SEAMS: an alternative techno-economic system to foster the sustainable development of renewable energy use in urban areas

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Abstract. To foster the sustainable development of renewable energy use in urban areas, we define an alternative, reciprocity-based, techno-economic system named SEAMS (“sharing energy amongst adjacent buildings”). We demonstrate its relevance through a statistical analysis of linear heat density across coastal cities from Northwestern mainland France, and a comparison of four implementations of three techno-economic systems within the perimeter of two adjacent building blocks, located in the city center of Lorient (Brittany). The SEAMS approach promises to address the multidimensional fragility issues currently surfacing with the conventional, market-based or redistribution-based, techno-economic systems, namely electricity and gas networks (EGN) or district heating and cooling networks (DHCN).

1. Introduction
Urban areas are now confronted with an ever-growing number of challenges and local authorities are actively looking for broader, deeper and faster ways to reach the United Nations’ sustainable development goals. However, current policies are often guided on beliefs of gradual change, while increasing scientific evidence of possible state shifts of the Earth System is surfacing [17], thus emphasizing the need for a major update of both techno-economic, socio-technical and political perspectives [4].

1.1. Dealing with multidimensional fragility
Over the 21st century, under the influence of climate change, damage to energy, transport, industrial, and social critical infrastructures is expected to multiply ten-fold in Europe [7]. Increasing complexity of systems, incentives for efficiency over robustness, path dependence, tight coupling and many other factors lead to multidimensional fragility [11], defined by the OECD as “the combination of exposure to risk and the insufficient coping capacity of the state, system and/or communities to manage, absorb and mitigate those risks” [5].

Many human-made systems, such as energy networks, are inherently fragile, while constituting core components of modern critical infrastructures. Technical fragility has been studied on electricity grids and is linked to spatially embedded [2], local topologic and geometric features such as network motifs [6], rather than global network characteristics. Economic fragility has been studied on district heating networks and stems from unbalanced value creation mechanisms [16] and a strong dependence...
to large-scale deployment, involving many stakeholders, for long-term financial viability [12]. There is a need for an alternative techno-economic system helping to reduce multidimensional fragility and to deliver climate change mitigation/adaptation “by design”.

1.2. Fostering onsite renewable energy
Within city blocks, buildings have access onsite to plenty of renewable energy sources, in particular solar heat, either directly through thermal collectors or indirectly through heat pumps, but also solar electricity [9] and waste heat recovered from wastewater and other urban processes [18]. However, these energy sources are often easily accessible to some buildings, but not to their neighbors, and their inhomogeneous abundance hinders their harvest, without organizing cost-effective heat storage [3] and electrical/thermal energy exchange amongst adjacent buildings [15].

Even though heating and cooling demand can often be covered completely at the block-level with onsite thermal energy sources, relying on conventional distribution grids to foster their use does not address techno-economic fragility issues [19], and this might explain why these urban renewable sources, while having high potential, are currently underdeveloped in cities. Thermal energy storage (TES) exhibiting the highest level of energy storage security [1], it could be a key component of a decentralized, small-scale, heterogeneous, adaptable and modular approach to foster onsite renewable energy use by neighboring buildings.

1.3. Mainstreaming energy reciprocity
Following Polanyi’s terminology [14], buildings are currently mostly relying on three economic systems to have access to electrical or thermal energy: autarky (“householding”), e.g. self-supply via solar electrical/thermal collectors on roof; market, e.g. competing transactions over electricity and gas networks (EGN); redistribution, e.g. long-term contracts with district heating and cooling networks (DHCN). However, these three economic systems are facing several hurdles, thus preventing buildings from efficiently sharing onsite renewable energy: (i) autarky implies a strong correlation between onsite energy supply and building need, therefore often preventing the full realization of the building’s energy supply/storage potential and the creation of new revenue streams beyond the rental of floor space; (ii) market (resp. redistribution) is dependent on high investment in development and maintenance of EGN (resp. DHCN) infrastructure, with renewable energy integration constrained by network equilibrium requirements and often insufficient built-in resilience capabilities, in particular through energy storage.

In consequence, this study aims at demonstrating the deep relevance for urban areas of the fourth and last economic system mentioned by Polanyi: reciprocity, e.g. reciprocal exchange of energy supply, storage or demand resources between neighboring buildings, potentially without financial transactions. Beyond the conventional, market-based or redistribution-based, techno-economic systems, namely EGN or DHCN, we therefore suggest an alternative, reciprocity-based one and name it SEAMS (“sharing energy amongst adjacent buildings”).

Our study of the SEAMS techno-economic system is divided into two parts: first, a practical demonstration of the need, using an existing heat density dataset; second, a theoretical comparison of key indicators, obtained by simulating variants of the EGN, DHCN and SEAMS techno-economic systems on existing building blocks. The paper is organized as follows: Section 2 presents our data analysis and simulation models; Section 3 summarizes the results obtained and discusses their support for the main hypotheses; Section 4 concludes on applications and possible extensions.

