Renewable and Sustainable Energy Reviews 161 (2022) 112388

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

# Factors and actions for the sustainability of the residential sector. The nexus of energy, materials, space, and time use

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ARTICLE INFO

*Keywords:*
Household metabolism
Nexus
Social innovation
Sufficiency
Energy efficiency
Construction sector

ABSTRACT

Residential end-uses represent a significant share of final energy consumption and material stocks. However, approaching sustainability of the residential sector merely as an environmental technical problem is insufficient. Home is the center of daily life providing essential functions to people. Household metabolism is not a matter of the sum of individual behaviors, typologies of buildings, or energy uses stripped out of context, but the system that emerges from the historical combination of these elements and the functions it performs. The residential sector comprises both families (units of organized individuals) and dwellings (within municipalities/urban forms). To analyze these dynamics, we draw upon practice theory and Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism (MuSIASEM) illustrating with data from Sweden and Spain in 2015. The objective is to establish an interdisciplinary framework for analyzing the sustainability of the residential sector. We also present a list of possible measures and their trade-offs in diverse dimensions: energy carrier consumption and greenhouse gas emissions, materials, floor area, human activity, social organization and institutions, finance and desirability. Even though the inclusion of all variables in a single model is not feasible, the holistic understanding of household metabolism can help build coherent anticipation scenarios by selecting plausible hypotheses. Ultimately, this allows making profound transformations to sustainability.

## 1. Introduction

Dwellings are a central part of daily lives and where we spend most of our time. They represent a big share of the in-use material stocks, greenhouse gas emissions, and final energy carrier consumption [1,2]. These large impacts but at the same time essential function generate great policy interest in improving its sustainability. In the European Union, it has resulted in diverse directives and initiatives approaching mainly its technical side: the Renovation wave for Europe, the New European Bauhaus, and the Energy Performance of Buildings Directive.

This interest is also reflected in a large and growing literature. Many methods, scopes, and dimensions to analyze the housing stock or buildings coexist, which can be divided in broad terms into social sciences and engineering. Swan and Ugursal [3] and Kavgic et al. [4] reviewed and classified models for residential energy consumption and Langevin et al. [5] updated Swan and Ugursal's classification. Even though each field irremediably includes aspects of the other, largely are only briefly mentioned, and truly interdisciplinary approaches are lacking.

Plain technological assessments assume given standardized needs. In many cases, they reduce the problem to the thermal performance. They analyze the artifact, i.e., the envelope and heating devices, but not its whole diversity of functions and contexts. Even though in most northern EU countries heating is the largest energy end-use in households, the functions and use of appliances become essential when analyzing sustainability and wellbeing. Governments and companies have put significant effort into decreasing energy use within the framework of technical energy efficiency. However, defining theoretically sound operational definitions of energy efficiency is not possible [6–8]. One of the most common definitions is spending less energy on the same service. Generally, the definition of service is not questioned, overlooking alternative solutions [9,10]. Yet existent technical solutions for sustainability are even acknowledged to be not enough [11–14]. Some models assessing housing stock development in time do include some social factors like occupancy or area per inhabitant. When they are included in models, these are generally more impactful changes than energy retrofits [14–19], but the compatibility with social dynamics has not been fully assessed yet. Therefore, understanding what home is, its

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https://doi.org/10.1016/j.rser.2022.112388
Received 25 July 2021; Received in revised form 24 February 2022; Accepted 16 March 2022
Available online 5 April 2022
1364-0321/

functions, and its relation to technical issues becomes essential.

On the other side, econometric models are the most commonly used approach the sustainability of the residential sector [20]. Econometrical or agent-based analyses are grounded on rationality, giving centrality to price signals and individual behavior. Yet the voluntaristic change of consumer choices is constrained by the option space framed by society. Daily life is neither made by a set of discretional individual actions nor determined solely by infrastructure. Therefore, it depends on the organizational and institutional systems and hardware of wires, pipes, and power plants: practices are socially ordered [21]. This means that daily life can be carried out in a variety of possible patterns of actions [22]. These must be coherent in their time use, family needs and duties, culture, existent infrastructure, and available external services.

Even though a case-by-case analysis of each building to assess its condition and possible refurbishment plays a key role, the mere sum of individual solutions will not necessarily increase sustainability. Solutions need to be scalable and coordinated in time and space. It is essential to have a broad overview of the combination of families (as institutions of meaning and competences, and as bodies with different characteristics) and dwelling stocks (technologies conformed by material elements heir to preterit practices). These systems have large inertia and thus changes are progressive. This large-scale perspective is useful for a variety of issues: the activities carried out by households and their insertion in daily lives, what should society do with existing housing, the need (or not) for its expansion, and how to maintain and build it.

It is not only the scale of analysis but also the multidimensional character of the residential sector that is important. When addressing sustainability issues and policy, it is unavoidable to face "wicked problems" [23], in which many relevant perspectives and non-equivalent dimensions coexist. They should be considered simultaneously because there are incompatibilities between goals. This unavoidable existence of conflicting criteria of performance makes that there is no optimal answer to social problems. Only when considering both the large-scale and multidimensionality, transformative solutions can be proposed for a democratic discussion, acknowledging the possible trade-offs and uncertainties.

Mata et al. [20] made a review of the most significant variables in models for energy and CO2 emissions studied in the literature for the residential sector. Mata et al. [24] made a review on non-technological and behavioral options for decarbonizing buildings. Hertwich et al. [25] also listed a set of strategies in the framework of material efficiency for buildings. However, a truly integrative perspective to the diversity and trade-offs of variables from both social and technological approaches in the residential sector is lacking.

The objective of this paper is to unravel the tight entanglement between social and technological issues in household metabolism and to explore possible actions for increasing sustainability of the residential sector. We analyze their trade-offs between a large variety of dimensions, focusing on the relation of the use of time, space, energy, and materials. To do so, we build on concepts from practice theory [21,26] and Multi-Scale Integrated Assessment System of Accounting (MuSIASEM) [27]. Throughout the paper, we detail points to consider in the analysis and possible actions to increase sustainability belonging to: (i) changes of social practices (adopted by the households, but only if an appropriate context is available) and (ii) technological improvements (applied to structural elements associated with the dwellings). They are summarized in Tables 1 and 2 (numbered for ease of reference in the body of the paper), including their effects on energy, greenhouse gas emissions, space, materials, time use, social organization, and desirability. Understanding these dynamics is essential to make plausible scenarios in models and effective policies.

We complement the explanations with data from Sweden and Spain in 2015. Sweden and Spain are both European countries but have significant differences in types of dwelling, income, and the organization of care [28], and thus in daily life patterns. Most of the included literature is referred to western countries. In this sense, ideas might be applicable to other contexts, but the analysis is centered in developed countries with a large amount of built environment and in this specific time in history. Homes have changed profoundly through the XXth century both in terms of size and types.

In section 2, we describe the theoretical frameworks where the rest of the paper is grounded: MuSIASEM and practice theory. Then, we define the residential sector as the combination of families or household units and dwellings. Afterwards, we explain the main dynamics of each of them in sections 4 and 5. Despite this organization in sections, it is impossible to isolate completely the topics, since their dynamics are entangled and co-evolve. In section 4, we analyze the members' composition and functions of families and put the focus on their time use patterns. In section 5, we present the housing stock, the social and technical issues affecting its use, performance, reproduction, and resource use. We also assess the economic role of the construction and real estate sectors. Finally, we present the main conclusions.

## 2. MuSIASEM and practice theory

MuSIASEM is a system of accounting to analyze societies and systems in a multi-dimensional and multi-scalar way that is based on Georgescu-Roegen's fund-flow scheme [29,30]. Funds sustain the activities of the society and must be reproduced. They are considered to remain the same during the period of analysis and define the size of the system. In this case, we consider human activity (in hours per year), floor area (in $m^2$, the space devoted to housing), and power capacity (in W, the power of devices and appliances).

Human Activity is a central variable of the social side of the residential sector: household units, who must manage their budget of time to fulfill their needs and duties. On the other hand, the most technological side of the residential sector (dwellings) is defined by the Floor Area and the Power Capacity. As we will see in the next sections, these dimensions are in fact connected.

When we talk of dwellings, we do not refer to a static monolithic structure. They consist of different parts or layers of different levels of flexibility and lifetimes (site, structure, skin, services, space plan, and stuff) [31,32]. Here we divide them into the two main funds, considering their broad functions and partaking artifacts: Floor Area and Power Capacity. The structure and envelope of buildings define Floor Area (in $m^2$) and are built in the construction sector (section 5.5.). Floor Area is a key variable for desirability and resource uses (materials, land use, energy, GHG emissions, etc.). Dwellings are full of an ever-increasing number and variety of appliances that carry out functions and/or reduce the required time and effort to perform them by metabolizing energy carriers, the Power Capacity (in W) [33]. The size, access, and use of these funds are key to understanding the performance of the residential sector. On the other hand, flows are those inputs and outputs that are metabolized or generated by the funds: GHG emissions, energy carriers, materials, etc.

A characterization of the metabolic pattern in terms of flow-fund relations allows an integrated analysis of the use of human time, energy, and materials inside the functional and structural elements operating in the residential sector. An overview of the set of relations considered to integrate the different quantitative assessments of the residential sector is given in Fig. 1. There it is possible to see how the concept of metabolism – i.e., forced relations over flows and fund elements within a metabolic pattern having the goal to reproduce the whole metabolic system – can be used to integrate information and indicators calculated using different metrics – flows per hour of Human Activity and flows per square meter of Floor Area or watt of Power Capacity.

Practice theory connects the use of time and daily patterns of people to the existent infrastructure and knowledge. Both societal patterns and technology are tightly linked. Practice theory defines the following elements: material elements, competence, and meaning [21]. The time uses require building competence (skill, know-how, technique) through

**Table 1**
Actions to increase sustainability of the residential sector at the household unit dimension (social innovation) and effects on diverse variables.

