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Buildings: The new energy nexus

Le bâtiment, nouveau nœud énergétique

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ABSTRACT

Buildings are the largest contributors to households' energy footprints. If both the energy for household mobility and the embodied energy are added to the energy for heating/cooling, domestic hot water, lighting, buildings are by far the main problem of energy consumption in France. This paper presents a review of the evolution of the main drivers of CO_2 emissions by buildings in France. Eventually, the paradox of the effect of density is discussed. Lower density of cities increases the energy spent per inhabitant, in particular for transport, but may also increase the production of low-carbon renewable energies, shifting the global energy balance and influencing the prospective studies of future, energy efficient, smart cities.

RÉSUMÉ

La consommation d'énergie par les bâtiments est un contributeur très important à l'empreinte climatique des ménages. Si on y ajoute l'énergie crise nécessaire à sa construction et l'énergie des transports, qui dépendent directement de sa localisation, alors la question du bâtiment devient le point focal de la problématique Énergie. Cet article présente une revue de l'évolution des différentes composantes des émissions de gaz à effet de serre associées au bâtiment dans le mix énergétique de la France. En conclusion, le paradoxe de l'effet de densité des villes est présenté. Les faibles densités induisent une augmentation de la consommation individuelle d'énergie, en particulier pour le transport. Mais elles permettent aussi une augmentation de la production d'énergies renouvelables réparties, ce qui modifie le bilan énergétique et la vision prospective des villes du futur, économes en énergie et intelligentes.

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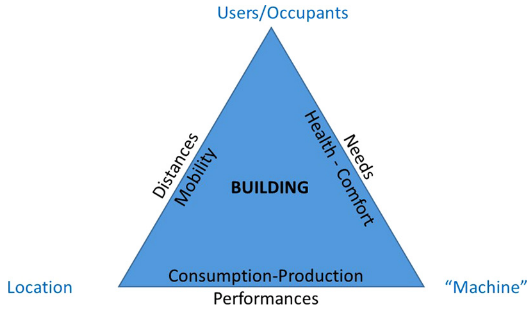


Fig. 1. Location, "machine", and users.

1. Introduction

Buildings are the witnesses of everyone's life, either at home for several aspects: private life, patrimony, family, relationships with neighborhood, or in other buildings such as school for learning, industrial and tertiary for working or commercial for shopping. Indeed, we spend 80% of our time inside buildings, which are traditionally the main places of consumption of all kind of products and where many goods consume energy to fulfill the occupant's needs. More recently, buildings and the built environment are shifting to the energy production side, mainly using photovoltaic, wind and biomass, a kind of "energy gardening".

Therefore, buildings, either single-family houses or collective housings or working places or culture and leisure locations can be investigated in different ways: technically, sociologically, or geographically.

"A house is a machine for living", said Le Corbusier in 1925. This very technical approach is often opposed to a very sensitive if not sensual approach, as underlined by Hölderlin's verse "Man lives as a poet" [1].

Beyond the "machine" and the poem, the first identifier of a building remains its address and, as generally claim real estate agents, "location first, location second, location third".

Fig. 1 briefly shows how location, "machine", and users interact and consequently contribute to energy consumption and GHG emissions during their life cycle.

Placing users or occupants at the center of the building environment is the leitmotiv of many actors of the construction sector [2], whether in residential or commercial or industry sectors.

Without looking in details the Maslow's pyramid of needs and by focusing only on residential sector, the living space must provide the basic needs for living, which are as follows: breathing, drinking, and eating [3]. This means enough fresh air to breathe, enough water to drink and foods for eating, but also "foods for brain & spirit" thanks to modern communications networks and services such as "cloud", which are growing energy consumers.

Even though most people have a sedentary lifestyle, mobility is an important aspect of their way of life, whether the chosen mobility for leisure and culture, or the mandatory one to go to working places, schools, or shops. Whether TV sets and more recently connected mobile devices may sometimes answer those needs without physical movements, they are also encouraging physical mobility, for longer range trips, either for work or leisure.

Finally, the location, the performance of machine named "building", and the efficiency of the equipment installed by the occupants, are the three pillars of the energy consumption that is considered in this paper.

What about energy? Generally, energy is claimed to be consumed by buildings, even though the technical object named "building" is responsible for a very little amount of energy consumption during its operational life [4], but much more during the conception, construction [5], and de-construction phases. In fact, most of the energy is consumed by occupants, despite they have no direct contact with energy vectors (fuel, gas, electricity) [6] and more precisely by equipment and goods offering services to them such as: I am hot/cold, I am cooking, I am using hot water for showers, washing and cleaning, I need light, fresh air from ventilation, I need to fill the tank of the car... Consequently, occupants do not feel directly responsible for energy consumption, as energy is consumed by equipment and, more generally, by buildings. Besides, it is interesting to note that energy consumption is counted in $\text{kW h/m}^2\,\text{yr}$ and not in kW h/person·yr. Moreover, if services were provided without fossil energy, people would not do matter.

2. Key numbers of energy/CO_2 for France

France is extremely dependent on imports for its primary energy: 98.5% of its oil, 98% of its natural gas, all its coal and uranium are also imported. Energy contribution to the international trade balance was as high as 32.5 billion € in 2015, and even 70 G€ in 2012 [7]. Due to its predominant position for transport needs, oil is taking the main part (64%) in GHG emissions, when gas contribution is only 24% and coal produces the remaining 12% [8]. In terms of primary energy, fossil energy (coal & oil) and nuclear energy (uranium) have an equivalent share, but in final energy terms, the weight of fossil energies is 64% and that of electricity only 25%.

In Table 1, the "transportation row" corresponds to all transportation systems (personal vehicle, public transportation, etc.), and it is assumed that "buildings" gather all types of buildings (public building, residential houses and dwellings,

Table 1
Final energy consumption for France in transportation, buildings, and industry [9].

