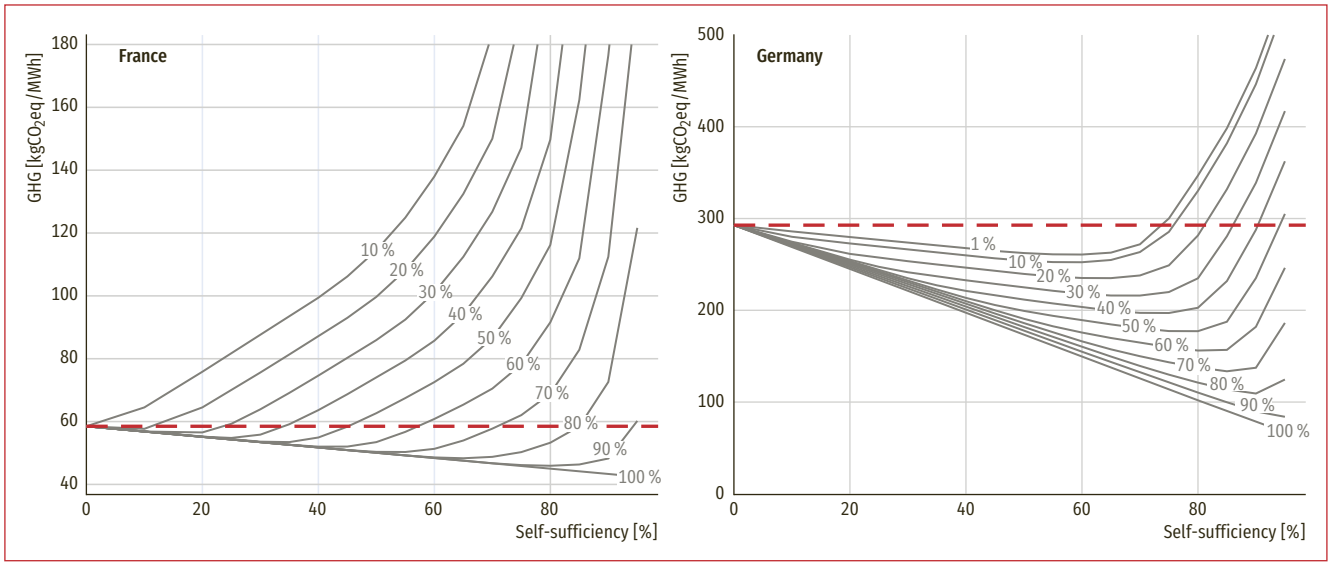

Fig. 2: Greenhouse gas (GHG) emissions as a function of self-sufficiency levels for profiles with 10 % to 100 % natural self-sufficiency, in France (left) and Germany (right). *Source: authors' own compilation*

respecting battery physics), as well as long-term considerations such as investment decisions, and equipment aging.

In this work, we consider an average carbon impact of 1040 $kgCO_2$/kWp for solar panels (ADEME 2021), and 158 $kgCO_2$/kWh for batteries (Peters et al. 2017). To simplify comparing different load profiles, annual average grid emissions factors are considered, for Germany 293 gCO_2Eq/kWh and for France 58 gCO_2Eq/kWh as per hourly data (electricityMap 2022).

self-sufficiency), the GHG emissions incurred by manufacturing solar panels are compensated by reducing day-to-day emissions from the main grid. However, greater self-sufficiency targets require the installation of larger solar panels and batteries, which also implies significant emissions. Especially, significant battery capacities are needed to cope with successive days of moderate solar production and supply power peaks. In such cases, the operational carbon savings do not compensate for the manufacturing emissions, and the global system GHG emissions can reach values well above those of national grids (especially in France).

Some energy sufficiency actions can be modeled by a homogeneous consumption reduction alone, e.g., lowering the heating temperature by 1° Celsius in winter, or disposing of a freezer.

Results

Looking at GHG emissions per kWh in France and Germany tells a completely different story (Fig. 2). Since GHG emissions for electricity usage are significantly lower in France, shedding 10 gCO_2Eq/kWh is challenging, (i.e., it requires a starting NSS of around 80 % with 3 kWp solar panels per house). Whereas Germany with much higher grid emissions can hope to shed 75 gCO_2Eq/kWh realistically (i.e., with a moderate NSS at 30 %, 3.5 kWp of solar panels, and 8 kWh of batteries per household).

Diving further in Fig. 2, we check that when self-sufficiency is at 0 %, all the energy consumption is imported from the main grid, as there is no solar generation installed. Thus, the normalized carbon emissions are equal to the average French and German grid emissions (red dashed line) respectively. In both countries, at low self-sufficiency targets (i.e., 20 %

Verifying the hypothesis on natural self-sufficiency

As mentioned earlier, we hypothesize that load profile differences can be summarized through the proposed NSS index when it comes to sizing renewable energy systems (for a given location). To verify this hypothesis, we expect that two load profiles with the same NSS will give identical results in Fig. 3. In other words, any load profile with a given NSS should fall within the corresponding NSS curves from Fig. 3. We then select 4 different load profiles from open-source data sets with NSS of 29 %, 31 %, 33 %, and 39 % respectively (Quoilin 2016; Delinchant et al. 2016).

