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How, When, and Where? Assessing Renewable Energy Self-Sufficiency at the Neighborhood Level

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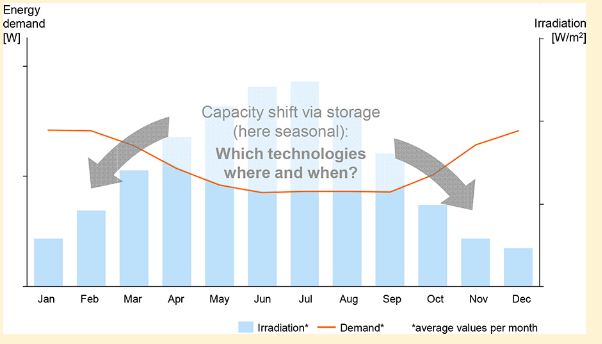
Supporting Information

ABSTRACT: Self-sufficient decentralized systems challenge the centralized energy paradigm. Although scholars have assessed specific locations and technological aspects, it remains unclear *how*, *when*, and *where* energy self-sufficiency could become competitive. To address this gap, we develop a techno-economic model for energy self-sufficient neighborhoods that integrates solar photovoltaics (PV), conversion, and storage technologies. We assess the cost of 100% self-sufficiency for both electricity and heat, comparing different technical configurations for a stylized neighborhood in Switzerland and juxtaposing these findings with projections on market and technology development. We then broaden the scope and vary the neighborhood's composition (residential share) and geographic position (along different latitudes). Regarding *how* to design self-sufficient neighborhoods, we find two promising technical configurations. The "PV-battery-hydrogen" configuration is projected to outperform a fossil-fueled and grid-connected reference configuration *when* energy prices increase by 2.5% annually and cost reductions in hydrogen-related technologies by a factor of 2 are achieved. The "PV-battery" configuration would allow achieving parity with the reference configuration sooner, at 21% cost reduction. Additionally, more cost-efficient deployment is found in neighborhoods *where* the end-use is small commercial or mixed and in regions *where* seasonal fluctuations are low and thus allow for reducing storage requirements.



1. INTRODUCTION

The energy sector has experienced a major shakeup in recent years because of the sharp decline in the cost of renewable generation technologies, in particular wind and solar photovoltaics (PV). The low variable costs and intermittent nature of renewable energy sources (RES) along with their deployment in decentralized settings by prosumers (i.e., agents that both produce and consume energy[1]), could pose significant challenges to the energy sector in general, and to the power sector in particular,[2,3] potentially undermining today's business models for utilities.[4−6] Decentralized production by RES disables the unidirectional grid flow and lowers the energy amount delivered by utilities, thus rendering many of their existing assets and capabilities obsolete, and requiring them to change their way of producing, distributing, and selling energy.[4,6,7]

The industry's shakeup could escalate to another level if prosumers at various levels—from building to neighborhood to district/region—are disconnected from a superordinate grid and operate fully self-sufficient units with RES.[8,9] Self-sufficiency brings a new value proposition to the market by satisfying the need for reliability/resilience, cleaner energy, and better economics, and by overcoming utility/grid frustration and regulatory changes.[8] Fully decoupled from the prevalent infrastructure, self-sufficient units could disrupt the current business logic of utilities and grid operators alike.[6,10,11] With partial self-sufficiency and the necessary grid connection, utilities retain their power to demand higher charges for grid access. With full self-sufficiency, however, the utilities' claim on grid access and power supply charges would lose its functional justification. As a result, infrastructure costs would need to be allocated to fewer customers, which would increase the grid costs per kilowatt hour delivered, an effect that would be reinforced as more and more units in the system became fully self-sufficient.

The essential technologies required for self-sufficiency in decentralized settings, i.e., RES and storage technologies, have experienced significant cost declines over the past decade. For instance, PV module prices decreased by about 70% between 2010 and 2014 and are soon likely to render solar PV profitable without subsidies.[12−14] These massive price declines, in turn, induce further deployment. Technological learning, that is, technology cost decreases with cumulative produced or installed capacity, can be observed for solar PV and is projected for battery storage in a similar vein.[15,16]

Few studies have investigated the conditions under which the concept of energy self-sufficiency could become a competitive

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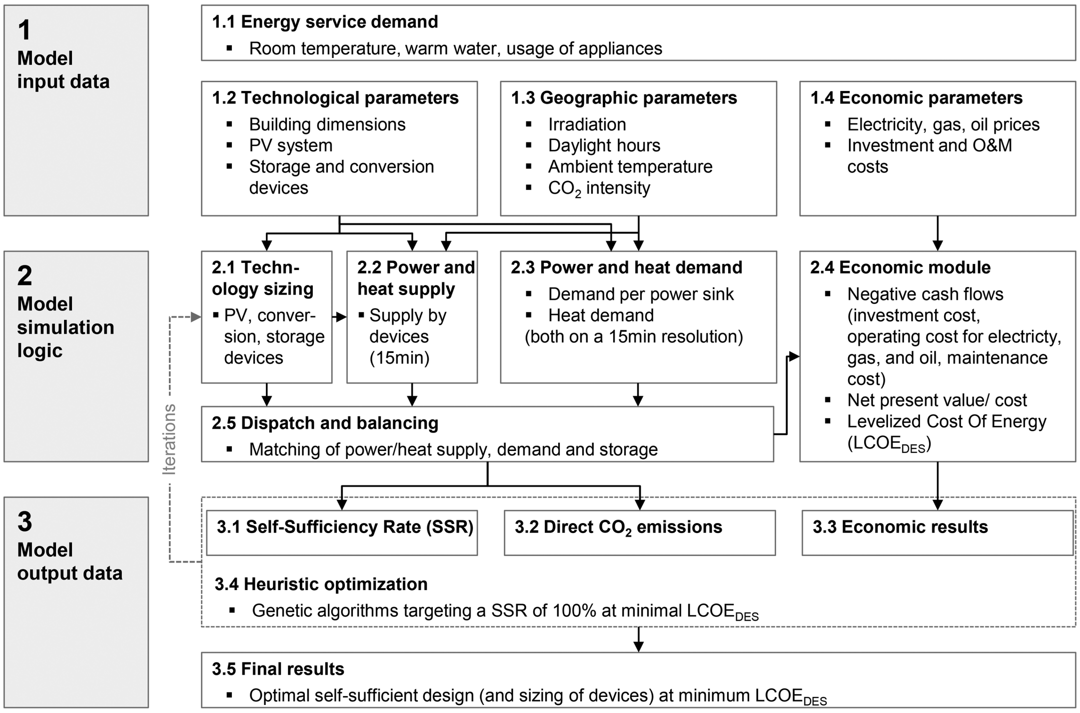