| Families/household units | | | Possible effects and trade-offs | | | | |
|---|---|---|---|---|---|---|---|
| | Action | Examples | Energy and GHG emissions | | Floor area, power capacity and materials | Human activity | Social organization and desirability |
| | | | Operational | Production | | | |
| Shareability and economies of scale. | (1.1) Increase household size: larger occupation. | Families living together for longer, avoiding individual households, transforming household units to larger multi-family units with common spaces and activities. | Decrease with economies of scale. Shared activities entail shared energy use.<br>If people live together but still do not commit to common activities (e.g., cooking), the operational resource use might not decrease significantly. | Decrease due to shared spaces (kitchen, bathroom), infrastructure, and devices. | Fewer dwellings, larger but relatively smaller.Basic services like kitchen and bathroom and many other devices are shared so less space per capita is needed.<br>Compatibility with current dwelling stock must be checked: number of rooms, size, etc. | Less overall time use if activities are shared (cooking, household maintenance, etc.) but larger synchronization and coordination. | Social acceptance of new family types and/or living in a community.<br>Requirement of organization and commitment (less individualism and loneliness, but potentially more conflicts). Purchasing power within the market enables individualization. . |
| | (1.2) Shifting activities from the household to the community or market. | Cooking in community kitchens or restaurants, organized childcare, product-service systems. | Less energy per unit of service (economies of scale). | Decrease (fewer devices are needed). | Fewer but larger devices are required. More collective space is required at expense of privative space (with economies of scale). This kind of space might lack in existent buildings. | Increase time in collective activities and/or requirement to give salaries if they are considered paid work. Potential economies of scale and quality improvement by specialization of work. | Requirement of organization and commitment in communities, or significant changes in companies from product to service provision.<br><br>Cultural change on how needs are fulfilled. Requirement of density of demand for providing the service at scale, related to the type of municipality and urban form. |
| | (1.3) Sharing the use/service of power capacity. | Carpooling, cooking for the whole household unit. | Less energy in use per unit of service. | Decrease (fewer devices are needed). | Fewer devices are needed. | Time of the device use is shared but it requires strong time-space synchronization with others. | Tight organization: less individual flexibility and more commitment to schedules. |
| | (1.4) Share power capacity. | Carsharing,laundry rooms in apartment buildings, tool libraries | Possibility to have better or more diversity of devices due to shared cost and to update their characteristics more often due to its more intensive use and thus shorter lifetime. | Decrease, but devices may be used less carefully, shortening their lifetime. | Fewer devices are required.<br>Less space is required at home but alternative common spaces to store those devices must be found. | No immediate access to devices. Sometimes devices are needed at the same time so their utilization factor cannot increase (e.g., special or larger cooking devices for Christmas or car use for commuting). | Requirement of organization and rules (less flexibility) and commitment to care for common devices.<br>The social distinction given by the ownership of devices might disappear when sharing. |
| Flexibility of time and level of services. | (1.5) Decrease quantitative or qualitative expectations of activities. | Lower indoor temperature in winter and higher in summer, not washing clothes every time they are used, simpler food, living closer to work. | Decrease. | | Less devices might be needed. | Decreasing time pressure. | Acceptance of lower standards or new daily routines (e.g., suits in offices in summer are not compatible with warm weather). |
| | (1.6) Give flexibility to the household time budget. | Members of the household without strong scheduling and with time to devote to household needs (e.g., childcare, elderly care): stay-at-home parents, part-time workers, retired. Flexibilization of paid working hours. | Flexibility in the time use budget makes the use of technology (and energy) less necessary due to the decrease in time pressure.<br>It could be useful to adapt to electricitiy systems with demand response. | | Less devices might be needed (e.g., car for matching multiple activities with strong scheduling such as paid work and childcare). | The time pressure of the household is relieved. Possibility that some members do not have access to sufficient own income and therefore have an economic dependency on others. | If household units are larger, retired members could provide support to other members. If household units keep the nuclear family model, the model would be a stay-at-home parent. Other alternatives for increasing flexibility could be found from paid work or public or private services. |

**Table 2**
Actions to increase sustainability of the residential sector at the dwellings dimension (technical) and effects on diverse variables.

| Dwellings | | | Possible effects and trade-offs | | | | |
|---|---|---|---|---|---|---|---|
| | Action/strategy | Examples | Energy and GHG emissions: Operational | Energy and GHG emissions: Production | Floor area, power capacity and materials | Human activity | Social organization and desirability |
| Amount of power capacity and its control. | (2.1) Use less power capacity. | Bike instead of a car, manual chopping instead of a blender. | Decrease. | Decrease. | Less materials and devices.<br>Potential increase in shareability of devices if they are used only seldom. | More time is required for the same activity ('Time investments in the environment') | Social structures should allow for flexibility and changing expectations of activities. |
| | (2.2) Smart homes and digitalization | Sensors, internet of things, automatization. | Higher stand-by baseline electricity use.<br>Use of appliances can be shifted given external information on energy prices allowing demand response. | Increase. | Increase of need of electronics, internet infrastructure.<br>Electronic devices are difficult to recycle and have an increasingly diverse of scarce materials. | Automation allows services to delink from presence of inhabitants (more flexibility in time use). More possibility for multitasking. | Comfort might increase with automatization (e. g., turning on heating before inhabitants get home) but might be expensive, difficult to accept or learn to use by certain parts of society. Its use can be associated with symbolical power, which increases its desirability. |
| Maintenance and renovation (trade-off of operational and manufacturing resource use) | (2.3) Improve thermal characteristics of buildings | Refurbishment of dwellings increasing insulation, construction of nZEB buildings. | With better insulation, buildings need less energy to provide the same service. Expectations and thus service might increase at a lower cost, increasing overall energy demand (Jevons' paradox).<br>Some characteristics for thermal performance are set in early design stage that are not changeable during refurbishment (e. g., orientation), so the improvement via refurbishment is limited. | Increase.<br>The distribution of emissions and energy use changes: a larger peak of impacts in the construction phase and lower operational in time. | More materials. | Maintaining jobs in construction sector. | Business as usual of practices.<br>Buildings with worse energy performance are usually related to lower income households. The high costs of refurbishment can be a burden to them or generate processes of renoviction. |
| | (2.4) Substitution of appliances for decreasing operational energy use | Replacement of heating systems or appliances with a better energy certificate. | Less energy in use but must be checked with energy in manufacturing (a shortened lifetime would increase overall energy consumption)<br>Possible rebound: e.g, a fridge that spends less energy by unit of food but that is larger and therefore ends up using more energy. | Increase.<br>The balance between lifetime and improvement in operational energy must be considered. | Larger amount and rarer materials difficult to recycle (e.g., more electronics, and sensors). | Maintaining jobs in manufacturing, less jobs in reparation. | Business as usual in daily life. |
| | (2.5) Extend life of devices - ensure durability | Repair, refurbishment, remanufacture, maintain, not buying up-to-date devices when old ones still work. | More energy in use (not updated technology and wear). | Less energy in manufacturing in the long term. | Less materials required in the long term. Possibly more materials are needed for the same product for sturdiness.<br>Materials stay in use longer (fewer recycling loops). | Less jobs in manufacturing but more in repair. | Acceptance higher risk of failure of devices.<br>Design for durability and repairability. |

(*continued on next page*)

**Table 2** (*continued*)

| Dwellings | | | Possible effects and trade-offs | | | | |
|---|---|---|---|---|---|---|---|
| | Action/strategy | Examples | Energy and GHG emissions | | Floor area, power capacity and materials | Human activity | Social organization and desirability |
| | | | Operational | Production | | | |
| | | | | | Devices must be designed for repair and maintainability. | | |
| | (2.6) Substitution of appliances for changing energy carriers | Electrification of cooking and heating, biomass for heating, electric vehicles (in order to decrease operational GHG emissions or avoid depletion of fossil fuels). | The important factor is the change of energy carriers and not so much the quantity of energy carriers, a more traditional definition of energy efficiency (which are not comparable when considering two different energy carriers). | If the transition of power capacity follows current renovation rates, it may not change. If the transition replaces devices that could last more time in use, it increases. | Material use depends on the recyclability of the replaced devices. | Acceptability of the replacement of old devices if new ones are considered expensive or old ones are in good condition. | |
| Design/layout (dwellings) | (2.7) Space reduction - Downsizing | Smaller rooms, smaller dwellings, kitchenless homes. | Less energy for heating. | Decrease. | Less materials in construction. If downsizing is related to adapting to smaller household size, this could overall increase the number of dwellings, area, and number of appliances. Activitiesshifted to dwellings may require extra space (telework, etc.). | Less time for household maintenance (e.g., cleaning). | Acceptance of living in smaller spaces. Reflection and definition of what sufficient space is. Sharing spaces with more people (larger household size) for economies of scale. |
| | (2.8) Give preference to apartments (vs houses) | Urban planning that concentrates new dwellings in apartments in the city instead of promoting houses in suburban sprawl. | Better heating performance in multistorey buildings. Less relative capturing area for solar energy generation in relation to consumption. Urban form more favorable to public transport and proximity of services and jobs (less energy in mobility). | Decrease also considering infrastructure (roads, pipes, etc.). | Reduction in land use. In turn, density of demand of services allows some collective services and more compact infrastructure (e.g., district heating, public transport, waste collection, sharing power capacity). Depends also on the existent housing: existent buildings can generate lock-in. | Density of population given by apartments allows proximity of services (less time for mobility, economies of scale). | Multi-dwelling buildings have shared spaces that require organization (stairs, lift, gardens, etc.). There are less privacy and private green areas. |
| | (2.9) Flexible housing. | Indeterminate spaces for diverse possible uses (avoiding scripting). | Larger in relation to climatization. | Decrease, since there is less functional obsolescence, and the space is used more effectively in the long run. | This type of flexible spaces is related to larger floor area. In this case, the material benefits are in the smaller obsolescence and thus longer use, and not in the sense of using less floor area. | | |
| | | Flexible floor plans with modular rooms or walls, foldable furniture, etc. | Potentially less energy for heating since spaces are more effectively used. | Decrease, since space can be adapted to the use. | The floor area can be adapted to the household size and thus can avoid overkill. However, this space must be well coordinated with the surrounding spaces (matching with the needs of all affected users). Flexible wall | Less time for cleaning and maintenance. | The dwelling can adapt to the different configurations of family along time, to alternative household units or to different uses. However, institutions and regulations should be able to manage the changes of |

(*continued on next page*)

**Table 2** (*continued*)

| Dwellings | | | Possible effects and trade-offs | | | | |
|---|---|---|---|---|---|---|---|
| | Action/strategy | Examples | Energy and GHG emissions | | Floor area, power capacity and materials | Human activity | Social organization and desirability |
| | | | Operational | Production | | | |
| | | | | | divisions might not have good acoustic quality. | | layout (contracts, ownership, etc.). |
| Materials | (2.10) Light-weighting. | Choose carefully structural elements not with a the minimum number of sections, but adapted to the specific load instead, increasing the variety of types of components. | Check impact in thermal load and thus thermal performance. | Decrease due to less energy for material production. | Less raw material is used.<br>Structural design with smaller safety factor. | More time in engineering design (high salaries) and also in construction (more carefully management). | Adapt work processes.<br>Business as usual in daily life of users. |
| | (2.11) Reuse of parts. | Demountable parts, modular structures. | – | Less energy for material and component production. | Less raw materials are required in the long run. Quality control to ensure mechanical properties.<br>Material use is less optimized: designs must be adapted to existent materials and might use more material than required if optimized for lightweighting.<br>In global terms, Housing stocks are growing, so more materials are required in new construction than the ones demolished. Old buildings that are currently being demolished were not designed for reuse. | Less work in construction in situ (prefabricated components). More work in deconstruction and selective deconstruction. Salaries are higher than current material cost. This could change with higher environmental protections and increasing raw material scarcity. | Requires new paradigm of design for disassembly: reverse logistics, design, risk assessment, etc. In general, professionals do not have experience in designing reusable buildings and manage deconstruction.<br>Logistics are more complex (space for storing large amounts of large compnents, transport of large parts).<br>Business as usual in daily life of users. |
| | (2.12) Recycling of construction material. | Recycled aggregate concrete, secondary steel. | – | Less energy for material production, but maybe it is required for sorting, collection and recycling. Energy for transport if it travels long distances. | Housing stocks are increasing (so more materials are required in new construction than that demolished). Most buildings that are demolished were not designed for recycling. Material can mostly be downcycled or cascaded.<br>Use of secondary materials requires also raw material and, in many cases, does not fulfill original characteristics.<br>Recyclability is limited by tramp elements and a sufficient concentration of scrap that allows sorting and collection.<br>The cost of recycled materials is higher than raw materials. | More work in deconstruction and classification of materials. | Maintenance of construction sector activity (but with higher costs).<br>Business as usual in daily life of users. |
| | (2.13) Change production | Steel production by hydrogen, carbon | – | Change of energy carriers, important | | – | These changes do not depend on the |