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Below 60 % self-sufficiency, Fig. 3 shows that our hypothesis holds, as all the curves remain within the 30 % to 40 % boundaries. This is a significant result as energy communities most often remain below 65 % self-sufficiency (Quoilin et al. 2016). Beyond 60 % self-sufficiency, the NSS index is not the only parameter to consider, as the GHG impact of batteries becomes significant. In particular, the maximum peak demand, and consecutive days with large energy demand influence the size of the battery required to reach a certain self-sufficiency. It ultimately leads to deviations from the expected GHG emissions given by the reference chart generated with load profiles computed following our methodology.

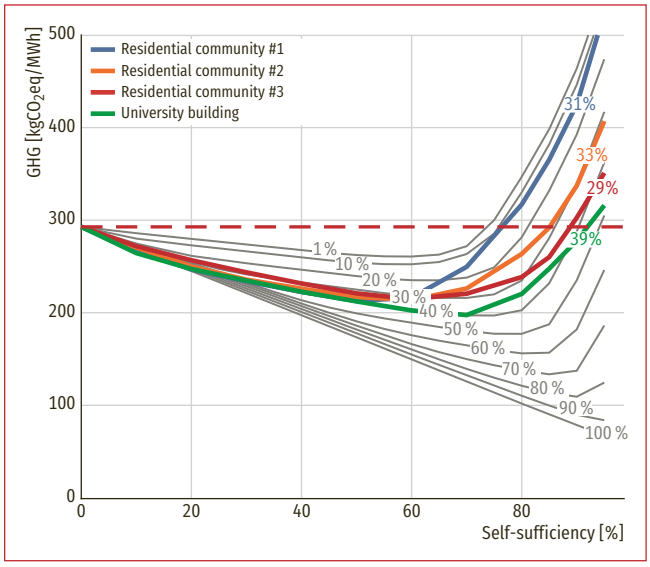

Fig. 3: Verifying the hypothesis on NSS for the German case using four different load profiles with various natural self-sufficiency (specified on each curve).
Source: authors' own compilation

Observing the effect of energy sufficiency with natural self-sufficiency

Motivations and methods

Energy sufficiency measures are complementary to other energy transition measures such as efficiency, and the development of renewable energies to replace carbon sources (Samadi et al. 2017). The definition of energy sufficiency is plural (Zell-Ziegler 2021). Here we adopt Bierwirth and Thomas' definition: "actions which reduce energy demand, […], whilst at the same time changing the quantity or quality of the energy services demanded in a sustainable way and not below people's basic needs" (Bierwirth and Thomas 2019, p. 6). Some energy sufficiency actions can be modeled by a homogeneous consumption reduction alone, e.g., lowering the heating temperature by 1° Celsius in winter, or disposing of a freezer. Yet energy sufficiency actions also relate to the shift and avoidance of particular energy uses (Erba and Pagliano 2021). As such, we model energy sufficiency through a combination of both homogeneous consumption reductions and flexibility in energy use.

We assume that increasing flexibility is analogous to increasing natural self-sufficiency with the ability of a user to 'align' his demand profile to sun peak hours. For instance, an increase of NSS by 10 % means that 10 % of the electric consumption has been shifted to be covered by local solar production (i.e., flexibility).

Further, consumption reduction is modeled as a homogeneous lowering of the load profile each year. While such modeling also corresponds to energy efficiency measures, it is here considered as a component of energy sufficiency as it may also represent a reduction in heating demand. Based on the evolution of buildings consumption in Northern countries (Grubler et al. 2018), we assume an annual reduction in consumption of 2,8 % over the 20-year study horizon (i.e., 23 % less consumption after 20 years). The work of Grubler et al. can be considered a best-case scenario in our study since it is one of the most ambitious scenarios regarding energy demand reduction. Moreover, it considers overall energy usage and not only electricity use, and energy demand reduction in this scenario is due both to energy efficiency and sufficiency.

The provided method and supplementary materials enable to explore various levels of sufficiency with different combinations of energy consumption reduction and flexibility. A perspective of this work would be to compare the obtained results to bottom-up approaches, for instance based on Brischke et al. work who consider the number, use patterns and technical characteristics of appliances to reflect reduction, substitution, and adjustment of consumption (Brischke et al. 2015).

Results

The results enable to compare the effects of homogeneous energy reduction and flexibility, and to observe the effect of energy sufficiency as their combination.