Figure 1. Structural overview of the techno-economic model. (Numbers refer to the subsections of the Supporting Information (SI), "techno-economic model" (A)).

alternative to the current paradigm of energy supply. Scholars have discussed the general concept of energy self-sufficiency (or *energy autarky*, *energy independence*, or *energy autonomy*) from various disciplines and perspectives.[17,18] The more specific idea of self-sufficient systems has been studied using different spatial perspectives (e.g., buildings to regions) and with varying technological or methodological scope.[19,20] At the same time, the economic performance of self-sufficient systems remains controversial,[21,22] especially as most studies analyze a particular site or case, i.e., a certain scale and location, or a given technological focus. A variety of pilot projects and initiatives for self-sufficient systems have already been implemented,[17,18] but they are oftentimes characterized by rationales other than purely economic and environmental ones.[18,23] However, there has not yet been a systematic study that examines how to equip these systems, at what point they would become economically feasible, and where to best apply them.

Our article addresses this gap in the literature on a more abstract level. We first evaluate *how* self-sufficient systems can be composed in a cost-efficient way and which technologies to employ. Second, we assess if and *when* these systems could become a viable alternative to a grid-connected reference. Third, we investigate *where* their deployment could be more cost-efficient due to different end-use and geographic factors, such as solar irradiation.

We evaluate a system in the context of small-size neighborhoods (i.e., residential and small office buildings) and undertake three types of analysis: (1) On the basis of a review of the literature and existing pilot projects, we conduct expert interviews to identify feasible technical configurations that are close to market introduction. We build on this to develop a techno-economic model to conduct a simulation for a stylized neighborhood in Switzerland. We assess its economic performance from an investor perspective for different technical configurations, including the selection of technologies and their optimal sizing. (2) We complement these findings by analyzing the effect of projected increases in energy prices and potential reductions in technology costs. In this way, we scrutinize their impact on the competitiveness of a self-sufficient neighborhood compared to an on-grid reference configuration. (3) In order to account for temperature- and irradiation-induced seasonality, we broaden the geographical scope by assessing the performance of the stylized neighborhood along varying latitudes. Furthermore, we adjust the composition of the neighborhood to cope with different forms of end-use, from residential to small commercial consumers.

The remainder of this article is structured as follows: Section 2 describes our methodology. We then present and discuss our results in section 3.

2. MATERIALS AND METHODS

2.1. Model Design and Logic. The challenge posed by seasonal and diurnal mismatches of local energy supply by RES to its consumption calls for flexibility measures, such as demand-side management or storage. In particular, storage technologies can cope with these mismatches by bridging the temporal gap and shifting energy from times of generation to times of actual use.[24] Moreover, the conversion of different energy carriers and their storage is considered promising.[19] In this way, a surplus from one energy carrier (e.g., electricity, gas) can compensate for a shortage from another by converting to the type of energy that is demanded at a particular time.

To determine the economic performance of different technical configurations, we developed a Matlab-based, techno-economic model that simulates an energy self-sufficient neighborhood, including the required capital investment and future cash flows. The model extends an existing PV self-consumption model by Lang et al.,[25,26] and can be structured into (1) input data, (2) simulation logic, and (3) output data, as shown in Figure 1.

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Table 1. Selection of Model-Related Parameters and Assumptions to Provide an Overview of Building, Technology, and Economic Information[a]

Building

	Parameter	Unit	SFH	MFH	SOB
Characteristics	L x W x H	m	10 x 7 x 6	20 x 9 x 14	22 x 15 x 10
	Number of stories	-	2	5	3
	Total floor area	m²	150	900	1000
	Window share	%	30	30	60
	Roof area	m²	80	180	330
	Number of people	-	4	20	90
Energy service demands	Power demand p.a.	MWh_{el}	3.0	19.1	49.4
	Heat demand p.a.	MWh_{th}	19.6	79.2	92.5
	Room temperature	°C	23		
	Hot water	liter	50-70 (at 60°C/person/day)		5-7
	Daily lighting	-	1223 Wh / day		76 Wh/m²
	Fridge/freezer	-	274 / 329 Wh/day/party		274 Wh/day
	ICT		1223 Wh /day		69.3 Wh/m²
	...				