Final consumption	Transportation				Buildings (residential and tertiary)				Industry			
Millions of TOEs	2005	%	2015	%	2005	%	2015	%	2005	%	2015	%
Oil	48.0	97.0	45.4	**92.0**	14.0	20.8	9.9	14.8	19.0	36.3	14.4	35.0
Electricity	0.8	1.7	0.9	1.8	23.0	34.2	25.7	**38.3**	11.8	22.6	10.0	24.2
Natural gas	0.0	0.1	0.1	0.2	22.2	33.0	20.4	**30.4**	13.9	26.5	10.1	24.5
Renewables	0.6	1.2	3.0	6.1	7.7	11.4	10.7	15.9	1.3	2.4	1.7	4.1
Coal	0.0	0.0	0.0	0.0	0.4	0.5	0.3	0.5	6.4	12.2	5.0	12.2
Total MTOEs	49.5		49.4		67.2		67.0		52.3		41.2	
%	31		33		43		45		33		28	

offices, etc.). The question of the underlying segmentation (or sub-segmentation) of sectors and category perimeters arises in Table 1, and the reader must keep it in mind when reading this paper to avoid too fast or wrong conclusions. From the figures of Table 1, it clearly appears that buildings and transportation represent 80% of final energy needs of France, with two main contributions, which are heating (almost 70% on average but of course more in old ones and much less in new ones) and individual cars, which represent 50% of transport consumption and 60% of road transports.

Even though the contributions of gas and electricity to transportation are growing [10], oil still fuels more than 90% of transports. This is why transportation is emitting more GHG than buildings due to its more diverse energy mix based on electricity and natural gas, which are much less polluting that oil and coal. Gas is more developed where a gas distribution grid exists. Oil heating systems are still common in less connected areas, such as rural areas. Coal is disappearing.

3. Key numbers: population and housing in France

INSEE shows that mainland France hosts 33.9 M dwellings [11] where 64.5 million people are living. The number of housings was about 28.3 in 2012. Among the 38.6 M vehicles, 31.9 M were cars in 2015 [12]. We notice here that the number of houses is almost equal to the one of cars, on average, between households with two cars and those without any, especially downtown, where public transportation systems are available.

Main dwellings are 28 M and represent 82.4% of the constructions. Among those ones, 50% where built before the first thermal regulation in 1974. Single houses are key for energy saving, as they represent 70% of the heating needs of private properties; they also offer a great potential for energy production thanks to the surface of their roofs.

Vacation homes and non-permanently occupied dwellings buildings represent 9.4% of the constructions, while non-occupied ones more than 8%. Individual houses are also the most common constructions in this segment.

The total surface of all living places is about 3 billion square meters, when tertiary building were about 1 billion square meters, of which 480 M are private properties. The size of housings has increased from 70 m^2 to 90 m^2 between 1970 and 2006, and today the average living space is around 91 m^2 for 2.3 persons. During the same period, the number of people living in one place has slowly but firmly decreased from 3.1 to 2.3. Those numbers mean that the available surface per person has almost doubled in the last 40 years from 22 m^2 to 40 m^2 [13], with a strong impact on GHG.

In most industrialized countries, new buildings will only contribute between 10% to 20% to additional energy consumption by 2050 (around 1% per year), whereas more than 80% will be influenced by the existing building stock and 75% of current buildings in OECD countries will still be standing in 2050. If refurbishing is not scheduled today, those existing buildings will become the energy problem of tomorrow.

Dwellings are located in the Paris area (more than 10 million inhabitants) for 16.3% of them. Then, metropolitan areas of both, more and less than 100,000 dwellings, host about 31% each. Rural areas host the remaining 21.9%, but also 44% of the vacation homes.

Those numbers clearly emphasize the importance of retrofitting of existing buildings to tackle the GHG emissions of the building sector. This challenge is not only a question of refurbishment and financing, but also a question of urban and rural planning to make smaller cities and rural areas, representing more than 50% of existing buildings, more attractive as they offer a lot of unoccupied dwellings and buildings. We will see further that these weakly urbanized areas might have strong assets in future post peak-oil or post carbon era thanks to surfaces, potentially available for PV production. Indeed, surface is the keyword to capture distributed renewable energies, such as solar, wind, hydro and biomass ones.

Furthermore, if we look at the Energy Performance Diagnostic,[1] even though its accuracy is questioned, 87% of the existing living places are expected to have a consumption rate of more than 150 kW h/m^2/yr [14]. It does not mean a real consumption as the occupants of these buildings are often no able to afford energy for heating their homes. This situation is called Energy Poverty; that is to say, your energy bill represents more than 10% of your income [15]. Energy Poverty is another challenge of the next years. In 2006, the energy cost represented 8.4% of the household's budget, 4.8% was spent [16] for home energy and 3.6% to fuel the cars.

[1] This Diagnostic is mandatory for every real estate transaction and then a large set of statistic is available. The global but simple procedure of the diagnostic make the result often different from that of the actual consumption of the buildings.

Table 2
Which resources and equipment to fulfill which needs of occupants?

Occupant's needs	Elements	Equipment	Energy vector	Energy source
House				
Breathing	Breathing air	Ventilation	Electricity	Coal
Comfort	Air	Heating	Wood coal	Fuel
		Cooling	Fuel, gas	Gas
			Electricity	Uranium
Drinking	Drinking water			Water
Eating	Eating food storage	Home appliance	Electricity	Sun
		(refrigerator, freezer)		Wind
	Cooking	Oven, cooking plate	Wood, coal, gas	Biomass
			Electricity	Biogas
Washing and cleaning	Water	Water heater	Coal, Wood, Gas	Agriculture food
			Electricity	
News	Paper	Paper and/or	Electricity	
Culture				
Entertainment				
	Electronics	Multimedia equipment		
Displacement				
		2–4 wheels	Gas, diesel	
		Urban transport	Electricity	

4. Uses: energy consumption and carbon emissions

As a "space for living somewhere", the building must answer the needs and desires of occupants, but energy consumption is hardly ever a primary decision criterion to select a building. People are more focused on location (quietness, job opportunity, shops, and schools, etc.) and well-being: natural lighting, acoustic comfort, air quality, none of this selection criteria are directly related to energy consumption, or only negatively when ventilation is noisy or combustion engines and boilers smell bad as they both, literally, "eat up" energy and produces "smokes", fine particles without considering other environmental and health impacts (noise, dust, dirt...).