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**Table 2** (*continued*)

| Dwellings | | Possible effects and trade-offs | | | | |
|---|---|---|---|---|---|---|
| Action/strategy | Examples | Energy and GHG emissions: Operational | Energy and GHG emissions: Production | Floor area, power capacity and materials | Human activity | Social organization and desirability |
| processes of primary materials. | capture in cement production. | | changes in the production infrastructure. | Creation of new infrastructure for new processes. | | construction sector itself. They must be carried out by material production companies that may be even foreign, whose infrastructure is very large, and that have long investment periods. |
| (2.14) Use of alternative biobased materials. | Timber as a substitute for steel and concrete. | Worse thermal performance. | Carbon sequestration depending on the end-of-life and management of the harvested forestry land. | Limited yearly supply of renewable material with increasing competition of other end uses (energy, chemicals, etc.). Not all forestry products are useful for building. Potential for reusable modular construction. | Reduction of building time (due to modular prefabricated parts). | The largest end-use of concrete and steel is construction. Decreasing demand would decrease activity and jobs in those sectors while increasing in Forestry and Wood industry. Building codes might still not be adapted to biobased materials. Professionals and companies do not have enough expertise. |

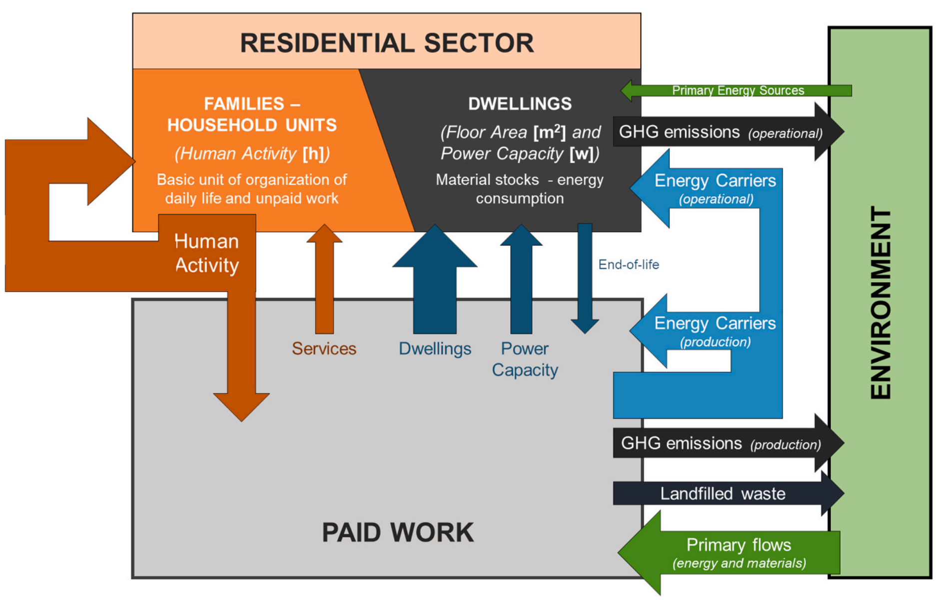


**Fig. 1.** The two parts of the residential sector (household units and dwellings) and simplified key flows from Paid Work and the Environment.

time in education and culture, and the material elements make possible and limit the allocation of time uses in different ways. Meanings are the cultural conventions and the expectations of people, therefore the desirability, which will also depend on the existent and expected material base. Devices materialize the sociotechnical imaginaries coming from society and at the same time affect the social organization option space [34]. Here, material elements refer mainly to Power Capacity and Floor Area, our funds. Therefore, there is not a single direction of causality or determination, but a co-evolution of the three elements of practice theory.

## 3. The residential sector

The residential sector is a central part of societal dynamics and of the daily life of people. In modern societies, it could be concisely defined as the sector complementary to paid work and the market economy that is responsible for the reproduction of society, as shown in Fig. 1. However, this is a very simplified view. The residential sector is the combination of

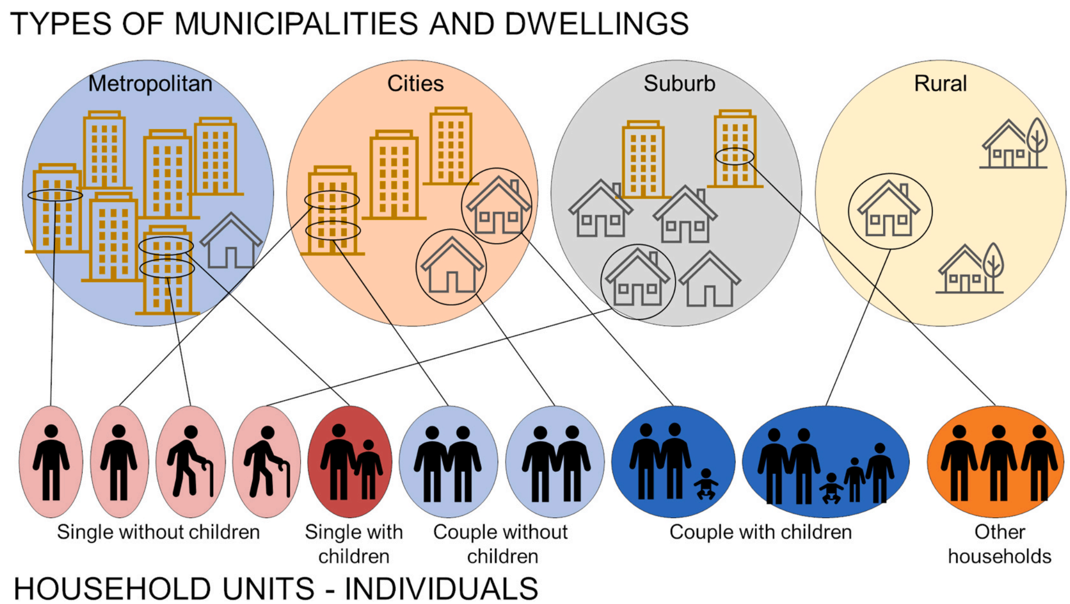


**Fig. 2.** The residential sector is formed by organized individuals in families that live in dwellings, which are located in and generate different types of municipality, affecting their access to services and paid work.

families/household units (of organized individuals) and dwellings (within municipalities/urban forms), whose functions adapt with the surrounding informal and formal sectors in paid work. This continuous adjustment makes the boundary definition and energy accounting more challenging. What happens in dwellings and home is variable and co-evolves with the material arrangements and daily practices. It has changed through history [35,36] and the concept is described differently among disciplines [37,38]. In short, we can say that it is not only a place of rest and leisure but also of (mostly unpaid) work and a center of organization of daily life and social reproduction. In dwellings, people carry out a large array of activities, including:

- Sleeping and rest
- Cooking (food management and cooking, washing dishes) and eating
- Personal care (showering, dressing up, etc.)
- Clothing care (washing clothes, ironing, drying, etc.)
- Leisure (reading, TV, computer, hobbies, social interaction, etc.)
- Caring for others (helping children with homework, helping with personal care, etc.)
- Telework and other kinds of work (workshops, agriculture, etc.)

The segmentation of "domestic" resource use does not adequately address modern life practices [39]. The residential sector is connected and interdependent to many other sectors to which can leak activities and their concomitant resource use. For example, food can be provided by cooking at home with diverse levels of support of processed products from the food industry, home delivery or by going to a restaurant. This means that functions that could be found within families in a type of society, can be collectivized or marketed partially or completely in others. These are especially important in the domain of unpaid work: food provisioning, care centers for the elderly and children, laundry, etc. For example, a couple with children could follow a male breadwinner model, where all reproduction tasks are carried out unpaid by the stay-at-home mother: cooking, cleaning, care, etc. On the other hand, a young professional may live on his own in a small flat. This professional works long hours, always eats out, contracts a worker for housekeeping, and even showers at the gym. In this case, all household services are marketed, and the dwelling is basically a place to store and sleep when he is in town. Much of the expected residential energy consumption is shifted to service sectors. Setting the boundary of the household sector is thus challenging and not universal.

In this sense, families rely on a large variety of out of home support systems, which could be classified as: non-formal (work groups, church, etc.), informal (extended family, neighbors, extended kin), and formal (school, health agencies, protective agencies, welfare agencies) [40] (see Fig. 7). Although the dichotomy shown in Fig. 1 between paid work and households may be too strict since there are other elements outside paid work, it is becoming a reality in countries like Sweden. There, the loss of informal care networks is compensated by a large state formal support within paid work [41], whereas Spain still relies largely on the extended family. The individualization of life and the loss of social interaction based on streets and neighborhoods broke down the balance of family life and the collective [42–44].

In part, this can be explained by the hypermobile society [45], which delinks people from the area close to home by means of the universalization of the private vehicle and other transport modes. The area and social network of daily life can be larger at the expense of being weaker. The set of dwellings plus other buildings form municipalities with specific urban forms and define accessibility to services, goods, and work through daily mobility (from a short walk to a long car drive) (Fig. 2). Metropolitan cities allocate the largest amount and variety of services, but rural areas are essential in their functions of the management of biomass and mineral flows and ecosystems. Compact urban forms that comprise multi-dwelling buildings generate higher densities of demand. In consequence, they make viable services such as retail and education and centralize water, energy, internet, transport, and waste infrastructure. Proximity and vitality, among others, enableenable active mobility and thus potentially decrease energy use and GHG emissions in mobility [43,46,47]. Single-family houses allow a life a priori closer to green areas, but the generalization of this model in suburban sprawl occupies large extensions of Land Use, increasing the distance to services and work. This entails a dependency on the private car for the most basic daily needs, overriding the initial individual benefits. Single family houses are thus private goods [48], that can provide benefits to a certain limited amount of people, but lose their intrinsic characteristics when they are extensively put into practice. Therefore, both the type of dwelling and the emerging context play a role in time and energy use in transport [49–51].

In general, each family or household unit lives in a dwelling, but there are other housing options (retirement homes, student dorms, jails,

| Households | Population (1000s) | Population (%) | People per household | Adults per household | Employm. full time (% of working age pop. (15-64)) | Employm. part-time | Not employed | Number of households (1000s) | Number of households (%) | Number of dwellings/ households (1000s): Apartment | House | Other |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Single without children | 1,753 | 18% | 1.0 | 1.0 | 48% | 16% | 36% | 1,753 | 39% | 1,096 | 401 | 256 |
| Single with children | 700 | 7% | 2.6 | 1.0 | 69% | 15% | 16% | 266 | 6% | 162 | 90 | 14 |
| Couple without children | 2,178 | 22% | 2.0 | 2.0 | 39% | 15% | 46% | 1,089 | 24% | 400 | 650 | 39 |
| Couple with children | 3,748 | 38% | 3.9 | 2.0 | 72% | 18% | 10% | 957 | 21% | 251 | 675 | 30 |
| Other households | 1,455 | 15% | 3.5 | 2.8 | 54% | 16% | 28% | 417 | 9% | 225 | 172 | 20 |
| TOTAL SWEDEN 2015 | 9,833 | | 2.2 | 1.6 | 40% | 13% | 46% | 4,482 | | 2,134 | 1,988 | 359 |
| | | | | | | | | | | 48% | 44% | 8% |

| Dwellings | Apartment | House | Other |
|---|---|---|---|
| Area per dwelling [m²/dw] | 77 | 152 | 58 |
| Rooms per dwelling | 2.6 | 5.3 | 2.4 |
| Rooms per person | 1.4 | 2.0 | 1.6 |
| Persons per dwelling | 1.9 | 2.6 | 1.5 |
| Floor area per person [m²/inh] | 41 | 58 | 38 |

**Fig. 3.** Combination of types of household and dwelling in Sweden 2015. Data: number of people [52] and households [53], employment [54], area per dwelling [55], rooms per person [56].

etc.). Households may have more than one residence for example for specific periods of time (e.g., holidays) or might have problems affording even one. Here we only account for dwellings in use, but there is always a share of unused housing.