Technology

	Parameter	Unit	Value
PV (cryst. silicon)	Angle Correction Factor	-	1.15
	Performance Ratio	%	20
	Module Efficiency	-	0.85
	Lifetime	a	10
Battery (Lithium-ion)	Capacity	kWh	10
	Power	kW	3.3
	Efficiency	%	92
	DoD	-	0.8
	Lifetime	a	10
	Cycle Lifetime	-	10,250
Fuel Cell (PEM)	Therm. Effic.	%	42
	Electr. Effic.	%	50
	Lifetime	a	15
	Cycle Lifetime	-	40,000
	...		

Economic

		Parameter	Unit	Value
Market parameters		Electricity Price	EUR/kWh	0.17
		Gas Price	EUR/kWh	0.07
		Oil Price	EUR/kWh	0.09
		Investment horizon	years	40
		Discount rate	%	7.0
Technology parameters	PV (cryst. silicon)	Investm. Cost	EUR/kW	451.57
		BOS	EUR/kW	901.89
		O&M Cost	%	1.5
	Battery (Li-ion)	Investm. Cost	EUR/kW	322.48
		BOS	EUR/kW	141.76
		O&M Cost	EUR/kW	20.66
	Fuel Cell (PEM)	Investm. Cost	EUR/kW	$= 6{,}506 \cdot P_{inst.}^{-0.18}$
		BOS	%	20
		O&M Cost	%	10
		...		

[a]The data is only an excerpt of the full range of information, which can be found in the SI.

On the input side, regarding the demand, the focus is on the neighborhood level. We consider mixed end-usage, i.e., a combination of residential and small commercial units, since they exhibit different demand patterns. Regarding technologies, we restrict our analysis to solar PV as RES technology because it can be easily deployed in buildings and decentralized settings and is considered the most cost competitive with further projected cost decreases.[27] Besides solar PV, building-related aspects and both storage and conversion devices complete the technological parameters. Geographic parameters (e.g., irradiation data, temperature) and economic parameters (e.g., energy prices, investment cost) complement the input side of the model.

Fed by all input parameters, the simulation of the model is initialized by the sizing of technologies (PV, conversion, storage) which then determines power and heat supply for every 15 min throughout a full year. In parallel, the neighborhood's temporal profiles for power and heat demand are simulated with the same timely resolution. Consequently, during the dispatch energy supply and demand are balanced on a 15 min basis throughout the year, where PV power is used to meet demand whenever available. The residual power, remaining demand or PV excess, is then provided or absorbed by the storage options. Following the dispatch, the economic module employs the concept of Levelized Costs of Energy (LCOE)[28] to compute the economic performance in an adapted approach of "Levelized Costs of Energy for Decentralized Energy Systems" ($LCOE_{DES}$). $LCOE_{DES}$ are defined as the total discounted costs of a decentralized energy system divided by its discounted energy demand. The $LCOE_{DES}$ comprise initial investment costs and cash flows (e.g., operations and maintenance (O&M), replacement costs) for generation, storage, and conversion technologies discounted over the investment period.

On the basis of a single full year simulation, the model derives three output indicators: Self-Sufficiency Rate (SSR), direct CO_2 emissions, and the costs of energy provision (in $LCOE_{DES}$). With the objective function of minimizing $LCOE_{DES}$ subject to a SSR of 100%, the model uses genetic algorithms to iteratively adapt the technology sizing, thus exploring an optimal solution. Genetic algorithms are applied because they qualify as a metaheuristic approach to coping with the complex problem of a nonlinear and highly multimodal objective function (see SI A3.4).[29,30] The optimal technology sizing and $LCOE_{DES}$ of the self-sufficient neighborhood are then displayed in the final results.

2.2. Context and Parametrization. The starting point for our evaluation is the techno-economic performance of a stylized neighborhood at the selected location of Bern, Switzerland. We chose the Swiss context due to its central location in Europe. In addition, the economic and political environment seems to favor innovative decentralized solutions, and a variety of pilot and lighthouse projects already exist in Switzerland. Later in the analysis, we broaden the geographical scope to examine the influence of seasonal fluctuation—in solar irradiation and ambient temperature—that shapes energy demand and power production.

We start our analysis by defining a stylized neighborhood that aggregates multiple buildings of three generic types, i.e., single-family houses (SFH), multifamily houses (MFH), and small office buildings (SOB).[25,26] In order to define a suitable composition, that is, mix of building types and end-use within the neighborhood, we evaluated a set of 56 global decentralized energy systems and analyzed the 20 certified Swiss "2000-Watt Sites."[31] Within the typical range of our project observations, our neighborhood is composed of three SFHs, three MFHs, and one SOB, with accumulated load profiles for each building type. The annual energy demand of this neighborhood, located in Bern, Switzerland, sums up to 115.5 MWh_{el} of electricity demand and 388.9 MWh_{th} of heat demand. Later in our analysis, we provide an additional step to begin widening the scope from this specific setup to explore the influence of the neighborhood's composition on the economic performance more generally by varying its ratio of residential to small office buildings (*where* question), an important factor as each type is differently suited to match local PV production.[26]