Despite the very sensitive aspects of those selection criteria, occupants will have to cope rapidly with more practical aspects, like air ventilation, hot and cold water, and home appliances or multimedia equipment used to access news, culture, or games.

Moreover, one should not forget that despite huge conception and construction efforts since 1975, heating or cooling systems are still needed to achieve the comfort expected by the occupants, which, of course, depends on the climatic area.

Finally, a dwelling is basically a place with an address, from which and to which, occupants move to any facility such as schools, shops, jobs, cultural places, etc. Therefore, the mobility equipment, whether individual (bikes or cars) or public (buses, tramways, undergrounds. . .), cannot be considered separately from the home, as displacements result mainly from the home address. Today, the energy burden associated with mobility is almost the same as the one for heating home.

Considering the needs for living, Table 3 clearly shows that air (renewal, heating, and cooling) and water (in particular, heated water) are both most essential elements of comfort. Table 3 also shows which energy sources and which energy vectors can be tapped to fulfill those needs.

In Table 2, one can see that electricity helps to meet most of the needs, and that gas is also very versatile. Today, electricity is already used for 35% of the final energy consumption in buildings and gas for about 30%. Wood represents about 19% of the needs and oil only 15%. Oil is used mainly for heating, when wood and gas can help both for heating and cooking. In addition to heating and cooking, electricity is used for home appliances and multimedia equipment. Between 1990 and 2013, energy consumption has increased by 43% because of the increase in household's equipment.

Nevertheless, heating still represents 84% of dwelling emissions, before water heating and cooking, and will remain in the next years the main source of improvement, especially in the building stock.

At the national scale, Fig. 2 demonstrates that dwelling, transport, and food represent respectively 27%, 25%, and 19%, and then more than two thirds of French carbon footprints. In this figure, the contribution of the carbon content of imports is added to the one of direct and indirect[2] emissions. In 2010, the carbon footprint was of 10.5 tons of CO_2 equivalent per head on average. This represents the sum of all GHG (CO_2, but also methane and others) needed for each inhabitant of France for building and operating its housing, for transporting and producing all the goods and services he needed throughout the year.

Concerning the weight of transport for the households who use mainly individual cars, the total yearly distance is about 20,000 km [17], when it is only 13,500 km for those with only one car. Assuming a mileage of 6.5 l/100 km, a net calorific value of 10 kW h/l and a 100 m^2 house; we find that the consumption by cars is equivalent to 88 kW h/m^2 yr, for one car and 130 kW h/m^2 yr for an average household, which is close to the need for heating.

[2] Which are emissions associated with the production of the goods, and services, even though not directly seen by the end user.

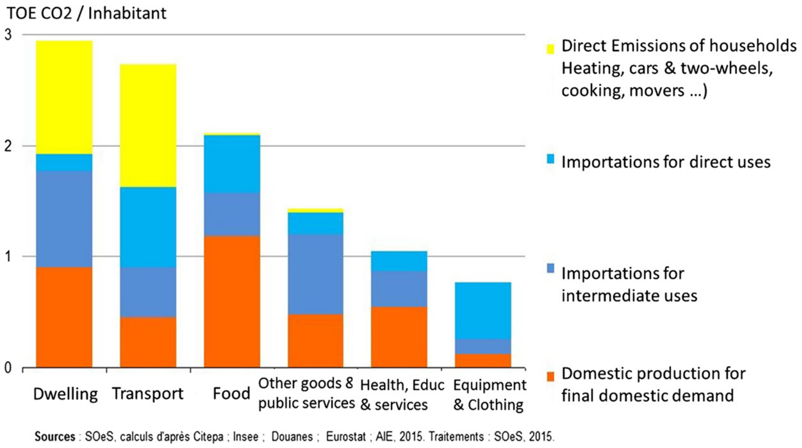


Fig. 2. France Carbon Footprint (2010). TOE: Ton Oil Equivalent.

To better illustrate the influence and the weight of human activities in terms of GHG emissions, let us use the equation proposed by Yoichi Kaya, a Japanese energy economist [18], who links human GHG emissions with four factors: population, gross domestic product, energy intensity, and CO_2 intensity. This equation is used to analyze and simulate the evolution of global GHG emissions and the impact of climate policy.

$$CO_2 = \text{Pop} \times \frac{\text{GDP}}{\text{Pop}} \times \frac{\text{Energy}}{\text{GDP}} \times \frac{CO_2}{\text{Energy}} \tag{1}$$

This equation can be transposed to housing [19] as follows:

$$CO_2 = \text{Pers} \times \frac{\text{m}^2}{\text{Pers}} \times \frac{\text{kWh}}{\text{m}^2} \times \frac{CO_2}{\text{kWh}} \tag{2}$$

Then, the four factors become:

(1) the number of inhabitants (person);
(2) the square meters per person (m^2);
(3) the energy consumption per square meter, which should be the sum of regulated consumptions (see § 5.1) and of specific electricity needs (multimedia, home appliances, etc.) and of indirect consumptions ("grey energy" from conception and construction of buildings);
(4) the carbon content of energy.

The first number is difficult to argue. The historical tendency of the last 30 years leaves little room to reduce the second term (see § 1). The third term has seen a major effort since the setup of thermal regulation in 1974 and has been since then regularly reinforced. The next step will be to consider home appliances and multimedia consumption and "grey energy". The last term appears as a new objective in the experimental label E + C [20] with the generalization of the so-called "energy-positive" & "low-carbon" buildings.

The same equation can also be adapted to transport, as shown by Equation (3):

$$CO_2 = \text{Pers} \times \frac{\text{km}}{\text{Pers}} \times \frac{\text{l-or-kWh}}{\text{km}} \times \frac{CO_2}{\text{l-or-kWh}} \tag{3}$$

As for buildings, the growing population, for which we have little leverage, will mechanically increase the need for transport. Urban planning and the density increase of cities may impact the second term, which will be discussed in part 6. Carpooling is also an answer to this term.