Fig. 3 and Fig. 4 show an overview of the organization of types of household units in types of dwelling in 2015 in Sweden and Spain, respectively. In Spain, the housing stock is mainly composed of apartments (67%), whereas in Sweden the percentage is smaller (48%). In Sweden, there is a strong distinction between the uses of apartments and houses. There, most single people live in apartments, while houses are occupied by couples and couples with children. In the case of Spain, all types of households live more often in apartments, whose size is larger ($86m^2$/dwelling compared to $77m^2$/dwelling in Sweden). The Swedish stock of apartments was designed more for one-person households, whereas apartments are common in Mediterranean countries for larger families.

Both demographic structures and the built environment have large inertia and change only gradually. This generates a strong lock-in effect. An incompatibility of dwellings and household units will require adaptation of housing in terms of layouts or number, or of expectations and practices. Otherwise, this could result in overcrowding or under-occupation. Akrich [59] coined the term “scripting”, the framework of action that technical objects define. In the case of dwellings, they embody a type of family/household occupants and of expected functions. For example, an apartment with three bedrooms, one of a larger size, would be adapted to a family of a couple and two children. This hierarchy of bedrooms or a one-room apartment would not be fitted for a household unit of three single adults [60]. These combinations would surely not be desirable, but could still technically work out.

Even though the area per capita is somewhat large in Sweden, the under occupation in terms of the number of rooms per capita is not substantial. Rooms in Sweden are larger than in Spain (Figs. 3 and 4). Apartments and houses are thus larger in terms per capita in Sweden, but they are designed for the number of people that occupies them nowadays in terms of the number of rooms. Therefore, occupancy cannot increase substantially without losing the privacy of a room per person or without construction work to change the layout. Two key questions to address in sustainability for the residential sector are the possibility to transform these prevailing notions on types of household units and dwellings, or/and to transform the existent dwellings to match new social realities. We are going to further examine them in the following sections.

| Households | Population (1000s) | Population (%) | People per household | Adults per household | Employm. full time (% of working age pop. (15-64)) | Employm. part-time | Not employed | Number of households (1000s) | Number of households (%) | Number of dwellings/ households (1000s): Apartment | House |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Single without children | 4584 | 10% | 1.0 | 1.0 | 36% | 5% | 60% | 4,584 | 25% | 3,339 | 1,245 |
| Single with children | 4528 | 10% | 2.4 | 1.0 | 55% | 14% | 30% | 1,898 | 10% | 1,322 | 576 |
| Couple without children | 7750 | 17% | 2.0 | 2.0 | 31% | 5% | 64% | 3,875 | 21% | 2,573 | 1,302 |
| Couple with children | 22773 | 50% | 3.6 | 2.0 | 62% | 10% | 27% | 6,253 | 34% | 4,033 | 2,221 |
| Other households | 6323 | 14% | 3.6 | | 36% | 9% | 55% | 1,737 | 9% | 1,114 | 622 |
| TOTAL SPAIN 2015 | 45,958 | | 2.5 | | 33% | 6% | 61% | 18,346 | | 12,381 | 5,965 |
| | | | | | | | | | | 67% | 33% |

| Dwellings | Apartment | House | Other |
|---|---|---|---|
| Area per dwelling [m²/dw] | 86 | 111 | |
| Rooms per dwelling | 4.4 | 5.6 | |
| Rooms per person | 1.8 | 2.1 | |
| Persons per dwelling | 2.4 | 2.7 | |
| Floor area per person [m²/inh] | 35 | 42 | |

**Fig. 4.** Combination of types of household and dwelling in Spain 2015. Data: number of people and households [57], employment [54], area per dwelling [58], rooms per person [56]. No data for "other" type of dwelling.

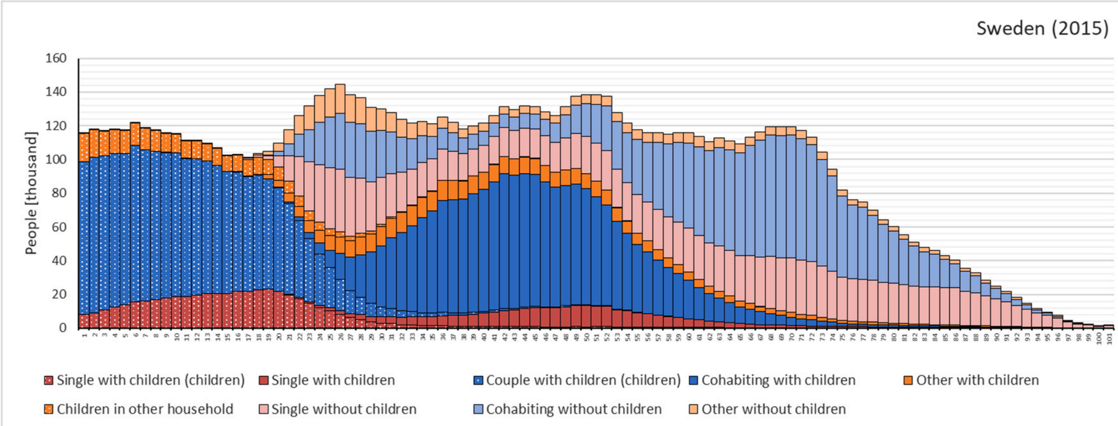


**Fig. 5.** Demographic structure of the population of Sweden in 2015 by type of household and role (adults vs children). Data from Statistics Sweden [52].

## 4. Families or household units

There are different types of families or household units: one-person households, cohabiting couples, diverse types of families with children (single parents, nuclear family model, or more extended alternatives), and other types without family ties, for example, student flats. The latter may not coordinate activities like cooking so much. The organization in household units is dynamic in time throughout life, namely the family life cycle or life-course trajectories [61]. People play different roles in different kinds of households along their lifetimes but also in communities and employment. These roles (carer, employee, friend, son, etc.) define the possible patterns of their daily lives and are reflected in their time use (section 4.1). Therefore, they are not mere individuals acting by their own interests and criteria. Their autonomy is limited. As family members, they participate in the organization and duties and/or receive care from others in different reciprocal ways [62,63]. Within the domestic sphere, unpaid work done by women still plays a central role [64–66]. This is important because it forces women to have a double shift (increasing time pressures) or to renounce fully or partially to paid employment, making them dependent on their partners.

The family distribution by age in Sweden in 2015 is shown in Fig. 5. At least half of the Swedish population between 31 and 53 years old lived with their children. The most frequent type of family with children are nuclear families with two parents, also with the largest average household size, almost 4. It only represents 21% of the households in Sweden. In Fig. 6, there is the demographic structure of Spain in 2015 by type of family. In this case, the share of the population in the family type "cohabiting with children" is larger (50% in Spain vs 38% in Sweden), mostly at expense of single and couple households (see Fig. 7).

In Sweden, as in other developed countries, women live on average longer than men and usually end up living by themselves. Few people live in retirement homes or with their adult children. The large shares of elderly living alone and of early emancipation from parental home define a short time of nuclear family with a household size larger than 2 people. Half of people by 22 have left the parental home, a younger age than other EU countries. This translates into a large share of one-person households (39%) compared to other EU countries, for example, Spain (25%). Changing these deeply rooted values of independence and autonomy is not an easy task, but these affect heavily resource consumption. Sweden is a telling example of families choosing their dwellings to accommodate expected "peak household" moments [68]. The prevision of young couples of having children and the subsequent "empty nests" years after results in an overkill: an under-occupancy of the nuclear family houses for long periods of time. In turn, there is a larger demand for housing for emancipated young people.

The combination of all these types of families makes that Sweden has an average household size of 2 persons, similar to Denmark or Germany, but a very low value compared to other countries such as Spain (2.5) [69,70], a value even higher than Sweden in 1980 (2.4) [71]. Both are far away from Spain in 1958 (4.5) [72]. While in the last decades household size has generally fallen all around the world, European and North American households are still way smaller than those in

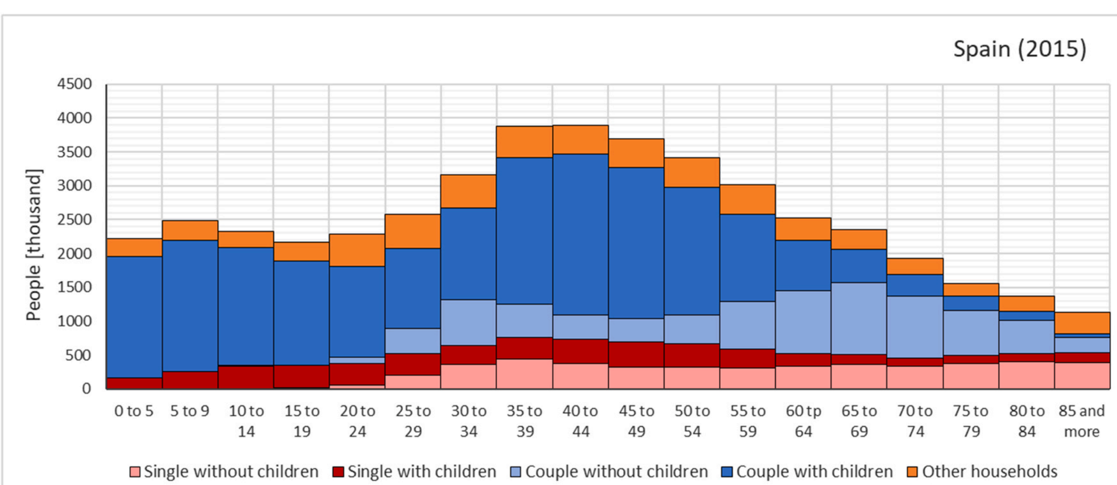


**Fig. 6.** Demographic structure of the population of Spain in 2015 by type of household. Data from INE [57].

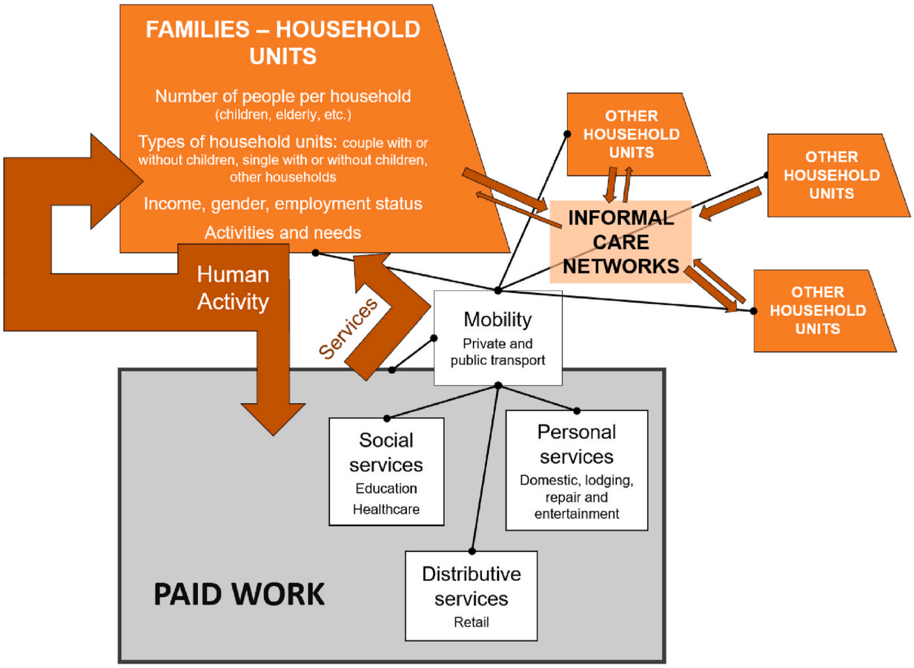


**Fig. 7.** Household units and their relation to services in paid work and informal care networks. Human Activity is provided from household units to paid work through employment and a share returns in the form of services to households. Some human activity goes to informal care networks, where different household units (community, friends or extended family) provide services in a reciprocal mode/unpaid work. These relations generally require mobility to take place. Classification of paid work services to people from [67].

developing countries (e.g., Colombia 3.53 or Chad 5.78 in 2015) [73]. This specific societal organization with small household units decreases internal coordination requirements within households but entails external support for care needs of children, elderly, and disabled people and larger material resources, both in area per person, energy, and power capacity (i.e., appliances and devices). In market economies and depending on the welfare state type, the external support depends heavily on the purchasing power and the choices defined by the market. What is more, the individualization of life generates loneliness, impacting health [74]. Considering all these drawbacks, we could make a thought experiment: if all adult single people in Sweden would live with another person, Sweden would need 26% fewer apartments and 10% fewer houses. We could assume an equivalent reduction in energy consumption in heating and common appliances (e.g., fridges) and a certain reduction in other types of energy consumption (cooking, lighting, etc.). Yet there is a crucial question: Would Swedish citizens consider that to be an acceptable solution?