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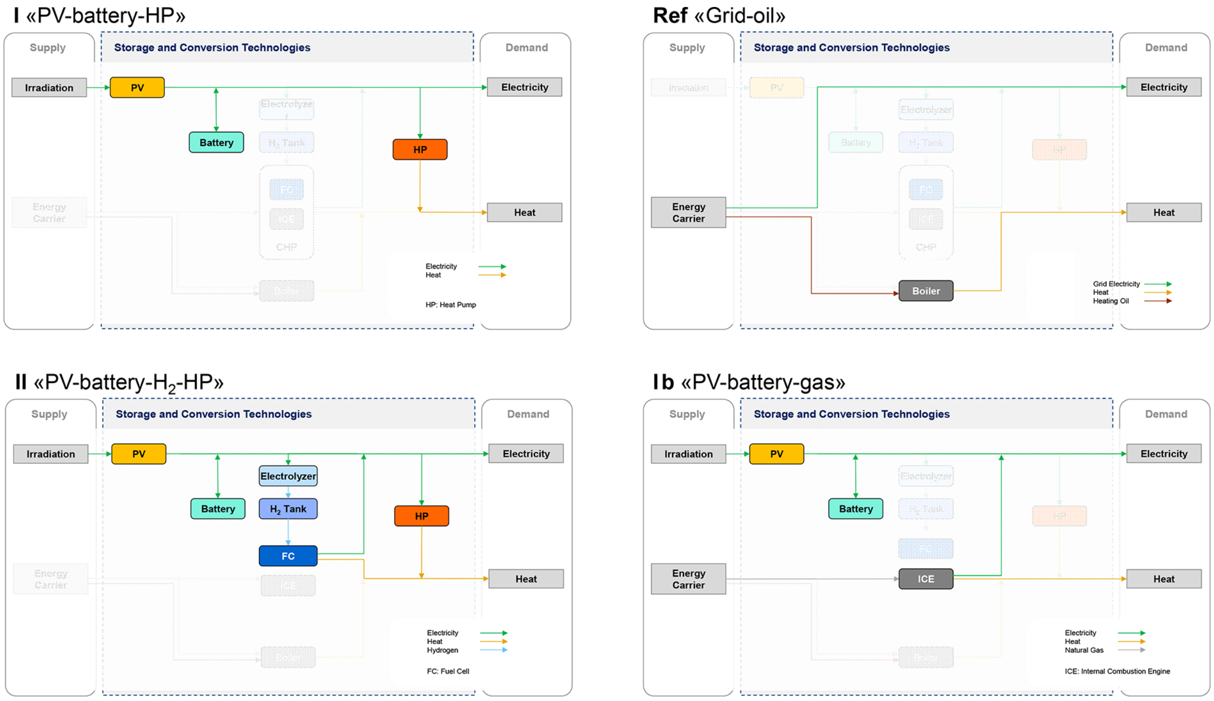


Figure 2. Overview of technical configurations (I, II, ref, Ib), their technical devices (i.e., storage and conversion technologies), and energy flows. (Acronyms: PV = Photovoltaics, HP = Heat Pump, H_2 = Hydrogen, FC = Fuel Cell, ICE = Internal Combustion Engine).

Each of the considered building types is mainly characterized by building-specific features, electric appliances and their usage patterns, room temperature, as well as the corresponding heat flows, which influence the calculation of electricity and heat demand. The model simulates synthetic load curves for electricity and heat for each building type on a 15 min resolution throughout a full year. The temporal demand profiles are based on the simulation of the building demands of the so-called "Household Model for Intelligent Energy supply and use (HoMIE)".[25,26,32] Technology data incorporates all operational parameters, such as efficiency or cycle lifetime, that are important to characterize the considered technologies. Economic data includes market prices for energy as well as the investment period and the discount rate (7%). The development of future energy prices is based on projections by the U.S. Department of Energy's Annual Energy Outlook 2015.[33] Economic assumptions for the technologies encompass upfront investment costs and O&M costs, as well as replacement costs for specific technologies with a shorter lifetime than the whole system's lifetime. Planning and installation expenses are excluded due to their site specificity. Table 1 provides an overview of selected model-related parameters and assumptions regarding building, technology, and economic information. The comprehensive set of assumptions is given in the SI (A 1.1−1.4).

On the supply side, local solar irradiation data are sourced from NASA for every quarter of an hour over a full year,[34] and subsequently used for the computation of available electricity yield by the solar PV plant. To account for a reference configuration, we include the option to source electricity from the local grid and to draw heating oil from a tank. As we aim to assess the general impact of seasonality (in the *where* question), we alter latitude-dependent environmental data, that is, irradiation,[34] temperature and daylight hours.[35]

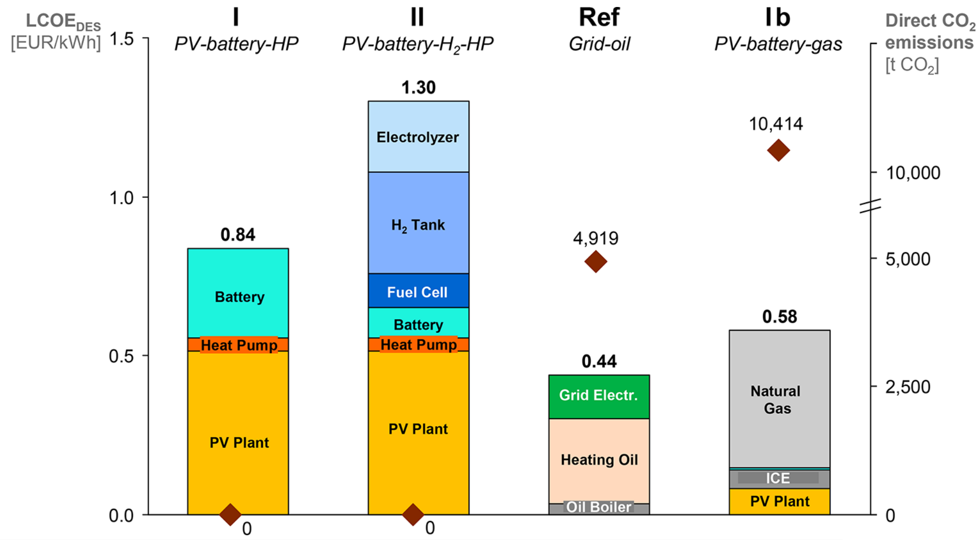
In addition to a literature-based approach for the parametrization of the model, we conducted 13 interviews with experts from academia and industry to (i) triangulate and validate specific assumptions, input parameters, and preliminary results, and (ii) distill interesting technical configurations for the analysis, i.e., addressing the *how* question (see SI "experts interviews" (B)). Apart from interviews, our modeling benefitted from close interaction and iterative development with academic experts on some of the individual technologies and their integration who partook in the research project.