The impact of consuming less energy, or being more flexible is illustrated in Fig. 4, with GHG emissions (in tCO_2Eq/house/year) as a function of self-sufficiency for various curves:

- a reference curve (in blue) that is the residential load profile of a 20 houses community with a NSS of 34,2 %,
- a flexibility curve (in orange) where the NSS of the reference curve was increased to reach 60 % (emulating flexibility),
- a reduced consumption curve (in red dotted line) applying the assumption of a steady 2,8 % per year consumption reduction with respect to the reference curve,
- and an energy sufficiency curve (in green) combining both flexibility and consumption reduction.

Let's consider different ranges of self-sufficiency, first between 0 % to 30 %, then between 30 % to 60 %, and finally from 60 % to 100 %. In the first section, with no investment in solar panels or other renewable sources (0 % self-sufficiency), then flex-

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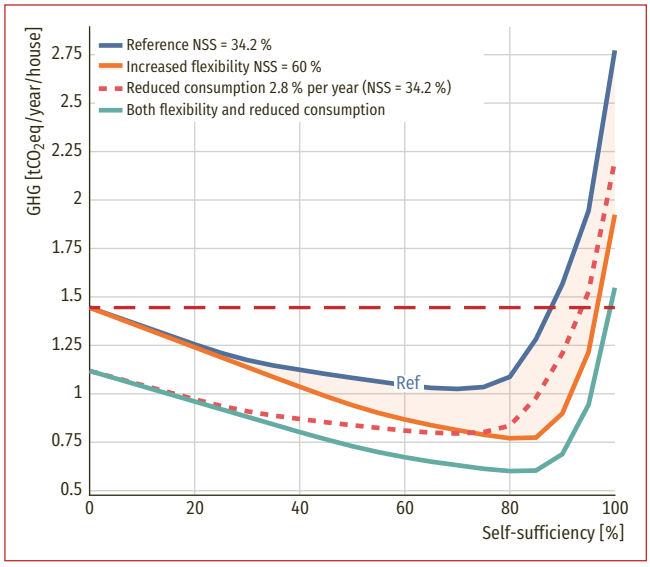

Fig. 4: Comparing flexibility effects and energy efficiency for a German energy community of 20 houses. *Source: authors' own compilation*

ibility is ineffective. Whereas energy reduction is impactful as carbon emissions are directly proportional to the consumption decrease.

In the second range, for households expecting between 30 % to 60 % self-sufficiency, flexibility steadily becomes as important as lowering energy consumption. At 60 % self-sufficiency, taking the flexibility route or the low demand route leads to different technological mixes. The flexibility route leads to a 69 kWp solar panel with 11 kWh of battery, whereas the reduced consumption requires a smaller 53 kWp solar panel but a much larger 107 kWh battery. In the end, flexibility acts as 'carbon-free' storage with users that actively adapt their load pattern. Although reduced consumption seems to be more impactful in this range, the best route is undoubtedly to work on both fronts at the same time, i.e., energy sufficiency.

The last range is more abstract and is getting closer to a case of energy autonomy since self-sufficiency rates are very high. In this case, flexibility becomes predominant, especially long-term flexibility where winter load demand is moved to summer.

Conclusion

In this paper, we address the sizing of solar panels plus storage in view of minimizing GHG emissions. We place ourselves in a context where power injection into the upstream grid (i.e., outside of a local energy community) is possible but no longer desired for technical and social reasons.

In that context, load profiles become critical in influencing GHG emissions from solar panels plus storage. Throughout this paper, we illustrate a methodology to quantify this impact for a variety of load profiles, in particular the impact of shifting energy usage during sun peak hours related to energy sufficiency.

From our results, we draw some trends rather than absolute certitudes. For instance, in the French case further reducing emissions by 10 gCO_2Eq/kWh is challenging. However, in Germany, communities can hope to shed 75 gCO_2Eq/kWh realistically, with an overall natural self-sufficiency of 30 %, and households equipped with 3.5 kWp solar panels, and 8 kWh batteries. Our results also speak to the limits of relying on high self-sufficiency levels, when simply reducing electricity consumption might be better in terms of GHG emissions. This is clear in France, less in Germany as GHG emissions still decrease until 70 % self-sufficiency.

We believe that our proposition for a natural self-sufficiency index and the methodology to modify load profiles is interesting to estimate results on a variety of load profiles (which is often not possible due to the scarcity of available data). In particular, this is a valid solution when load profiles cannot be modified from the ground up using individual appliances' consumption. If local energy communities want to gain confidence with regard to potential load profile changes (e.g., due to unexpected new members), they may use our methodology to apply some variation to their load profile. Further, we expect that this methodology can evolve, for instance by including other parameters like consecutive days without solar production.

Finally, it would be interesting to see how results may change if we account for some GHG emission offsets when exporting power to the upstream grid. Depending on the magnitude of this offset, this would potentially favour installing more solar panels, delay the use of storage systems, and lower the importance of shifting energy usage to daytime.

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Research data

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