The third term is linked to the efficiency of the engine. As liquid and gas fuels are systematically associated with heat losses [21], a switch to electricity may contribute to the reduction of this term.

Fig. 3 shows that three options may help to reduce the CO_2 emitted from well to wheels and reduce the fourth term: bio-methane, hydrogen, and electricity, which may be used as new energy vectors for transportation, if primary sources used to produce these vectors are themselves low-emitting-carbon ones [23].

On the one hand, the evolution of the different terms of Kaya's equation for Dwellings between 1990 and 2016 can be seen in Fig. 4a. Despite the increase of the surface/person ratio and the increase of the population, CO_2 emissions by buildings have decreased. This is due, first to the setup of thermal regulation, second, to the reduction of the carbon emission due to the switch from coal and oil to nuclear electricity, and to the increase in gas consumption.

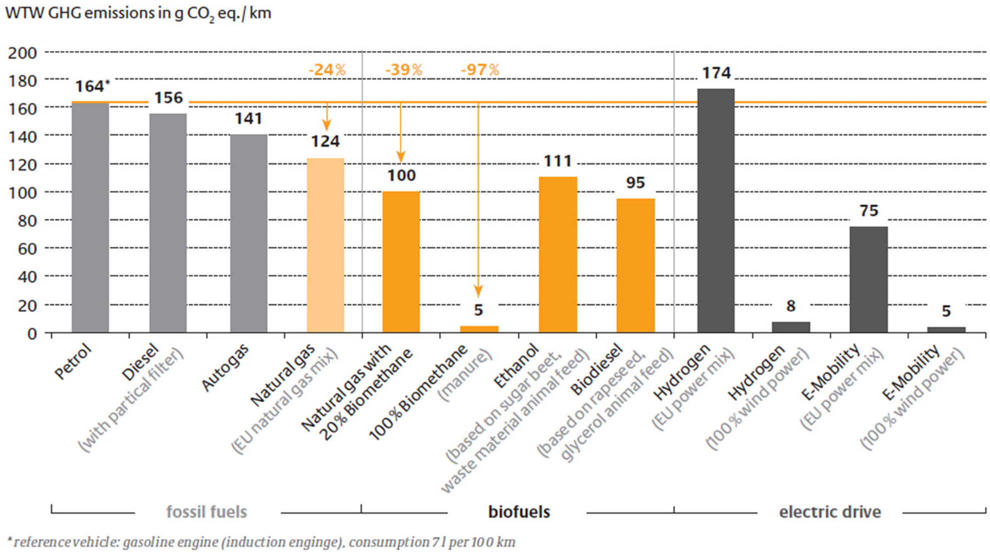
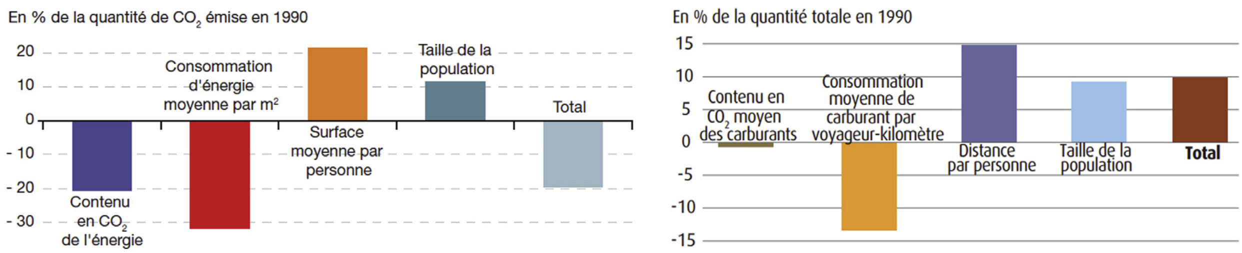


Fig. 3. CO_2 emissions by vehicles as a function of their fuel [22].



(a) (b)

Fig. 4. Evolution of CO_2 emissions. (a) Evolution of CO_2 emissions by buildings from 1990 to 2016 [24]. (b) Evolution of CO_2 emissions associated with personal vehicles from 1990 to 2007 [25].

On the other hand, one can see in Fig. 4b that the situation for transport has worsened because of the monopoly of cars and of oil as fuel for cars. Despite the improvement of the engines' efficiency, the increases of distances per person and of the population increased CO_2 emissions.

5. The performances of buildings

The main role of housing is to protect the residents from aggressions, whether physical or climate related, and to provide them safety and comfort, as well as a healthy and pleasant living space. In this paper, we analyze only the health and wellbeing aspects.

Let us first remind that the concern with air quality is not new: in the 1900s, the obligation to evacuate combustion emissions (already!) was already in force. In the 1960s, prior to the first thermal regulation, a global and permanent ventilation became mandatory, so as to provide the residents with good air quality. Since then, ventilation regulations have evolved, and the energy efficiency of the ventilation devices (low energy motors, variable flow, hermetic air network, ventilation with heat exchanger, etc.) was considered in the succeeding regulations. This demonstrates the growing importance of ventilation both, in the conception and the construction of buildings, not only because of energy efficiency, but also for safe interior air quality leading to increased wellbeing.

5.1. Thermal regulations for consumption reductions

Following the first oil crisis in 1973, France adopted its first thermal regulation (RT) in 1974 to reduce its energy bill. The first steps deal with improving the thermal insulation of the outer envelope. Subsequent regulation considers the efficiency

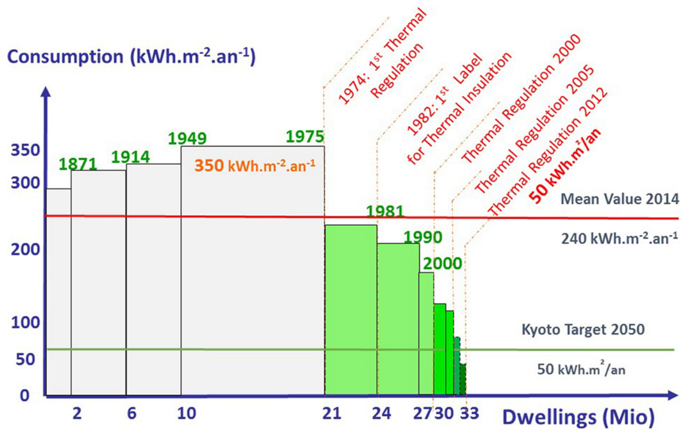


Fig. 5. Housing energy consumption and thermal regulation.