3. RESULTS

We report and discuss *how* (3.1), *when* (3.2), and *where* (3.3) renewable energy self-sufficiency at the neighborhood level can become economically feasible and what alternative pathways are (3.4).

3.1. *How*: Examining Technical Configurations. On the basis of the existing literature and expert interviews, four technical configurations evolved for our analysis. Figure 2 displays these configurations, along with their technical devices and energy flows.

We identify two dominant configurations for achieving a fully independent, renewable self-sufficient energy supply at the neighborhood level. The first configuration ("PV-battery-HP") relies solely on batteries for storage technology and supplies the heat by means of a heat pump (HP). The second configuration ("PV-battery-H_2-HP") adds hydrogen (H_2) storage to complement the battery storage. The latter is a promising configuration that is observed in pilot projects and discussed in the literature,[36−40] and it splits storage requirements technically into diurnal and seasonal components. The *PV-battery-H_2-HP* configuration requires further technical devices, such as an electrolyzer to convert power to hydrogen, hydrogen storage tanks, and a fuel cell to reconvert hydrogen to electricity with heat as a byproduct. We compare the self-sufficient configurations to a conventional, grid-connected configuration, the reference one (ref "Grid-oil"). This



		I	II	Ref	Ib
Technologies	PV Plant [kW_p]	893	893	-	112
	HP / Boiler / ICE [kW_{th}]	111.5 (GS)	111.5 (GS)	111.5 (Boiler)	111.5 (ICE)
	Battery [kW]/ [kWh]	330 / 1100	111/ 370	-	9/ 30
	Electrolyzer [kW]	-	170 kW	-	-
	H_2 Tank [Nm^3]	-	191 Nm^3	-	-
	Fuel Cell [kW]	-	27 kW	-	-
System	Discount rate [%]	7	7	7	7
	System lifetime [years]	40	40	40	40
	SSR [%]	100	100	0	100[a]
	Mitigation cost [EUR/t CO_2][b]	216.21	466.12	-	-68.38

a Still, provision of natural gas needed, thus not considered as fully autarkic mode.
b Cost-effectiveness in terms of money per CO_2 emissions avoided compared to Ref.

Figure 3. $LCOE_{DES}$ split, direct CO_2 emissions, and technology sizing for the four technical configurations: I, II, ref, and Ib. (Acronyms: $LCOE_{DES}$ = Levelized Cost of Energy for Decentralized Energy Systems, PV = Photovoltaics, HP = Heat Pump, GS = Ground-Sourced, ICE = Internal Combustion Engine, H_2 = Hydrogen, SSR = Self-Sufficiency Rate).

configuration sources electricity from the grid and uses an oil-fired heating boiler, the predominant configuration in the existing Swiss building stock.

An alteration to the first configuration is Ib ("PV-battery-gas"), which has been discussed in the literature and practice in recent years.[41] It relies on a natural gas-based combined heat and power (CHP) solution that uses an internal combustion engine (ICE) to cosupply heat and electricity, and additionally benefits from a small battery to compensate for demand peaks. This configuration relies on the provision of natural gas, either by making use of an existing gas grid infrastructure, on-site production (e.g., biogas), or through its storage (e.g., tanks, caverns). Given its gas dependence, *PV-battery-gas* cannot be considered a fully autarkic configuration in the strict sense, which is why we report its results in this section but disregard it in the subsequent result sections.

Figure 3 presents the technology sizing of each technical configuration, as well as the $LCOE_{DES}$. It reveals that configurations I and II require both a high electricity supply by the PV plant and large storage capacities to cope with the typical Swiss seasonality of energy demand. Specifically, the large PV installation of 893 kW peak power, which exceeds the available rooftop area, is due to fulfilling the demand peaks during winter daylight hours from the PV plant. However, rising module efficiencies resulting in higher yields, combined with facades that contribute to solar gains via building-integrated PV and higher efficiency standards to lower the buildings' or neighborhood's overall energy demand, can alleviate this situation in the future. In configuration I, the battery system needs to be sized extensively to bridge the seasonal gap, thus accounting for about one-third of the total cost. Comparing $LCOE_{DES}$ of the two genuinely self-sufficient configurations (I and II) using commercially available technologies shows that both are more than twice as expensive as the reference configuration but produce zero direct CO_2 emissions (compared to ref and Ib). Moreover, the cost of *PV-battery-HP* is 35% lower than the hydrogen-based configuration. The PV power plant itself accounts for an important share of the total cost, with 61% (I) and 39% (II) respectively. In the hydrogen-based configuration, the storage and conversion technologies have higher costs than the PV plant and comprise the three main components of the hydrogen system: Hydrogen tank (25%), electrolyzer (17%), and fuel cell (8%).