### 4.1. Human activity and social organization

In Georgescu-Roegen's fund-flow scheme [29,30], where MuSIASEM is grounded, time is considered a fund: Human activity associated with the physical existence of human beings [27]. Families reproduce human activity physically by raising children and maintain it by means of care activities. Although the residential sector is the central actor, there are also activities in services within paid work that take part in the reproduction of the fund Human Activity, for example, education and healthcare (Fig. 7).

Human time is one of the key but rather overlooked variables in sustainability, albeit it is required for all activities. Some residential energy models have already recognized the role of time use and have made it the central variable [75–82]. People can already generally acknowledge the centrality of time. We feel the pressure and hurriedness of the 24 h/day in our daily life, even more on weekdays [83]. People and families organize the allocation of their time considering all constraints and activities in and outside the home. In this sense, duration is not the only important aspect, but also other many dimensions of time, such as synchronization, sequence, and rate, among others [84]. The hourly and daily organization is defined by coupling with others and by authority constraints [84]. In this sense, paid work and family care play key roles in the organization of daily life and generate great temporal constraints. This shows the limited autonomy and choice of the individual.

There are some strategies that can be followed in order to save time [85,86]. These go beyond the residential sector but are useful to understand the trends. To make more of the day and ease the time burden, people (i) use Power Capacity and energy, (ii) decrease their expectations on quality or quantity of activities, (iii) increase the household size, (iv) buy services in the market or use public services, (v) or collectivize activities outside the household. These strategies have impacts as well in the material dimensions, listed in Table 1. For decreasing GHG emissions and energy use, the first strategy, using Power Capacity for time compression, should be reversed considering always the impacts in time use and daily patterns. Therefore, in order to improve the energy performance and sustainability of the residential sector in a broader sense, we could shift the usual framework of technological change to that of social innovation [87]. For this approach to succeed, desirability plays a significant role. Citizens must accept the social conditions of these alternative arrangements to provide the subsequent benefits in terms of environmental feasibility and social viability [88,89].

#### 4.1.1. Decrease use of Power Capacity

There is a trade-off or nexus between the fund Human Activity and energy. Some Power Capacity allows to carry out activities with less time and effort by the use of energy, defined as time-saving technology [90]. In contrast, time-using technology would enhance the perceived quality or allow different kinds of leisure, for example the TV. This generates an energy-time nexus, quantified in the MuSIASEM framework with the Energy Metabolic Rate [MJ/h], which defines the amount of energy per human activity [27,91].

The availability of technology makes that more activities can be performed in the same time, potentially generating a time rebound. Ecological changes in lifestyle such as moving by public transport instead of a private vehicle could be considered "time investments in the environment" [92] (strategy 2.1 in Table 2). These investments are in many cases not individually possible without certain waivers, or not universally possible, and therefore only generalizable through societal change. For example, living without a car in the many areas of the US is not possible due to the sprawl urbanism, the lack of public transport and/or services and jobs close to homes. Social and infrastructure changes to allow making these time investments and depend less on energy-consuming power capacity, are the precondition for time wealth (*Zeitwohlstand*) [93]. This is considered key to a more sustainable life and includes sufficient time, plannability, synchronization, and sovereignty [94,95]. This all-rounder outlook of time is important because the operation of appliances is not always only directly related to duration. For example, fridges and freezers work continuously to preserve food. They affect food provisioning by reducing the frequency of trips to buy groceries and allowing the consumption of otherwise perishable foods, for example dairy or cooked food. Through innovation, the technical object might use less energy by volume of stored food. But this might make people use larger freezers in order to reduce the number of trips to supermarkets or to avoid planning meals, backfiring the relative efficiency per unit of food [96].

#### *4.1.2. Decrease quantity or quality of activities and provide flexibility*

The increasing energy use and power capacity ownership is the current main strategy to overcome the daily personal and family budgets of time. The availability of technology has raised the expectations of the quality or quantity of activities carried out during the day and it the end normalized the ownership of certain Power Capacity and activities. This has accelerated the pace of life and compressed activities, reducing the pauses between activities or increasing multitasking [97]. For example, the existence of washing machines has not reduced the time in this activity due to the increased frequency linked to the higher standards of cleanliness. Some authors state instead that the time pressure in modern societies is closely related to a middle-class expectation of levels of leisure [98].

Therefore, to ease the strain on the time budget, the number, time, and quality of activities could decrease (strategy 1.5 in Table 1). For example, due to the time in childcare, parents of young children opt for more part-time jobs or staying at home (at expenses of income dependency), for a job closer to home so mobility is reduced, or could have fewer sleep hours, affecting their health and wellbeing.

In the specific example of quitting a job in the family unit or relying on extended family members without a job, this does not only entail a liberation of a quantity of time, but also it would give flexibility to the family time budget (strategy 1.6 in Table 1). Both childcare and paid work have generally strict scheduling which may be difficult to make compatible. It must be taken into account that it is women that normally take this role nowadays and that we could find alternatives to address this inequality while providing flexibility.

#### *4.1.3. Shareability and economies of scale*

Furthermore, we could make further deeper structural changes in the mode of provision to yield economies of scale by decreasing the labour and resources per person. These are increasing size and organization within households, building communities, and providing services in paid work. Most of these strategies run counter to the current individualization trend. These social innovations require a broader analysis of the needs and how they are provisioned. For example, stay-at-home parents and kindergartens are two ways of coping with childcare, and people can cook at home, or alternatively, they can enjoy the service in a restaurant or canteen.

Sharing a dwelling and its activities (strategy 1.1) requires negotiation, coordination, and commitment with more people, but at expense of overall lower resource use and duration of tasks. Literature shows that larger household units use fewer resources per capita [99], for example, energy in Denmark [100], energy in Australia [101], water in 4 European countries [102], and energy and carbon footprints in EU countries [103]. When sharing is not voluntary but by necessity and not built around a household organization of tasks, it may backfire the expected savings (e.g. see Klocker et al. [104]). Nowadays, only 9% of the households in Sweden and Spain (Figs. 3 and 4) are "other households" (about 3.5 inhabitants per dwelling). These household types different from the strict nuclear family or one-person households could be extended family or peer-shared types. This arrangement might not be currently desired by citizens, but the only way compatible with their economic and/or care situation. To become a compelling alternative, it requires the establishment of rituals, negotiation and conflict resolution, and a revision of power dynamics within families.

Taking a further step, there are examples in the whole reorganization of space and activities in larger units or with collective areas in the residential sector under different names: cohousing, collaborative housing, coliving, communal housing, or collective housing [105–108], also specific for older people including or not care and support services [109,110], and historical examples such as the history of collective housing considering reproduction work [111] or apartments with collective housekeeping services in New York at the end of the XIXth century [112]. In this kind of larger collective organization, the coordination takes a higher level with external management and/or regular meetings and working groups [108,113]. Yet energy or greenhouse gas emissions savings associated with these solutions have not been studied enough [106]. The existent power capacity and infrastructure does not match the needs of these alternative modes, which would include shared or public spaces and larger and sturdier common appliances.

Neighborhood organizations, the market or the government can support specific functions which are traditionally associated with households, such as public kitchens or canteens, daycare centers, laundromats, or tool libraries (strategy 1.2). Some of these strategies are framed with the concepts of product-service systems, where the objective of companies is not to sell products anymore but to enable ownerless consumption of goods, or to offer the services that those products provide [114–116]. However, these collectively provided services are only viable if people are willing to do them as unpaid work for the community or if companies can sustain wages for their workers. The viability of waged employment is one of the main challenges raised by product-service literature [114–116]. It also entails a complete transformation in the companies' structure and functioning [114]. To some extent for some sectors, this shifting to paid work has already been implemented. While in Sweden jobs in education, health and other care are common in the public sector, Spain does not have such broad public support, and extended families play a great role in child and elderly care. Also, wage workers usually carry out more specialized tasks and can invest in their education and improve the quality of the service, whereas within households, adult members must carry out a large variety of activities. For example, in terms of food provisioning, professionalization could improve logistics (e.g., reducing food waste and packaging), and fulfill societal expectations of quality and healthy eating, instead of laying the burden on individuals and families. Yet collectivization could entail the loss of the cultural load and intimacy of house and care work made by families (mostly women).

These changes in social organization and the function of the household can lead to radical changes in the layout of dwellings as we understand them now, for example with kitchenless homes if they take cooperative housekeeping to the maximum level [111,117,118]. The changes in layouts and the existence of less privative space for the benefit of communal spaces with economies of scale can be also in relation to leisure and social interaction [119]. This transforms the dwelling into a multi-scale space (privative and communal), opening the definition of the household and including the community.

The expected functions and form of dwellings can be adapted in relation to the services provided by its context in paid work. For example, what is considered a paradigmatic example of a minimum dwelling, Le Corbusier's *Cabanon de vacances* (13.4 $m^2$), does not include a shower and kitchen. This small size is possible due to its location, adjacent to a restaurant, and surrounded by a large natural area, including a beach.

#### 4.1.4. Demand response

The electricity mix is a key variable regarding indirect impacts from electricity end uses in buildings [17,120]. The intermittency of the ever-increasing share of renewables in the mix could make that the national or domestic electricity systems cannot adapt anymore to demand at all times as it does now in developed countries. This change for sustainability forced by the energy system also affects daily practices. Demand response strategies aim to shift activities in the everyday activity context or via smart systems. On the one hand, daily practices might have to change actively by users, requiring flexibility from the rest of activities to adapt to the price signals (related to strategy 1.6) [121–125]. On the other hand, electronics and smart systems (strategy 2.2) allow the disconnection between functioning of appliances and the presence of users (for example with programmed laundry and heating), and the possibility to adapt demand to information from the network or aggregator companies (for example, charging electric cars at night when electricity demand is lower). These systems are expected to cut down energy consumption even with an rise in standby energy or to allow demand-side management by the electricity system operator. While they may decrease or shift energy use, they have impacts in other dimensions such as material depletion [126]. Electronics are hardly recyclable and use an increasing variety of scarce materials [127–129]. Moreover, these technologies are not necessarily inclusive due to the cost for lower income households [130] and due to the complexity of their control [131].