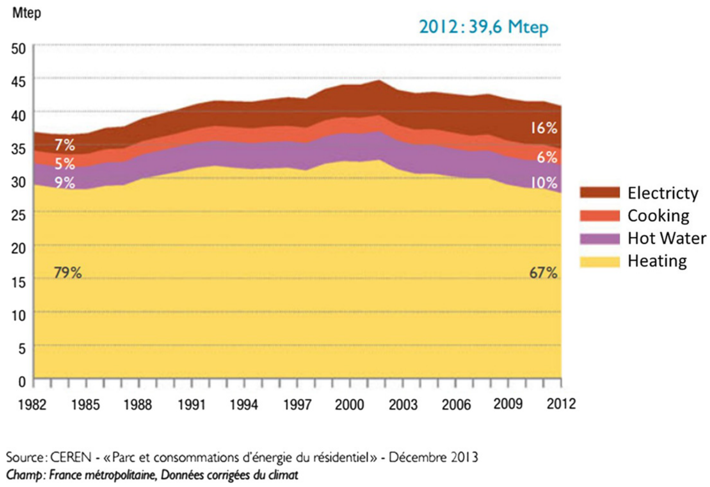


Fig. 6. Final energy consumption in residential buildings [26].

of heating devices, internal and solar heat gains, airtightness, and renewable energies. Today, the RT 2012 regulation limits consumption to 50 kW h/m^2 yr for the 5 RT energy users (heating/cooling, hot water, ventilation, lighting, and auxiliaries[3]).

As presented in Fig. 5, thermal regulation has progressively decreased the regulated consumption target for new buildings, to reach, in 2012, 50 kW h/m^2 yr; unfortunately, with no impact on the 20 million dwellings built before 1974, which have a heavy weight on the global values of energy consumption.

Let us examine each consumption component. Figs. 6 and 7 show that the successive RTs have operated a drastic reduction in heating energy in residential buildings (while the values in Table 1 in §1 bear on all buildings), but that the heating energy curve of the whole of buildings started to decline as late as 2001, or 25 years after the first RT.

Figs. 6 and 7 show that the final consumptions for hot water and cooking are practically constant, while specific electricity use (household electrical appliances and multimedia) increases.

The CO_2 emissions decline can be explained by the impact of the RTs and the transition from firewood, oil, and coal to electric and gas heating, which are less CO_2 intensive. Note that hot water, electrical appliances (including cooking), and multimedia items are determined by the household composition and the way of life more than by the building's performance. Heating needs can be reduced, thanks to the high quality of building conception and construction: insulation adapted to the local climate, thermal bridge exclusion, reinforced airtightness.

5.2. En route to energy-producing buildings

While the initial regulations aimed at reducing energy consumption without lessening, but rather increasing the wellbeing of the residents, the trend since 2005 is to develop local energy production, on-site, or near the building.

[3] Lighting and auxiliaries are grouped as one item because they consume only electricity. Auxiliaries comprise pumps and ventilators required for heating and ventilation.

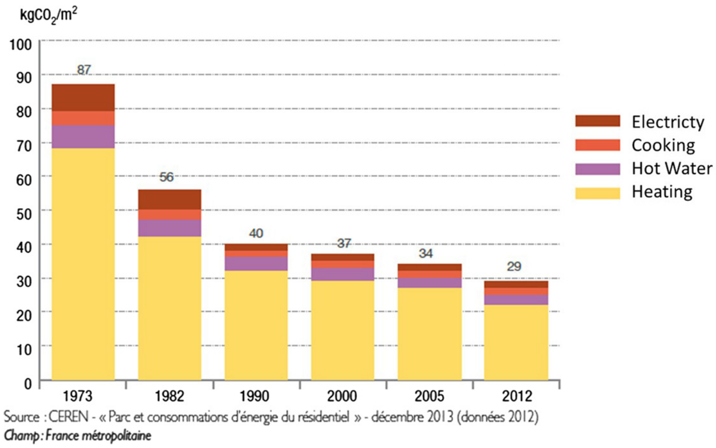


Fig. 7. CO_2 emissions and final energy consumption in residential buildings [27].

Table 3
Energy burden of households.

5 RT items average, standard (ADEME)	5 RT items RT2012 new	Specific electricity	Mobility fuel ICE	Electric mobility	Embodied energy average, building only (CSTB)	
240	50	67 (26 final energy)	88	52 (20 final energy)	53 (on 50 yr) for building construction only	kW hPE/m^2 yr

kW hPE/m^2 yr: kW h primary energy/m^2 yr.
Hypotheses: 100-m^2 house.
Private car: 13500 km/yr, 6.5 l/100 km – (primary energy coefficient = 2.58).
Specific electricity: 2600 kW h/yr for a household – source RTE [30] – (primary energy coefficient = 2.58).
ICE: Internal Combustion Engine.
Missing: embodied energy for appliances and transportation, the production of energy.

As early as 2004, the "Centre scientifique et technique du bâtiment" (CSTB, Scientific and Technical Center for Building Construction) had proposed to move towards positive-energy buildings (BEPOS) [28], an asymptotic concept aimed at inviting innovation in the building sector. This concept, of course, has its weak points. On the one hand, it concerns the building alone, while the consumption perimeter is not well defined and, on the other hand, the carbon content of local production units must be compared with that of other production units. In the BEPOS appraisal, should only the five items of the RT be considered, should the specific uses of electricity be added, and what about transportation and the embodied energy? These questions remain open.