From an economic perspective, the discount rate is an important factor with a strong impact on the overall performance. For the presented results, we chose a conservatively high discount rate (7%), which favors the reference configuration with its constant negative cash flows for energy purchase, both electricity and heating oil. A drop in the discount rate by two percentage points, for instance, improves the economic performance of configurations I and II compared to the reference configuration (factor 1.49, instead of 1.91, higher costs for configuration I than the reference configuration, and factor 2.36, instead of 2.97, for configuration II compared to the reference configuration). The most sensitive technology-related parameter is the investment cost, which has the highest impact on the economic performance. With a

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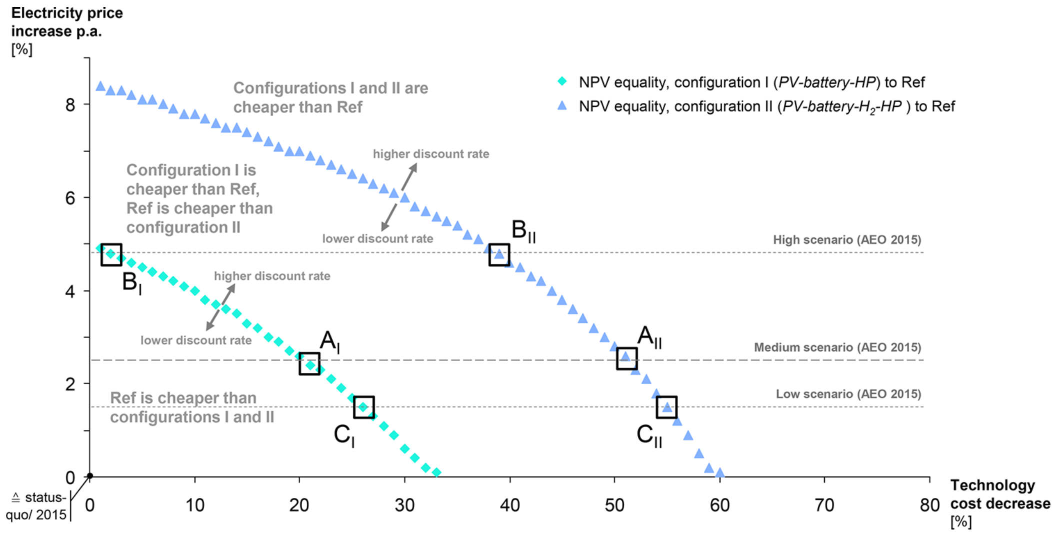

Figure 4. Indifference curve of ref to configuration I and ref to configuration II ($LCOE_{DES}$ equality) with development of technology costs (aggregated over all technical components) and electricity price. The oil price increase is set to AEO's medium scenario of 2.52% per annum. The underlying discount rate is set to 7%.

weaker overall effect, the technology lifetime is the second most sensitive technical parameter (see SI "sensitivity analysis" (C)).

Since the *PV-battery-HP* system exhibits lower costs than the *PV-battery-H_2-HP* system, cost-optimal sizing by the genetic algorithm results in zero component sizes for the hydrogen devices. Therefore, in configuration II, we assume a PV plant size identical to configuration I, and we limit the battery size to a capacity large enough to cope with diurnal fluctuations.

3.2. *When*: Investigating Technology and Market Development. Energy prices and technological learning are major factors that influence the point at which self-sufficient systems will become cheaper than the grid-connected reference configuration. On the one hand, energy prices strongly determine the cost of the reference configuration. These costs are prone to variation and could increase in the future because of rising electricity and fossil fuel prices or because of policy measures, such as environmental taxes or regulations. On the other hand, technological learning strongly affects the technology-intense configurations *PV-battery-HP* and *PV-battery-H_2-HP*, as solar PV, battery, and hydrogen technologies are the largest contributors to total costs for these configurations. Costs for all these technologies are expected to decline because of further technological learning (both learning by doing and learning by researching).[12,15,16,42−45]

Figure 4 illustrates how costs for the three configurations under consideration (I, II, and ref) depend on these two factors. Specifically, the indifference curve for both self-sufficient configurations I and II represents $LCOE_{DES}$ equality to the reference configuration. We find that self-sufficient configurations would become competitive under a medium energy price scenario (both for electricity and heating oil) of the Annual Energy Outlook (AEO)[33] and a decrease in technology costs by 21% for *PV-battery-HP* (see A_I) and 51% for *PV-battery-H_2-HP* (A_{II}) from 2015 cost levels. AEO's high electricity price scenario would render these two configurations competitive at even lower technology cost reductions of 2% for *PV-battery-HP* (B_I) and 39% for *PV-battery-H_2-HP* (B_{II}), whereas the AEO's low electricity price scenario would require technology cost reductions of 26% for *PV-battery-HP* (C_I) and 65% for *PV-battery-H_2-HP* (C_{II}), respectively. In general, such cost reductions are possible, as we briefly illustrate for AEO's medium scenario.

On the basis of projections from the scientific literature on annual learning rates—PV cost decreases of 5.5% per annum according to IRENA (International Renewable Energy Agency)[46] and 7% for the lithium-ion battery[15]—configuration I could achieve the required 21% in cost reduction (A_I in Figure 4) to draw level with the reference configuration within four years from start of operation. As hydrogen technologies are in an earlier phase of development, these cost projections are more challenging to make.[47] Still, cost parity with the reference configuration (51% cost reduction, see A_{II}) could be reached if technological learning during production combined with the use of the technologies translates into sufficient cost reductions. On the basis of estimated technological learning coefficients of 20% for the alkaline electrolyzer and the proton exchange membrane fuel cell, as well as 10% for the pressurized storage tanks, this would require an increase in cumulative deployed capacity by 2 orders of magnitude. Such a development seems plausible based on observations from technologies at similar maturity levels and might render hydrogen-based solutions cheaper than the *PV-battery-HP* configuration in the long run.[43,47−49] In addition to energy prices and technology costs, the discount rate also influences the indifference curve. As presented in Figure 4, the competitiveness of self-sufficiency systems is accelerated with lower discount rates and delayed with higher discount rates.