2. Methods and data
We start our study with a statistical analysis of linear heat density across French cities on the Atlantic and Channel coasts. During Spring 2020, data from 2605 (resp. 236) homogeneous heat density paths, located in the Northwestern mainland France (resp. Greater Lorient) geographical area, were accessed on the Via Sèva website. Paths were presented on detailed interactive maps together with their linear heat density, allowing us to measure their total length, and therefore to compute their total heat load.
In order to emphasize coastal mitigation/adaptation opportunities, we considered only paths located less than 1 km from the coastline, except for the Greater Lorient area, where the entire dataset was retained. In practice, this filtering did not seem to have an influence on our statistical analysis, whose results are presented in Table 1.

We continue our study by comparing four implementations of the three EGN, DHCN and SEAMS techno-economic systems within the perimeter of two adjacent building blocks, one made up of a school (3300 m²) and the other of commercial (7000 m²) and residential (7500 m²) buildings with small shops on the ground floor. While this site exhibits the characteristics of the Collège Brizeux site, located next to a marina in the city center of Lorient, the buildings’ models were reused from previous optimization studies conducted with the Pleiades software suite, due to time and budget constraints. We simulated energy sources/sinks and made realistic additive/subtractive assumptions to take into account energy exchange and storage in/between buildings. Technical and economic calculation procedures were performed according to the standards ISO 52016 and EN 15459. Regarding energy demand, we considered only heating, cooling and domestic hot water (DHW) uses, all buildings complying with the French RT2012 insulation standard and relying on the same water-based energy distribution. We excluded from the study the electricity demand for other uses (e.g. ventilation, lighting, computing) by assuming this relatively constant share of the total energy demand is managed onsite by a French “collective self-consumption” contract, allowing building owners to exchange PV electricity over the already existing local public grid.

Four implementations of the EGN, DHCN and SEAMS approaches were considered. For each of them, we describe its “system case” and the main characteristics of its onsite energy network, in particular its multidimensional fragility, by analogy with their computer network equivalent, as illustrated on Figure 1. Variant 1 is a conventional EGN reference with gas boilers for the school and apartments and reversible air-source heat pumps for the offices; it relies entirely upon the fragile tree topology of conventional electricity and gas grids. Variant 2 is a low-carbon EGN option with ground-source heat pumps equipped with 20, 60 and 55 boreholes on the school’s, apartments’ and offices’ plot respectively, plus gas backups everywhere and ground-source cooling for offices only; it exhibits the same fragility dimensions as Variant 1. Variant 3 is a fourth-generation DHCN choice with district heating everywhere and district cooling for offices only; it relies entirely upon the fragile bus/ring topology of conventional district heating and cooling grids. Variant 4 is a SEAMS design with ground-source heat pumps everywhere, equipped with 25 boreholes on the school’s plot only, large-scale solar thermal

| Category name | Category count | Category share | Total length (km) | Median heat density (MWh m⁻¹ yr⁻¹) | Total heat load (GWh yr⁻¹) | Total heat load share |
|---------------|----------------|----------------|------------------|-----------------------------------|--------------------------|----------------------|
| Intrablock    | 1901           | 73%            | 211              | 3.7                               | 1432                     | 45%                  |
| Interblock    | 613            | 24%            | 247              | 3.1                               | 1310                     | 41%                  |
| District      | 91             | 3%             | 98               | 2.6                               | 439                      | 14%                  |

Table 1. Statistical analysis of linear heat density across urban areas from Northwestern mainland France. Linear heat densities are sorted into 3 categories, according to the lengths of the corresponding homogeneous heat density paths: intrablock (less than 250-meter long), interblock (between 250- and 750-meter long) and district (equal to or more than 750-meter long), referring to classical urban morphology features.

Figure 1. Analogy between four physical topology types of computer networks and those of the three techno-economic systems described in this study. The point-to-point/mesh network topology corresponding to SEAMS is particularly able to satisfy short-distance needs without relying on expensive space-filling curve patterns. This topology also addresses in part the multidimensional fragility issues that go along with the star-bus a.k.a. tree (resp. bus/ring) network topology corresponding to EGN (resp. DHCN). Graphics are courtesy of Wikimedia Commons.
installations of 120 m² and 1000 m² on the school’s and apartments’ roofs respectively, mostly for DHW, with excess heat from solar thermal collectors, and waste heat from offices’ cooling sources, partly stored underground; this design is entirely different from a fifth-generation DHCN one, since there is no thermal loop at ambient temperature but a mesh of point-to-point thermal connections with varying temperature levels, according to usage and storage requirements; it relies upon a robust mesh topology, instead of a fragile bus/ring one, for onsite thermal energy distribution, and minimizes its dependence on the fragile tree topology of the conventional electricity grid for thermal energy supply.