In Table 3, the estimated respective weight of the main household energy content is given. Building stock and personal car [29] appear as the largest items, an indication that consumption reduction and decarbonation efforts should concentrate on these two sectors.

An RT 2012 dwelling associated with electric cars has a direct primary energy consumption 70% lower than that of a standard dwelling with a traditional car.

The values in Table 3 suggest that the embodied energy in a new building (RT 2012) is equivalent to the consumption of the 5 RT items (about 50 kW h/m^2 yr) on 50 years. For existing buildings, the embodied energy is only 20% of that of the five items, due to a very high energy consumption. Similarly, if the package (mobility + embodied energy + specific electricity use) were considered, this ratio would be modified again. Thus, great care must be taken when handling these values, and the perimeter of the consumptions considered must be detailed when arguing about energy efficiency.

In a recent study [31], the total embodied energy of a building (building + mobility + household appliances) is estimated to be around two thirds of the energy footprint of a household. In this analysis, a household's footprint is estimated at 343 kW h/day. Considering a 100-m^2 house, this corresponds to 1252 kW h/m^2 yr. With today's consumption, a household must produce several kW h/day to balance its direct consumption, and more than a thousand to compensate for its total energy footprint.

For existing buildings, more than 30,000 kW h/yr would have to be produced to balance the direct consumption for housing and transportation, requiring 2 to 3 m^2 PV panels per square meter of living space, i.e. for a 100-m^2 house, about 200 to 300 m^2. Indeed, with about 1000 kW h/yr/m^2 of solar insolation and PV panels with 20% efficiency, a 100-m^2 roof would yield 20,000 kW h/yr, hardly enough to cover direct consumption needs for housing and transportation. This objective is even further away for (multi-story) apartment buildings. Then, a so-called BEPOS would require a drastic consumption reduction, before seeking appropriate surfaces on which to produce the necessary energy with renewables (solar, wind,

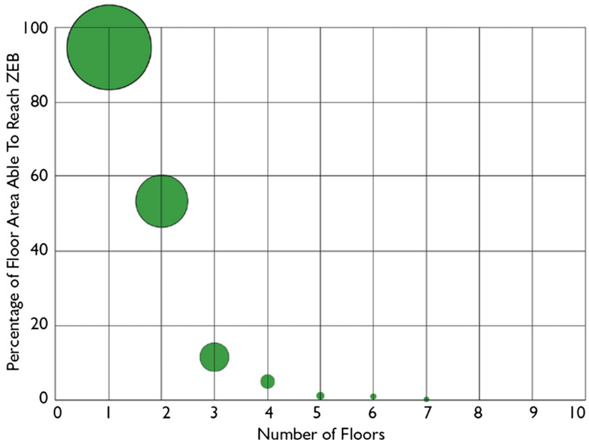


Fig. 8. Positive energy potential versus the number of floors [33]. The size of the disks shows the proportion of commercial buildings concerned. In the USA, these buildings tend to have one floor.

biomass...). As an example, Fig. 7, taken from an NREL [32] study, shows that for commercial buildings with more than five floors, it is impossible to reach the ZEB (Zero-Energy Building) target – even without including mobility. The ratio of the well-exposed exterior surface to the area of the habitable space is essential (but one must be careful about the projected shadow and the "right to sunlight", particularly in cities).

Today, for an RT 2012 building, one third to one half of the roof surface (about 50 m^2) would have to be covered to satisfy the needs of the building (RT + specific electricity), and the whole parking space for the electric car. In terms of annual energy consumption, the objective can be reached over a year but, in terms of instantaneous power, it would be quasi-impossible without a network connection that absorbs the production surplus and provides power when local production is not enough.

However, since the early 2000s, electric systems undergo a drastic evolution. This revolution is shown in Fig. 8. The post-war centralized system was unidirectional (Fig. 8a), with electricity produced by centralized utilities and then transported and distributed to the subscribers. Following the "Grenelle de l'environnement",[4] the consumer/producer has received financial incentives, via an attractive feed-in tariff (Fig. 8b), to produce electricity sold to the historical supplier at a very attractive price [34]. The purpose was to support the development of a French renewable energy industry, which never happened.

If the total amount of electricity consumed today in France – it was 473 TW h in 2006 [35] – were entirely produced with PV panels, the panels would completely cover a mainland department [36] or between 4000 and 5000 km^2. At the national mainland scale, this corresponds to about 60% of built surface, or 10% of artificialized surface.

With the new legislation [37] which fits into the local business & market trend, self-consumption, which was not forbidden, is now well identified from a legislative point of view. The producer may consume his production but must declare his installation to the grid manager, essentially because of safety considerations.

Self-consumption can be characterized by several indicators listed below:

SCI Self Consumption Indicator $\frac{\text{On site used PV Production}}{\text{Total PV Production}}$

SPI Self Production Indicator $\frac{\text{On site used PV Production}}{\text{Total Electricity Production}}$

CR Coverage Rate $\frac{\text{Total PV Production}}{\text{Total Electricity Consumption}}$

These three indicators vary with the measurement time step (hour, day, week, month, and year). In practice, they are generally evaluated on an annual basis, ignoring the demand curve and the renewable production variability. Still, the first two indicators give an evaluation of the site's capacity to satisfy its own consumption needs and consume its PV production. They consider the correlation between PV production and consumption. As for the coverage rate, it is no more than the ratio of PV production to total consumption.

To overcome these limitations and take interactions with the grid into account, power indicators have been introduced [38], in particular:

- the maximum power fed into the grid when production exceeds consumption,
- the maximum power taken from the grid when production does not cover consumption.

[4] The "Grenelle de l'environnement" debate was a political consultation process launched by the French President in 2007.