## 5. Housing

Homes are places full of symbolism and meaning. Despite this strong cultural dimension, dwellings are a very material reality. Dwellings as a technical object are in fact the most common framework in sustainability analysis of the residential sector. In many cases, this even only includes heating, ventilation, and air conditioning (HVAC). The housing stock is made of physical realizations of structural types, where large shares of the total final energy in society are transformed into end uses providing services. Therefore, the analysis must be centered not only on the amount of energy carriers but on the services that they are providing.

Following the central idea presented in section 3, there must be a match between families and dwellings. This connects what could be considered "purely technical" with the inherent social side of housing. However, only considering the technical side there are important conflicting criteria for diverse dimensions (e.g., smart home systems may decrease operational energy carrier consumption by increasing material use) [25,132]. Therefore, strategies to tackle a specific point might be shifting important impacts outside the picture if we do not address the issue in a holistic way. The incomparability of the diverse dimensions adds to the large uncertainty in the future: discount rates, climate, availability of new technologies, future patterns of use, population, distribution in household units, etc.

This section starts with the current state of the housing stock, its characteristics, its path dependence, and lock-in. Afterwards, we focus on the sufficiency framework, analyzing the economies of scale and levels of service that affect energy use. These measures might have a larger impact than technical changes. We also analyze the trade-off between production and operational GHG emissions and energy. Then, we address the growth of the fund floor area, its material requirements, and impacts. Finally, we analyze the role of the construction and real estate sectors.

### 5.1. The state of dwellings

The existent housing sets the initial conditions. It consists basically of houses and apartments, but there are other types such as residential housing for students or the elderly, prisons, etc. Within the set of dwellings, there may be parts that are not used for long-term residential uses, such as holiday homes or tourist accommodation.

A great amount of built environment exists already. While some has been refurbished and will last long in the future, other is of poor quality and expected to be short-lived. The renovation of the stock of buildings is slow due to the long lifespans and cultural values. This locks in practices and uses [133] and consequently might generate different kinds of obsolescence: poor construction or design, weak market position, or location [134]. Changes in specifications and requirements for new buildings will take decades to have a deep effect on the performance of the whole system. In Fig. 9 and Fig. 10, there are the demographic structures of the housing stock in Sweden and Spain divided into houses and apartments. The decade where most of the Swedish dwellings were built was the 60s. This is a consequence of the million homes program (*Miljonprogrammet*), which was made by the Swedish Parliament in 1965. Following the oil crisis of the 70s and the referendum to replace

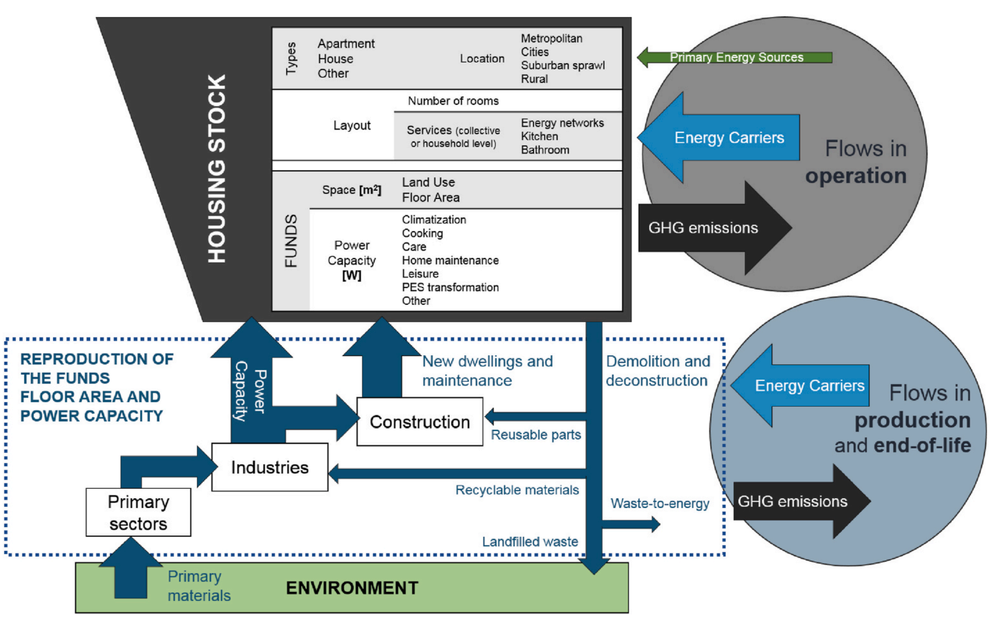


**Fig. 8.** Housing stock characterization and reproduction of funds floor area and power capacity. Flows in operation, and production and end-of-life.

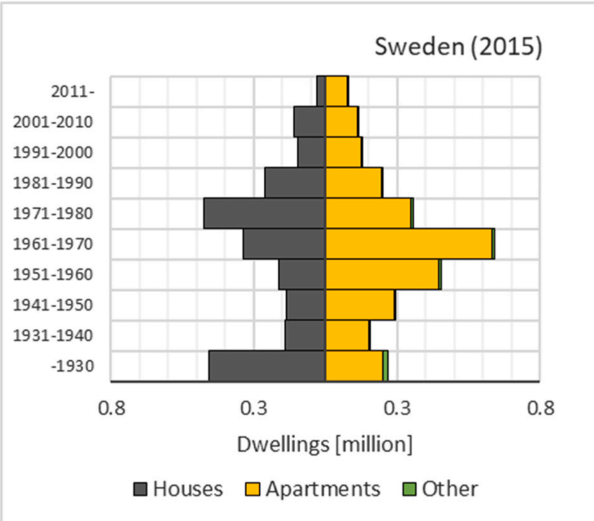


**Fig. 9.** Demographic structure of housing in Sweden (2015) [136].

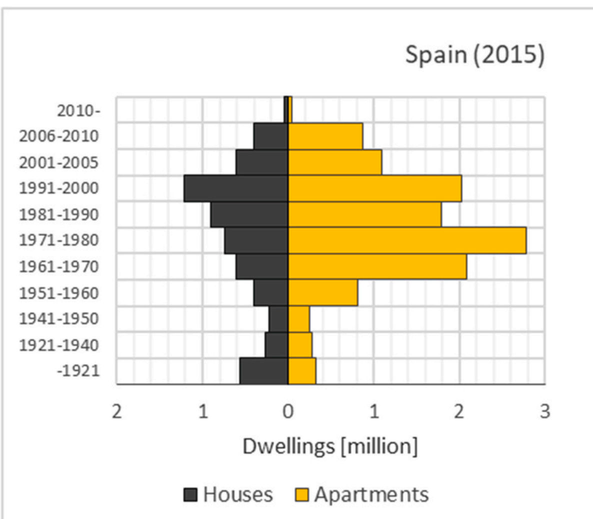


**Fig. 10.** Demographic structure of housing in Spain (2015) [57].

nuclear power, a Building norm was introduced in 1980, SBN 1980, which tightened the rules for insulation of buildings [135]. Of the existent buildings today in Sweden, most were built before this building norm. Therefore, the different regulations and building codes are reflected in their contemporary cohorts and qualitative changes in the whole stock take decades to take place.

In Spain, the largest cohort existent today was built in the 70s, where the average family was of almost 4 members [72], but the customs in space were lower. To some extent, the construction in a given year matches current or expected types of household units. The only possible low-cost flexibility in the current building stock leans towards individualization (more space per person in a dwelling) instead of towards larger household units, which would require larger refurbishments or the acceptance of downward changes in space per capita.

### 5.2. Economies of scale and level of service

Knowing the characteristics of the dwelling and the power capacity, we could make assumptions on energy throughput and direct emissions in use (operational). A specific performance rate for a building or a device can lead to a large variety of end uses per capita depending on the social configuration around it. Both the household size (economies of scale) and the different types of families, their incomes, and practices affect energy use and emissions. We could even say that a fridge used by 4 people is 4 times as efficient as one used by a single person. These and other issues touched upon in the introduction make essential a framework widening from efficiency to sufficiency, aiming to decrease total consumption in absolute terms by assessing the needs [137–139]. This means not only considering the energy quantity or a specific relative improvement but also characterizing the functions and qualitative aspects (space, temperature, shareability, cleanliness, etc.) associated with energy uses.

For that matter, the social dynamics explained in section 4 regarding time pressure and its nexus to energy must be understood. The amount and type of appliances and dwellings will depend on social organization (types of household units and size) and the existence of systems of shareability of devices at the community level, which affect time use and daily patterns, on the shift of activities to paid work, which requires the viability of wages, on the ability of states to levy taxes and develop welfare state and the desirability of society to support them, and other changes in daily patterns regarding the expectations on quantitative and qualitative aspects of the activities (e.g., choice, leisure types, space, room temperature and cleanliness).

Structural domestic services are subject to economies of scale in terms both of Power Capacity and Floor Area. Any dwelling customarily has at least a bathroom and a kitchen, with its subsequent equipment, irrespective of size and number of occupants, and these coevolve with legal, infrastructural and cultural conventions [140]. If a dwelling is occupied by one or more people, it will affect mainly their size and the size of the devices, only at substantially larger occupations, the number of bathrooms and appliances will increase. Shareability of devices within or between households (washing machine, laundry room or laundromat, fridge, TV, or those used less often such as tools) also reduces the number of appliances that must be manufactured. The case of the washing machine is paradigmatic. In some countries such as Sweden, it already represents an appliance that is commonly shared between households of the same apartment building, requiring organization and rules. Klint and Peters [141] estimate that the GHG emission savings of a shared laundry room can be 26% in comparison to having washing machines in every apartment. Collective power capacity can be of better quality or performance due to shared costs. This is also true for district heating systems, which operate at a larger scale and increase efficiency compared to individual devices but require a certain level of density of demand.

Some household devices are even used very seldom, i.e., they have small utilization factors (e.g., printers, tools, or specific cooking devices). Consequently, their largest impact lies in their embodied energy and materials, within the manufacturing and material extraction sectors. Ownerless consumption of these items could exist in the form of collective ownership or rental, increasing the utilization factor and reducing the embodied impacts per unit of service. However, the widespread penetration of devices [142] and thus immediate availability allows patterns of daily routines that require less planning. Ownership in many cases represents a tool of social distinction and symbolic power [116,143,144].

Moreover, the energy, GHG emissions, and time use can also be divided if tasks are shared so more than one person enjoys its outcomes (cooking, washing clothes, etc.). This means that fewer resources per capita are required for the same function when, for example, cooking for 1 or for 3 people [105,145]. Therefore, we can work with fewer devices and/or space (and their embedded resources) (strategy 1.4), or even with fewer devices and time in use if tasks are shared (strategy 1.3). However, this affects current lifestyles, expectations of choices and autonomy, or typologies of families and communities, explained in section 4. This depends thus on desirability.

Another key aspect of operational energy use is to understand the level of service that is expected and to understand what the end use or need to fulfill is. Here, we are going to use the example of heating to illustrate it.

The difference between calculated theoretical energy and GHG emissions from an expected level of service and the actual monitored one defines a performance gap [146]. For example, in a sample of 410 homes in the UK, Palmer [147] found a large discrepancy between the real measurements and their energy performance certificate. The societal availability of cheaper energy services when technical improvements are put in place might ultimately increase overall energy consumption due to the Jevons' paradox [148,149]. This difference between expected and effective energy use can be also in terms of lower energy consumption, then called the prebound effect [150]. The expected energy performance of a building will not be fulfilled if users cannot afford the price, which is common for heating in poorly insulated buildings.