3. Results and discussion

In the first part of our study, we conclude from the analysis of Via Sèva data presented in Table 1 that nearly 90% of the relevant homogenous heat density paths are of intrablock/interblock length, i.e. shorter than 750 m, while roughly 50% of the total heat consumption is gathered into intrablock-sized paths, i.e. shorter than 250 m. Therefore, we make the hypothesis that addressing the heating and cooling needs of the buildings located along those paths will call for a different approach, emphasizing small-scale connectivity, as in SEAMS, instead of considering them as fully independent by default, as the EGN approach does, or fully connected on a large-scale, as required by the DHCN approach.

In the second part of our study, the comparison of the key indicators presented in Table 2 strongly suggest that, while the LCOE and carbon abatement cost of the SEAMS techno-economic system are competitive with the LCEGN (resp. DHCN) ones, when taking into consideration not only its decarbonisation efficiency of +467% (resp. +2500%), but also its peak shaving capability of +335% (resp. +572%), it delivers more value overall. Our hypothesis is that beyond energy sufficiency, measured using the imported energy indicator as proxy, for which SEAMS ranks again first, peak demand sufficiency should also be carefully considered, since peak demand has a direct influence on energy networks’ sizing, the related CAPEX and OPEX of these critical and climate-sensitive infrastructures, and in the end the evolution of the price of network energy.

Therefore, we decided to perform for each variant an analysis of the overshoot frequency of network demand thresholds. In fact, frequency analysis of rare events with important consequences seems more relevant for describing the evolution of unstable dynamic systems than conventional comparison of maxima or averages [13]. Results presented in Figure 2 stress clearly the different types of offsite network dependency: SEAMS is weakly coupled, LCEGN (resp. CEGN) is partially coupled.
for high (resp. low) demand thresholds, DHCN is strongly coupled. This analysis demonstrates the benefits of the SEAMS approach in removing from the energy networks the burden of managing surges in demand, therefore meeting the “smart grid challenge” not by enforcing stricter and costlier monitoring and control, but by loosening the probably unsustainable coupling between network demand and site need, still required by the EGN and DHCN approaches. By taking these observations one step further, we could define for future studies the multidimensional fragility footprint as an evaluation of the risk exposure of a given techno-economic system variant to various types of breakdowns (e.g. technical, economic, governance), together with an estimate of their associated costs.

Taking into account the results from the first and second part of our study, we could sketch an explanation of the overall efficiency of the SEAMS approach by describing some of its system design principles: (i) buildings require large amounts of thermal energy, this form of energy is expensive to distribute over long distances but can be stored efficiently on the supply site in many different ways, from concrete floors to water tanks and boreholes; (ii) thermal energy is abundant in urban areas, since most built surfaces, from streets to building façades and roofs, behave as solar thermal collectors, and waste heat is a common byproduct of many local activities; (iii) intrablock/interblock needs trigger reciprocal exchange of energy resources, either demand, supply or storage, and unused spaces (collector surface on the roof, storage volume in the basement or under the pavement) can be transformed into assets with immediate valuation; (iv) as mentioned in Figure 1, a mesh network topology is robust and adaptive, fostering endogenous growth and step-by-step innovation.

4. Conclusion and future work
We started this study with the ambition of developing an urban energy system, at the building- and block-level, able to withstand the escalating impacts of climate extremes. We then realized that the conventional techno-economic systems, namely EGN and DHCN, were in fact delivering suboptimal results when considering them from a multidimensional fragility perspective. We introduced SEAMS, an alternative techno-economic system, which strives to address this issue and at the same time foster the decentralized supply of zero-emission renewable energy, relying on onsite sources. The SEAMS approach successfully demonstrated its ability to: (i) be cost-competitive with both the low-carbon EGN and fourth-generation DHCN ones; (ii) reach Paris Agreement-compatible energy sufficiency
and decarbonization targets; (iii) lower the overall demand on the local public electricity grid, thus reducing the risk of power outage and requiring no reinforcement of this critical infrastructure. These benefits were obtained thanks to the extensive onsite recovery and storage of solar and waste heat.

In the future, several other questions could be worth investigating regarding the SEAMS approach, in particular: ensuring with better heat storage a “graceful degradation” of the quality of service in case of public grid failure; investigating how benefits at the block-level could translate into benefits at the city-level when the mesh of point-to-point connections spread between blocks. We are convinced that the SEAMS approach could potentially bring in many benefits in fragile contexts, thus promising to improve both climate change mitigation/adaptation and territory resilience of urban areas.

**Author contributions.** DB initiated the research, conducted the linear heat density analysis and wrote most parts of the article. PC provided data and feedback. FA conducted the detailed site analysis, supervised simulations and produced most of the figures.

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