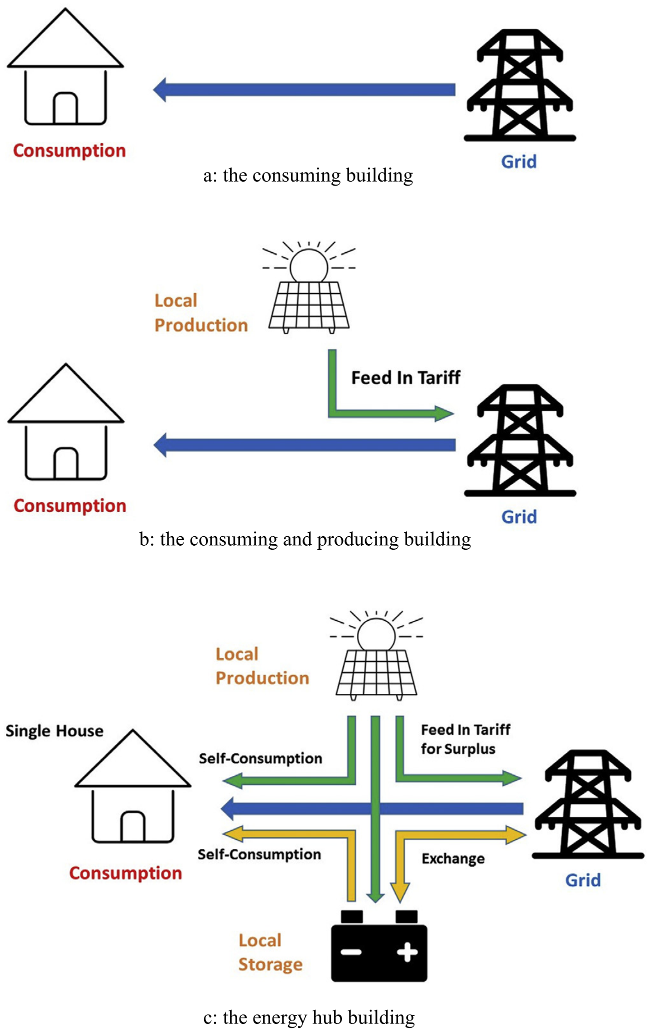


Fig. 9. Evolution of the role of buildings in the energy system downstream from the network.

These two indicators are not yet widely used, they require metering that new connected smart meter will provide.

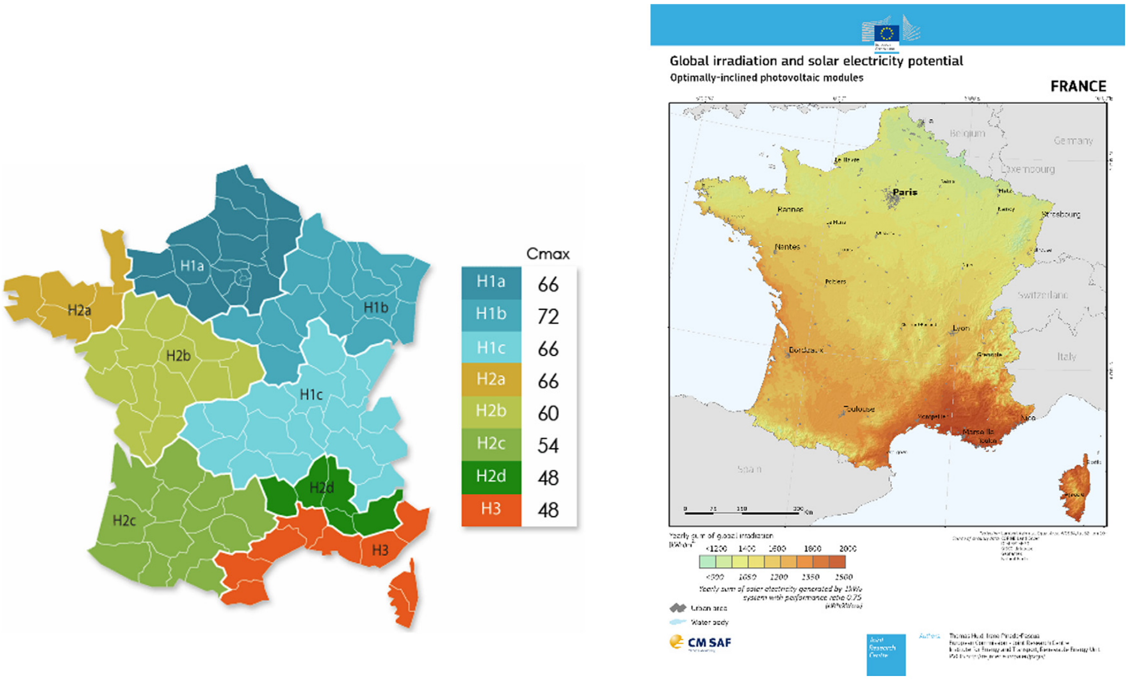
Clearly, while it is easy to consume all or part (in the summer, production well exceeds consumption) of the production, it is very difficult to satisfy daily demand all year round. Matching production and consumption implies fostering consumption equipment that is in phase with production (e.g., PV) and existing storage means such as:

- air conditioning or swimming pool pumps (direct consumption in summer),
- building inertia (walls, floors, ceilings, partitions...),
- hot-water tanks as thermal batteries,
- batteries of equipment for mobility (telephone, laptops, tablets, electric bicycles, electric cars...),
- cooling equipment, without deteriorating the cool chain.

Furthermore, energy exchange between cooling (refrigerator/freezer and air conditioning) and hot water equipment, energy recovery on many appliances (oven, cooking range, data processing devices...) are certainly routes to be explored when the industry begins to open up rather than working in closed silos. The objective is to offer more services by sharing and interconnecting household devices so as to reduce the carbon impact of new systems.

6. Location

The address remains the first building indicator and location predetermines the quality of life with potential contradictions (neighborhood and calm, proximity, and space...) and also the household residence cost [39] (housing + transportation index). The address is also often an indication of the housing's patrimonial and rental value.



(a) (b)

Fig. 10. Location-dependent consumption and production. a: Map of the climatic zones in RT and consumptions in kW h/m^2 yr [40]. *C*max: kWh/m^2 yr – Primary energy. b: Sunlight potential in France [41].