Figure 4 allows us to estimate the impact on the competitiveness of various other scenarios for increasing energy prices or decreasing technology costs. Among them, policy measures can promote or hinder the development of self-sufficient systems directly (e.g., technology push or demand pull measures[50]) or indirectly (e.g., increase in electricity price) by worsening the reference configuration. It is worth mentioning that the reference configuration might also enhance its own economic performance, e.g., via the sailing ship effect (efficiency gains in established boiler technology), through hybrid solutions (grid-connected PV prosumers), or by upgrading from fossil-based to state-of-the-art heating (heat pumps).

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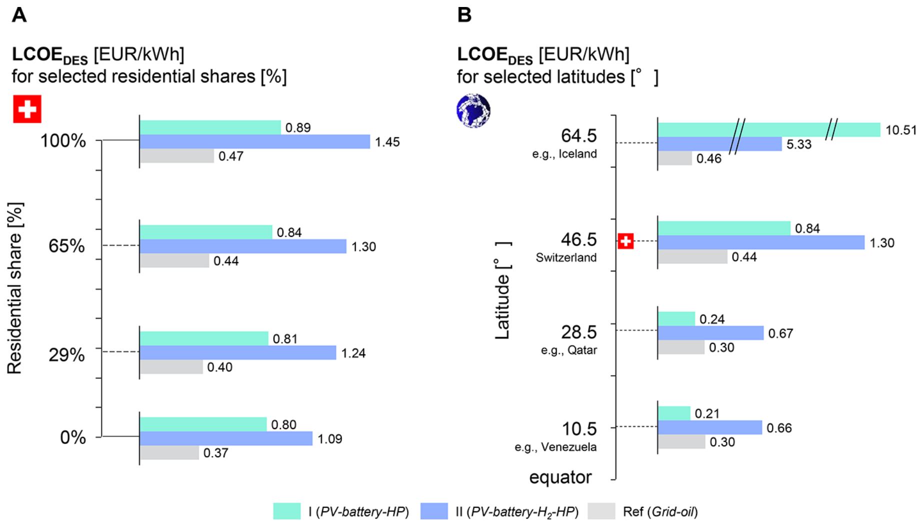

Figure 5. (A) Comparison of LCOE$_{DES}$ for configurations I, II, and ref at selected residential shares, by aggregating the three building types (SFH, MFH, SOB) to different combinations (100% = 7 SFHs + 4 MFHs, 65% = 3 SFHs+ 3 MFHs + 1 SOB, 29% = 3 SFHs + 1 MFH + 2 SOBs, 0% = 3 SOBs) at the location of Bern, Switzerland. (B) Comparison of LCOE$_{DES}$ for configurations I, II, and ref at selected latitudes in the Northern hemisphere (64.5° = Reykjavik, Iceland, 46.5° = Bern, Switzerland, 28.5° = Doha, Qatar, 10.5° = Caracas, Venezuela) for the stylized neighborhood of 3 SFHs, 3 MFHs, and 1 SOB.

3.3. *Where*: Exploring End-Use Composition and Seasonality. We examine the *where* question by changing (1) the neighborhood type and (2) the geographic location. First, we discuss the neighborhood type with respect to composition and size. We find purely commercial usage—in our case, small office-buildings—as the most suitable, as their load profiles exhibit higher overlap to PV generation profiles than a purely residential composition. This allows a reduction in peak capacity, and therefore lower costs for storage and conversion devices. Accordingly, mixed-use compositions exhibit lower costs than residential-only compositions. Size is another element of neighborhood type that has an economic impact. The larger the neighborhood size (within the scale of a low voltage, local distribution grid), the lower the LCOE$_{DES}$. This is due to two factors: (1) economies of scale in the procurement and maintenance of technology, and (2) leveling out of demand profiles for individual users. The latter is in line with previous studies that demonstrate the considerable impact demand profiles have on overall performance as a result of their effect on technical configuration and sizing.[51,52]

Second, the seasonal fluctuation exhibits a strong impact on the selection and sizing of technologies. We find that in locations with lower latitudes (equatorial areas) the seasonal influence is not prominent, which allows the battery to close short-term power deficiencies. By contrast, in regions with higher latitudes (toward the polar circles), strong seasonal fluctuations render the configuration of battery complemented by hydrogen storage (II) more cost-efficient at bridging the seasonal gap than the battery only configuration (I).

To account for both of these aspects, we calculated LCOE$_{DES}$ for the reference configuration *Grid-oil* and the two self-sufficient ones, *PV-battery-HP* and *PV-battery-H$_2$-HP*, at selected compositions [residential share in %] and latitudes [Northern latitude in °]. The results shown in Figure 5 point to a composition- and location-specific fit for each technical configuration, e.g., revealing small office and mixed-use as economically superior to solely residential applications (Figure 5A), and rendering *PV-battery-H$_2$* economically more attractive than *PV-battery* at latitudes with high seasonality, here 64.5° (Figure 5B). Beyond that, higher seasonality generally results in higher costs for running a neighborhood self-sufficiently.