Indoor temperature is a key parameter for calculating heating and cooling loads and thus HVAC energy consumption, one of the largest end-uses in many countries. People expect to live in comfortable environments no matter the external climate. This has generated a convergence of inner temperatures among countries and seasons [151]. Even though the maintenance of an adequate temperature is normally framed as a technical problem that must be approached with technology and innovation, it is heavily affected by the conventions on comfort, which are not universal. 'Adequate' has a different meaning for different people. Temperature comfort is socially and technically constructed [152] and has changed over time [153]. Technical systems are designed according to pre-established and not contested conventions of average temperature defined in building codes, for example, those listed in Guillén-Lambea et al. [154]. The questioning of these conventions on temperature is another example of strategy 1.5: decrease quantitative or qualitative expectations of activities (Table 1). Mata et al. [155] have modelled a set of measures for the housing sector in Sweden. According to this paper, decreasing the indoor air temperature to 20 °C provides the greatest energy savings. The rest of the measures require physical changes with energy and material investments in buildings, and only give marginal returns in part because the thermal technical specifications of Swedish building sector are already high. Guillén-Lambea et al. [154] modelled the energy consumption for heating and cooling of conventional and nZEB buildings in diverse cities in Spain and found significant differences in energy demand even within a small range of room temperatures (for example, savings from 13 to 23% for conventional dwellings when decreasing heating temperature from 20 °C to 19 °C). Sahakian et al. [156] organized a living lab "heating challenge" in 8 European countries where the participants ended up acknowledging that an inferior temperature than usual could be considered enough. That said, the whole paradigm of space heating for temperature comfort can be challenged as well. Further alternatives to heating spaces can also be a solution, for example, clothing and personal heating devices [157]. Verhaart et al. [158] reviewed literature on personalized comfort systems and their combination with common HVAC systems have an energy-saving potential of up to 34% and an increase in occupant satisfaction.

### 5.3. Energy retrofits and the trade-off of production and operational energy

For the improvement of the energy and emissions performance of the residential sector, we must always consider the social innovation strategies and preanalytical framework explained before related to shareability and economies of scale, and the conceptualization of services. However, the technical improvement of dwellings and power capacity and the substitution of devices with updated technology also play important roles.

The construction of new dwellings or production of power capacity is in part related to the substitution of old appliances to phase-out of certain energy carriers (e.g., electrification of kitchen appliances) (strategy 2.6) or improvements in energy efficiency or lowering emissions (strategy 2.4). In this case, there are trade-offs affecting the two main variables (energy/GHG emissions and materials) and phases (manufacturing in diverse sectors/operational in the residential sector/end-of-life), which at the same time involves different actors (companies, public services, and households). There are two different types of resource uses which are allocated in different societal sectors and depicted in Fig. 8: (i) the flows metabolized by the funds – i.e., operational resource uses (residential end uses); and (ii) the flows needed to produce and maintain the funds – i.e., production of power capacity and construction and maintenance of floor area (in the construction and upstream sectors). For example, energy efficiency strategies such as buying a fridge with new technology might shift impacts to manufacturing and upstream sectors in terms of both materials and energy. In practical terms, the end-user, the household, might be perceiving a lower energy consumption, but in overall terms, this might not be true if we consider the embodied resources in production of both the new and the substituted fridge. The construction and manufacturing of new updated products may not always pay back the potential future savings if the substituted product is still new. If the substitution is required at a higher rate for phasing out of energy carriers due to scarcity, the overall energy and GHG emissions balance might be challenging to evaluate. Also, models exploring payback times or building service times involve making assumptions of very uncertain variables such as future uses and innovation in technological upgrades.

In terms of thermal performance, buildings with conventional energy standards generate most of the GHG emissions in their use phase [49]. Although Nearly Zero Emission Buildings (nZEB) or other low-energy building standards decrease energy in use for thermal end-uses, there is a larger initial investment [159,160]. Vilches et al. [161] indicate that the share of operational energy in the life cycle of a building is decreasing from 80 to 60%. The timing of the transition becomes important due to the large peak of emissions and other resource uses in construction. Also, the reduction in technical energy carrier consumption clashes frequently with the material efficiency and circularity, for example, with smart homes and the concomitant deployment of hard-to-recycle electronics.

The thermal performance of a building is defined at different levels and is more or less changeable depending on the layer of the building. Some of the characteristics of the outer layers are considered to be especially relevant: orientation, shape, and building aspect ratio [162], which are set in the design phase and therefore not changeable with a retrofit. This includes the distinction between houses and apartments (strategy 2.8), where houses tend to have larger operational energy and GHG emissions due to heating. This shows that the renovation wave can have a limited effect and that existing building stock has a lock-in in terms of both function and performance.

Coming back to the thermal performance, the level of insulation is calculated with the transmittance (U values) of walls, floor, and roof. In the Swedish case, the U values of windows are equal no matter the age of the building [163], because the change requires minor work, whereas changing the insulation of the walls and roof represents a deeper retrofit. However, in comparison to other EU countries, overall Swedish U values are relatively low [58]. Deep refurbishment with an upgrade in thermal characteristics is still not put into practice at the pace that would be expected. While 12.3% of the residential buildings in the EU28 were renovated in 2012–2016, only 0.2% of the residential buildings in EU28 were deeply renovated in energy terms (more than 60% energy savings), 0.1% in the case of Sweden and 0.3% for Spain [164].

### 5.4. Expansion of the fund floor area

Housing is currently expanding, with still low rates of demolition in relation to construction. The expansion of the fund Floor Area, provided that monetary dynamics are favorable, is driven by population growth, expectations of space per capita and functions, the increase of one-person households, change of preferred location or type of dwelling ((peri-)urbanization/ruralization) and the demand for other uses (e.g., second homes and tourist accommodation). This expansion is a key driver of materials, energy, and land use. It also determines the functioning of the construction sector and its supplier industries and locks in the demand for resources in the subsequent use of buildings. Therefore, it requires a deep analysis of the existing stock and future needs. This will be large in developing countries such as China, with intense urbanization and expansion of the floor area [165].

The construction of new dwellings generates impacts, but most of them are induced in upstream sectors related to material production [2, 166–168]. The production of construction materials represents about 11% of the global energy and GHG emissions, and more than half are related to steel and cement manufacturing [159]. The bulk of materials for buildings in weight corresponds to those most consumed overall: concrete, steel, other non-metallic minerals, and timber. However, there is increasing diversity and amounts of rarer materials, both in power capacity and parts of the building (e.g., insulation).

If it is considered that new buildings are required, some strategies could decrease the impact of materials and construction. These must be a central criterion in the design phase and are difficult or impossible to implement in later stages in the life cycle of buildings. These include: (i) reduction of floor area or downsizing, (ii) lightweighting, (iii) new or improved production technologies of primary materials, (iv) substitution of materials, (v) recycling of materials, (vi) reuse of parts, (vii) increase durability and (vii) increase flexibility.

#### 5.4.1. Reduction of Floor Area or downsizing

Reducing the available space (strategy 2.7) reduces the quantity of materials (embodied resources) and also thermal operational energy. However, it must come with a reflection on what is sufficient space. This can be related also to larger household sizes and economies of scale explained in Sections 4.1.3 and 5.2. Zhong et al. [18] define space reduction as the most powerful measure to reduce emissions in material production for buildings. It is also relevant for thermal energy uses, for example as shown by Cordroch et al. [169] in a model for the German housing heating demand. Pauliuk et al. [14] define increasing household size by 15% and decreasing floor area per capita as the combined measures that can cut down GHG emissions by 53% in the Norwegian dwelling stock by 2050. Very high thermal performance standards could be backfired by the increase in the size of dwellings [170–173]. Therefore, assessments of energy efficiency using only intensive variables such as energy per area may be misleading [172]. Moreover, larger floor area per capita and lower energy per area are usually related to higher incomes [174].

While the fund Floor Area is growing due to both population and household increase, also floor area per capita is increasing. Space standards have evolved through history concomitantly to the expectations of privacy and the number of rooms required by families [175–177]. Moreover, new realities may require duplicate spaces, like in the cases of joint custody of children, and telework. A larger dwelling also defines more work to maintain it clean and working. While there is a trend of downsizing due to the decreasing household size and the shortage of land in cities, data indicate that dwellings are getting relatively larger per person overall [178]. This is due to the fact that, for example, two apartments for one person are generally larger than one apartment for 2 people. The average housing standards in Europe define minimal aggregate living space (living and dining rooms, and kitchen) of 21,9 $m^2$ for 2 inhabitants and 19.6 $m^2$ for 1 inhabitant [179]. Moreover, downsizing, as performed nowadays, is not framed within sufficiency but driven by rising land prices in cities. This reduction is not compatible with prevailing perceptions of sufficient space [180,181].

#### 5.4.2. Lightweighting

Another approach is to reduce the quantity of materials and their embodied impacts: lightweighting (strategy 2.10). Nowadays, the construction paradigm is that of building rationalization, which uses standardized beams with a limited number of cross-section sizes [182]. This entails the use of oversized beams and defensive design strategies used by engineers and required by codes [183]. Therefore, they use more material than would be required in order to ensure stability and load-bearing. If the objective of minimizing overall cost would shift to that of optimizing loads at all points, steel and other material use could be minimized at expenses of higher costs and complexity in design. Alternatively, lightweighting could be done by changing materials with a higher strength ratio per weight, for example, composites. However, the initial savings in material quantities entails a future difficulty to recycle them.

#### 5.4.3. Changing production processes of primary materials

Emissions from primary material production of steel and cement are process emissions challenging to decarbonize [184,185]. The production processes of these materials could be transformed (strategy 2.13). The transformation of production chains involves a large number of strategies depending on the material that we are not going to detail here but are available in the literature [185–187]. These include direct reduction with hydrogen instead of coke for steel or increasing use of cement clinker substitutes and include carbon capture and storage systems for cement production. The transformation of the supply chains of primary steel and cement depends on large investments that are made in long investment cycles [188] and are out of the direct control of the construction sector.

#### 5.4.4. Material substitution

Another way to avoid the emissions of primary material production is to find substitutes to those materials. biobased materials play a special role (strategy 2.14). Timber is gaining traction as a carbon-capturing and low material intensity alternative to the emission-intensive materials concrete and steel [189]. Increasing wood use in construction is the most impacting material efficiency strategy for reducing GHG emissions considered in the global model of Pauliuk et al. [190]. However, timber has worse thermal performance than concrete due to its lower heat capacity (less thermal mass and more overheating) [120,191]. It must be also protected from humidity and plagues and parts must be sized for adequate fire resistance [189,191].

Sawnwood and wood-based panels come from renewable resources, but their availability is determined by the maintenance of the fund land use (quality of the soil, use of fertilizers, irrigation, etc.), forestry harvest, the increasing competition of other uses (materials, energy, and chemicals) and the conservation of natural areas for biodiversity. In the model of Churkina et al. [189], only the lower timber content (10 and 50% timber) building scenarios could be satisfied with current harvest rates plus re-directing a part of other end uses such as fuelwood. However, not all forestry products can be used for construction.

In Sweden, wood is used largely for frames in detached houses (around 80–90% [192], very large compared with other countries such as Germany: 2% [193]) but still minor in multi-dwellings (around 8.8% in 2014 (TMF 2016)). This shows that it is already conventional practice in some countries for some building types. However, in many cases bio-based are still to be introduced in regulations to make possible its generalized use in structures other than low-rise buildings.