The energy-related aspects of location, transportation set aside, are taken into account by RT, which defines climatic zones (Fig. 10a), and the renewable energy production potential from solar energy (Fig. 10b) or from wind, for example. Most buildings are connected to the drinking-water and wastewater networks as well as to the electric grid. Fewer are those connected to the gas grid or district heating.

Between the dense city and its periphery arise the "area paradox" [42] and the distance issues. This concept highlights the following contradictory objectives:

- reducing the area of a building's envelope so as to limit heat leaks and embodied energy,
- increasing the well-oriented surfaces so as to increase passive inputs (sunlight, natural ventilation, solar collectors on the facade, rainwater collection...).

In a post-oil or post-carbon perspective, the main issue will not be consumption anymore, but the production using low-carbon and low-waste resources. But producing from renewable sources demands surface area. As shown in Fig. 9, dense cities cannot provide sufficient per-resident surface, which, by contrast, is available [43] in small provincial towns and rural areas. The large cities that have gradually destroyed their "feeding ring" will have to create new connections and new economic models with the surrounding territories [44]. Of course, constructed surfaces and artificialized areas will have to be given priority, in order to protect agricultural zones, although some of these could be developed with "agro-photovoltaics" [45] systems and biomethane.

This paradox has been discussed in several studies [46–50], and the effects are well illustrated in Fig. 10. The starting point is the well-known Newman & Kenworthy curve [51] (solid curve in Fig. 10) that plots the energy consumption of vehicles for mandatory mobility (commuting) versus different urban densities. This curve shows that consumption increases exponentially with the spread of cities, leading to the conclusion that densifying cities would limit this impact. Scenarios of simultaneous PV and electric vehicle development demonstrate a gradual inversion of the curve, coming to the opposite conclusion, thanks to efficient electric vehicles and the PV production potential of less dense cities.

Note that the curves in Fig. 10 take into account the consumption of private cars for transportation, without including the energy embodied in the construction and maintenance of the infrastructures (roads, highways, bridges...). This infrastructure issue is essential, whether for individual (roads, highways...) or collective (underground or surface rail) mobility, the latter being already mostly electric (subway, tram, train). Tomorrow, which, of autonomous electric cars on road or automated public transportation on dedicated lanes or tracks will have the smallest environmental impact, and the most support from the public?

Besides, leisure mobility (week-ends and holidays) should also be considered when analyzing the connections between urban density and household energy consumption [53].

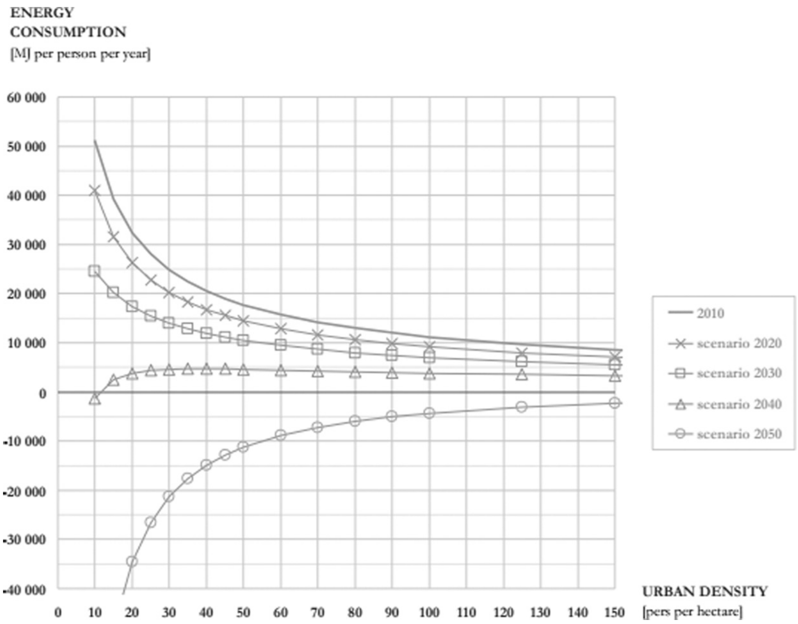


Fig. 11. Housing and mobility; urban density and energy choices [52].

Furthermore, the energy consumption of the building discussed in § 5.2 should not be forgotten. The 26 kW h/m^2 yr of specific electricity consumption, discussed in Table 3 of § 5.2, represent about 10,000 MJ/y per person. Be that as it may, the curves in Fig. 11 show that today's conclusions may well differ from those of tomorrow. Indeed, predicting the future by improving the fossil world of yesterday, for example, by reducing energy consumption only, could lead us to conclusions in contradiction to those that could be obtained by thinking today in a post-carbon world that everyone calls for.

Nevertheless, the curve beam in Fig. 11 indicates that the conclusions of a day are sometimes no longer that of tomorrow, because predicting the future by improving the fossil world of yesterday by reducing consumption only could bring us to conclusions opposed to those that could be obtained by anticipating today a post-carbon world that everyone calls for.

7. Conclusion

Can buildings become the site of energy sobriety, "energy gardening", and the hub of a new energy-sharing model? Yes, undoubtedly, all buildings, whether residential, tertiary, industrial, or public are good candidates to contribute to energy transition. Sobriety will be achieved, on the one hand, through improvements in the building itself (structure, envelope, surface usage) and in the equipment (heating, ventilation, lighting) and on the other hand, through the implication of its occupants in a frugal energy management. Their implication will increase if they become actors of their energy production and if they realize how difficult it is to produce low-carbon energy. Local production will also imply sharing and solidarity, potentially giving grid utilities a new role, moving from distribution to redistribution.

The energy hub building could also become the "filling station" for individual or collective autonomous, shared electric or biogas vehicles. In the vicinity of the building, the vehicle could be better used and play several roles: mobility, energy transport, office, even living room [54]. The general idea is to move towards less equipment and more services, to abandon the notion that "if you can move mountains, you can move molehills", and to do more with less.

Decarbonate, decentralize, digitize, and break down the walls between sectors are all among the priority actions that should be pursued today in the building sector and the associated amenities.

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