The geographical application of this study is limited because economic parameters are not adjusted to a specific location (e.g., energy prices, regulations), which is why the relative trend of the results in Figure 5 is more meaningful and indicative than the absolute values for locations other than Switzerland. At the same time, while both generation and demand profiles are subject to seasonal variation of weather-related parameters (outside air temperature, solar irradiation, and daylight hours), the demand side is limited to the synthetic load profiles from the three generic building types. Future work would benefit from a more diverse portfolio on the demand side, scrutinizing different types of end-usage, especially for small commercial buildings other than office buildings, and taking measured load data instead of simulated loads into account due to their potential discrepancies.[53] Nevertheless, the results indicate where potential early implementations of these neighborhoods could be reasonable. Specifically, the road to self-sufficient systems—at least when the economic rationale is primary—will not be paved with single, purely residential buildings, but rather with larger neighborhoods in areas with lower seasonality that include commercial buildings.

3.4. Alternative Developments. In this section, we discuss potential alternative developments for the evaluated pathway. We have explored *how*, *when*, and *where* self-sufficient neighborhoods might disrupt the market by becoming cost-competitive with current baseline technology. Table 2 summarizes the main findings for these questions.

Battery and hydrogen storage-based configurations can be feasible and cost-effective self-sufficiency solutions. With technological learning and increasing energy prices, these solutions can become cost-competitive. This could occur even sooner for applications in areas with low seasonality (favoring the *PV-battery-HP* configuration) and small commercial to mixed end-usage.

However, potential alternative developments for the evaluated pathway also need to be discussed. At least in the short term, development of self-sufficient energy solutions will

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Table 2. Summary of Main Findings to How, When, and Where Questions

How			When	Where	
	Carrier	Technology	(under medium energy price scenario)	Location	Composition
I	Electricity, Heat	PV, Battery, HP	Cost competitive if and when technology costs decrease by 21%	Competitive in areas with little seasonality (low latitudes)	More cost-efficient with lower residential share and larger neighborhood size
II	Electricity, Heat, H_2	PV, Battery, HP, Electrolyzer, H_2 storage, Fuel Cell	Cost competitive if and when technology costs decrease by 51%	More competitive than I in areas with high seasonality (very high latitudes)	
Ref	Electricity, Heat, Oil	Boiler, Grid	Cost competitive at 2015 energy prices and technology costs	Cost competitive in areas with medium to high seasonality (medium to very high latitudes)	

differ from the outlined pathways because niche markets follow different rules. Given today's technology and energy costs, the pursuit of self-sufficient neighborhoods still comes at a high price. Total costs exceed reference costs by a factor of 2 to 3, depending on the technical configuration. Today, therefore, cost-competitive applications can be found in remote, rural, or island areas, where the high technology investments compensate for the cost of providing grid access and the space requirements for the PV plant and the respective storage technology are less rigid.[54,55] Additionally, on the adopter side, decision-making is not based exclusively on a purely economic rationale, but involves other motivations, such as overarching goals including environmental leadership, energy independence, or power reliability. Accordingly, we observed pilot projects in areas where cost-effectiveness does not hold but adopter preferences for a lighthouse project are high.[56,57]

While we evaluated fully self-sufficient solutions in this study, moving from negligible niches to a wider deployment of self-sufficient systems (buildings, neighborhoods, districts/regions) can be a multifaceted journey. Reaching fully autarkic, grid-disconnected solutions means progressing through various increments of self-sufficiency along the way. Today, there is a broad range of hybrid solutions in manifold combinations of diverse technologies, where prosumers can meet their energy supply demands for the most part autonomously and rely on the fallback power provision by the centralized grid only in rare cases.[20] This will be accelerated by the looming phase-out of feed-in tariffs and the resulting incentive to increase self-sufficiency rates. While regulatory issues may still restrict a community-based "self-supply" approach in some places, it is likely to gain momentum in the future because of entrepreneurial activities or progressive policy-making in other places (e.g., "self-consumption regulation" in Switzerland[58]). Moreover, the sectoral convergence (e.g., energy, transport, building) will affect future technology trajectories on the one hand, and overall system design on the other.[19,59] The extent to which these semi- and close-to self-sufficient systems challenge the existing paradigm of a centralized infrastructure remains to be determined, as does the question of whether fully autarkic, off-grid systems pose a more severe threat to this infrastructure. An important unknown is the potential reallocation of grid charges, which could push self-sufficiency on prosumers' agendas as a logical next step toward an independent energy supply.

It is also conceivable that, despite their radical characteristics, self-sufficient systems will not cause major disruption to the overall energy system if the industry and its main actors adapt and transform accordingly. Not least because of the high deployment rates and the technological trajectories of distributed RES (wind, PV), incumbent actors are starting to change their business models to cope with these developments. Among these innovations, new pricing schemes (e.g., charging a premium for providing back-up capacity) and the buildup of system integrator capabilities (i.e., mastering the integration of different energy services, technologies, and adjacent markets) are likely to play a role. Assuming a gradual shift over time, self-sufficient systems may not cause a major upheaval in the energy landscape and industry.

Interesting avenues for further research can be identified for both the competitiveness and disruptive potential of self-sufficient solutions. In terms of cost-competitiveness, quantifying and determining the relative profitability of various increments of self-sufficiency—below the full autarkic, off-grid 100% self-sufficiency rate—and the model expansion by further technologies (RES, storage) are of high interest for future work. Beyond that, potential additional benefits of these technologies, such as higher reliability of supply, reduced environmental impact and increases in the connected buildings' property value, need further evaluation.

Additionally, overall implications for the existing infrastructure, as well as societal effects triggered by a higher diffusion of truly self-sufficient systems, need to be thoroughly assessed to give business and policy makers a basis for deciding on the *if* and the *how* of their potential support.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.est.7b02686.

(A) Techno-economic model (1. model input data, 2. model simulation logic, and 3. model output data), (B) expert interviews, and (C) sensitivity analysis (PDF)

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Notes

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