#### 5.4.5. Recycling

Existent buildings and their parts are hardly reusable or recyclable. Most of the construction waste is currently deposited in landfills, or downcycled (e.g., backfilling). This cascading of materials can also increase the secondary inputs to construction. Currently, old scrap is mostly recycled into construction steel, which has lower specifications in comparison to other steels [194]. We will face a challenge in the future management of the end-of-life of current building stock, which has been mostly built in the last decades without consideration of reusability or recyclability and it could become obsolete simultaneously.

The recycling of materials (strategy 2.12) could still be possible to a certain extent, but it would require dismantling buildings carefully separating the different materials instead of demolishing and disposing of them (more labor and planning). Logistics, cost, lack of regulation, and time are considered the main barriers to recycling [195]. On the one hand, the large amounts of materials that are in a building facilitate their recycling (potential higher collection rate), but, on the other hand, the fact that they were constructed with wet joints and composite materials difficult to detach (e.g. reinforced concrete) hinders it.

The production process of secondary materials can be 10% or 50% of the primary production for aluminium and steel [13], respectively. In some cases, the incentive to recycle does not come from the reduction in resources in secondary material production since it might not be as beneficial considering sorting, collection and transport, but from the scarcity of raw materials [196]. The overview of the system puts into question circularity. The building stock is expanding and therefore accumulating more materials. Therefore, the system requires continuous inputs of raw materials. Buildings designed now for recyclability will take decades to be actually recycled. Demolition does not play a sufficiently large role in providing secondary materials yet. And even in a steady-state context, there are always a limited maximum recycled content potential, losses due to dissipation and low concentration, and the inclusion of tramp elements limit recyclability [129,194,196–198].

#### 5.4.6. *Design for disassembly*

Another strategy is to implement design for disassembly in new construction (strategy 2.11). This way, the structure and envelope of a building are not a monolithic unit with a clear lifetime anymore. Instead, the life cycle of components is expected to be longer than the buildings in which they take part. Parts are kept within the technosphere and must be useful in the future for further uses in new buildings.

The new projects with modular buildings with reusabe parts would affect a very small share of the current housing stock. Now, these reusable parts are in fact newly manufactured, but a system (regulations, market, etc.) must be created to manage their future reuse. The design objective is not to calculate an optimum with standardized new parts anymore, but adapting the design to the available parts from deconstructed buildings or standardized parts [199]. This entails potentially extending the life of parts but decreasing material efficiency and limiting lightweighting at the level of the building [200,201]. Also, not all types of materials and parts can be reused at the same level [202]. Reusable parts require more work, special transport, storage space, and infrastructure to maintain and guarantee their functionality [203], while business as usual depletes the available materials by simply throwing them away into landfills [204]. This represents a whole new paradigm that requires new logistics, design methods and tests to ensure the mechanical performance and geometric tolerances of reused materials [32, 199,205]. This includes creating reverse logistics and reused component markets, defining disassembly plans in the design phase, and more specific technical aspects such as using dry or reversible mechanical instead of wet connections. On the other hand, it has other potential advantages: industrialization of processes, standardization, and prefabrication of parts. This multidimensionality is shown in Küpfer et al. [206], which proposes a multi-criteria decision framework for diverse levels of reuse of structures and dimensions: environment, risk, costs, and construction complexity.

Both recycling and disassembly require more working time than demolition, challenging the financial viability of deconstruction and reuse. The current low cost by volume or mass of primary construction materials in comparison to wages does not enable their reuse or recycling. Transport distances also play a key role in the economic and environmental gains and if very long could even overtake avoided impacts of primary materials and components [207,208].

#### 5.4.7. *Durability and flexibility*

Buildings could be designed to be long-lasting. Studies point out that making sturdier and long-lasting products pays off when the initial investment is large [209,210] (strategy 2.5). This also requires good maintenance during the lifetime.

Durability is not only a matter of sturdy structures but also of an adaptable function and/or form (strategy 2.9). In fact, in many cases, the demolition of a building is not due to the degradation of the structure or components, but due to functional or locational obsolescence. The lack of flexibility does not only affect the materials and their future uses in new buildings, but also the possibility of adapting the use of existing buildings by changing their layouts [211]. For example, the evolutionary change in size and number of rooms could accommodate a family throughout its different phases over time. In this sense, there is the paradigm of flexible buildings [211–214] (strategy 2.9), which could rely on indeterminate spaces (soft vs hard use [212]: multi-functional rooms) or the modularity and changing partitioning of buildings (soft vs hard technologies [212]: e.g., flexible wall divisions, switchable rooms joinable with adjacent apartments, folding components). Indeterminate spaces use to be linked to a provision of more space [212], thus potentially backfiring in the short term the resource use improvements in the long run. The invested resources might be useful for a longer time but are larger in the first place. In any case, flexibility must be projected as a core objective from the design phase, which implies a cost that developers may not be willing to take [215]. The structure and services (e.g., wiring, and electrical outlets) and types of construction, which are not currently flexible, may lock the possibilities of rearranging floor plans. Therefore, most existent buildings cannot accommodate large changes over time. This flexibility of function and form is expected to be required in a society in permanent change and innovation but might not be as much in a steady-state economy.

### 5.5. *Construction and real estate sectors*

The functions of the construction sector are refurbishment, maintenance, demolition, and new construction not only of housing but also of other types of buildings and infrastructure. In other words, it adapts the fund Land Use for different functions and multiplies it into Floor Area.

Moreover, it is a key economic sector. The construction sector represented directly in 2015 6% of the gross value added and 7% of the working time in paid work for both Sweden and Spain [216,217]. The sector needs a continued expansion of the stock or an important investment in refurbishment. It is not only the sector devoted to building houses to fulfill societal demands, but it requires a continuous demand for housing to maintain production and therefore the existence of the sector. In Spain, during the years previous to the housing bubble burst in 2008, the vertically integrated construction employment represented 19.7% in 2004 of the Spanish economy [218], with 12% directly devoted to the construction sector.

For the sake of the immediate revenue of construction activities, the additions to the built environment are designed according to current or near-future expected most profitable demand instead of having a strategic long-term perspective. Therefore, the existent housing stock is a stockpiling of dwellings designed according to needs at the time of construction as perceived by developers within the limits of regulation. The future needs of the users, the municipality or the country are not necessarily included if governments do not enforce them.

In consequence, homes are not only the place where people live but also an economic asset. We cannot conclude the paper without mentioning this aspect, which is crucial because people spend a significant share of their income to access housing by means of rent or mortgage. Rents represented 11% in Sweden and 3% in Spain of the monthly expenses in 2015 [219]. In Spain, ownership of housing is more common than in Sweden, and it represents 8% of the value added (L68A – imputed rents of owner-occupied dwellings). This is important when assessing the capability of households to access a dwelling and the further large investments in maintenance and refurbishment. The lower income population tends to live in buildings with worse thermal performance and landlord-led retrofits might entail processes of renoviction

[220].

The economic character of dwellings is most clear in the real estate sector, its financial manager. In the case of the EU28, it represented in 2015 11% of the value added (including L68A – imputed rents of owner-occupied dwellings) and 1.1% of the HA in paid work [216,217]. In this context, dwellings are not only the places where people live but an economic asset. This has led to financialization and housing bubbles [221–224]. The ratio of household mortgage debt to GDP in 2009 was 64% in Spain and 82% in Sweden [221]. The material dynamics are more tightly driven by financial cycles rather than by the needs of the population.

Several dynamics and trade-offs described in the paper are influenced by access and other property rights over dwellings. For example, distributing dwellings not through the current logic based on private property (purchasing capacity and inheritance rights), but to other socioeconomic characteristics (e.g., distance to work and social network, household size, age, etc.) would help improve the relations between people and buildings and sustainability. Also, the property or access format affects the form. Property or access types enable or limit the flexibility in distribution of space and rooms between adjacent apartments. In a similar way, the provisioning of services generates technical requirements. For example, the payment of electricity defines the way meters and wiring are installed. The institutions involved in dwelling ownership or access and the provisioning of services also affect the possibility of investments (e.g., retrofits) and the policies that governments can implement.

## 6. Conclusions

Interdisciplinarity is key for sustainability. Technical solutions are insufficient and should be adequately contextualized. We must really understand social dynamics and their entanglements with technology to propose coherent and transformative practices. In this paper, we have provided an overview of factors for the sustainability of the residential sector and assessed qualitatively trade-offs and impacts in energy, materials, time use, and social organization of possible measures ranging from social innovation to construction methods. To this effect, we have framed biophysical flows and funds using MuSIASEM, as well as around current cultural and institutional settings using practice theory. Some important variables are left out of the analysis, such as health, water, and contamination.

The residential sector is the center of daily life. Homes have changed throughout history, both in functions and form. Household units of organized individuals live in diverse typologies of dwellings (houses, apartments, and others, with different layouts) and these configurations have shaped the diverse dwelling cohorts. A clear definition of the functional boundaries of the residential sector is not possible, even more since activities at home are intimately related or even partially substituted by those in paid work.

Strategies such as downsizing and shareability are often used in models without considering their social consequences: the coherence with practices. People organize in diverse types of household units now mainly based on the nuclear family and increasingly in the individualization of life. The steady fall in household size has increased the number of dwellings in use while the shareability of space, materials, and devices is decreasing. Alternatives based on sharing and collectivization generate economies of scale but pose a desirability challenge. Some of the social innovation strategies that could be put in place require deep changes in the way we frame households, institutions regulating access to dwellings, and also in the organization of communities and companies. Time use is a key variable for sustainability not sufficiently acknowledged in the literature, with an important nexus to energy use and appliance ownership.

The built environment consists of large already invested materials, emissions, and energy. The merely technical side of dwellings has many trade-offs. The concepts of durability, material and energy efficiency (in operation and production), monetary cost, recyclability, flexibility, and modularity can be mutually exclusive. The emerging combination of long-lasting housing and other infrastructure in types of urbanism and municipalities generates strong lock-in in their uses and related dynamics such as mobility. Therefore, new construction concepts may only tackle new buildings, which take decades to take over the whole system due to the large life of buildings. Moreover, it requires a new culture of work for architects, engineers, town planners, and other construction workers. Finally, we must consider that many of these technical strategies may entail higher up-front costs that might not be acceptable for developers, which do not have a high interest in the future uses of buildings. The longevity of buildings sets a challenge for future uses and potential lock-in of functions and resource use, and also in regard to the accountability for maintenance and end-of-life.

The current centrality of the narrow definition of energy efficiency does not provide a robust enough framework to improve the residential sector. Sustainability oriented to artifacts and individual behavior should be shifted towards functions and systems. This would make it possible to contextualize local efforts, generate truly innovative processes and provisioning of services and evaluate trade-offs across scales and dimensions. In this paper, we have reviewed and discussed a set of actions to improve the sustainability of the residential sector. Beyond this review, we have proposed an interdisciplinary framework to analyze the sustainability of the residential sector as the integration of families/households units and dwellings, identifying key entanglements between them, with paid work sectors, and with the environment. We expect this work to help in the holistic interdisciplinary understanding of household metabolism that will ultimately set the foundation for transformative changes and policy for social, economic, and environmental sustainability.

## Declaration of competing interest

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

## Acknowledgements

Laura Pérez-Sánchez gratefully acknowledges financial support of the Catalan administration/AGAUR (Grant number: 2019FI_B01317). The authors also acknowledge financial support by the government of Catalonia (AGAUR), through the support for research groups (2017-SGR-230), and the Spanish Ministry of Science and Innovation (MICINN), through the "María de Maeztu" program for Units of Excellence (CEX2019-000940-M). This work reflects only the authors' view; the funding agencies cannot be held responsible for any use that may be made of the information it contains.

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