Dense cities in 2050: the energy option?

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Abstract

In 1989, a widely-publicized article by Newman and Kenworthy revealed the correlation between urban density and energy consumption linked to the car. It summarized in a "logo-curve" the chaos of urban sprawl. In its apology, this paradigm of hyper density has most certainly over encouraged land speculation in urban centres, this phenomenon causing in turn urban sprawl. The present paper re-examines this correlation: we assess the energy consumption loads generated by the use of the automobile and productions due to renewable energies installed in urban areas. A prospective vision is associated to two major technological developments.

Cars: 20 years after the publishing of the Australian article, the automobile industry has slowly started to initiate a change in energy policy: downsizing the engines, efforts to reduce weight, reducing friction, generalization of micro-hybrids, plug-in hybrids and the popularizing of electric vehicles.

Renewable energies: for the photovoltaic market as an example, where one can expect in 2015 a crossover between the cost of production of photovoltaic electricity and the sales price of the network. As a result, the decentralized storing capacities made possible by the use of electric vehicles shall offer a more satisfying answer to the intermittency of renewable. More generally, annual production of renewable energies is in direct relation to the spatial extent of their surface.

As a result, low density implies the increase of potential production (brought to the inhabitant of the urban area). The addition of these two phenomena is outlined and analyzed in this paper. Nearing 2040, it's very likely that the energy balance be more favourable for urban areas of low density (and for CO_2 emissions as well). This tendency should therefore influence political incentives in order to develop first and foremost automobile efficiency and a decentralized production in those urban locations.

Introduction

BACKGROUND

Urban density and car use

Twenty years ago, Newman and Kenworthy (Newman, 1989) highlighted the relation between urban density and energy consumption due to individual car use. From data collected worldwide over large metropolitan areas, this correlation revealed that as urban density increased, fuel consumption was reduced. This asymptotic behaviour has been largely popularized for the past twenty years. The said curve became the logo and an introductory slogan for ecological advantages of the compact city. On the other side of the mirror, this study quantified the impact of automobile devastation as a result of urban sprawling. Fouchier (Fouchier, 1997) furthered this study taking for examples some new towns in outer Paris. The correlation revealed an identical behaviour to the one demonstrated by the Australian researchers. In other works (Banister, 1997), urban density is the predominant parameter on modal choices for ground transportation, annual distances and energy consumption.

Shortly after Newman and Kenworthy had published their article, other articles appeared which challenged their conclusions (Gordon, Richardson, 1989). Breheny (1995), and Gordon and Richardson again in 1996, did not agree at all with the idea that the compact city was the answer to reducing pollution, underlining the effects of congestion that would be generated and the drastic measures that the diffusion of a model based on high densities would impose. This research strives to demonstrate that a territory with more than one hub-and-spoke network, can also reduce the distances of displacements (Breheny, 1995).

A "decentralized concentration" would be, for the opponents of density in the strictest sense of the word, a more effective model of urban development to reduce automobile displacements (Jenks et al., 1996). Owen refocused the debate a year later by demonstrating that although density is an essential element it is not enough to noticeably reduce car transportation. In spite of notable divergences in the quantitative results, the majority of research accepts the idea that the role of combinations between rate of compactness, level of concentration around an economic centre, density, structure of displacements and localization of employment and services are as many urban levers to reduce consumption of energy and the GHG emissions.

Climate change and energy outlook in car industry

The Automobile is a key issue in global warming context: cars are responsible for 10 to 15 % of fossil carbon dioxide emission. Considering this background, the European Parliament has adopted a compromise which envisages bringing back the average of the CO_2 emissions of the new cars to 130 grams per km by 2015. Jointly, the recurring tensions on the price of oil, like the uncertainties upon peak oil, encouraged the car manufacturers to progress in the efficiency of the motorizations (cars absorb nearly 35 % of the world oil consumption).

With the diffusion of gasoline engines, the development of «downsizing» (reduction of the engine's cubic capacity and addition of a turbo-charger), the reduction in solid and aerodynamic frictions, generalization of the micro-hybrid systems and the appearance of plug-in hybrids (hybrid motorization and electric capacity with an autonomy of about 30 to 50 kilometres in electric mode), all aim to reducing the average consumption of the new cars on the worldwide market (CCFA, 2009).

There remains nonetheless the danger caused by the race for hyper-comfort, and advertisements encouraging the purchase of the "big car" (success of the Sport Utility Vehicle, all-wheel-drive vehicle, imposing minivans and other Crossovers) generate overweight and also contribute to reducing the lever of energy efficiency (Roby, 2006; MacKay, 2009)

Contemporary integration of energies in urban context

As a rule, cities do not produce energy. The presence of a heating district network or power plants inside cities need essentially routing of energy vectors extracted from urban areas: fuel, gas, wood, electricity etc: the cities convert or consume fossil and final energies. They are poorly equipped with systems authorizing the conversion of the renewable energy flows.

In few cases development of green neighbourhoods encourage integration of renewable power plants like photovoltaic and solar thermal, wind power often in an anecdotal way, geothermal heating when the resource is available and finally biomass (famous case of the eco-neighbourhood, Vauban, Freiburg in Germany). In the latter case, pellets are imported: places of collecting energy remain broader than the perimeter of consumption.

Considering photovoltaics (Weller, 2010), its detractors evoke either the consequences of a bad architectural integration (multiplicity of micro-production without a good e-m strategy), or the complexity generated by the management of connection to the local electricity grid (and also polemic surrounding policies of feed-in tariff). In particular, the fall of the production cost of solar panels (Euros per Watt peak) and the global capacity of world production (MW peak produced per year as a unit of panel production) makes grid parity tangible after ten years (BCG, 2008).

And photovoltaics (PV) are certainly the renewable energy source with the greatest potential for integration in cities. The type of energy provided (electricity) is perfectly adapted to the needs of the electric car or the hybrid (Menard, 2008): 20 m^2 of PV-panels produce each year the equivalent of 10,000 to 20,000 km for an electric-driven car.

MOTIVATION OF THE STUDY

The present study reconsiders this interdependence and advances a theoretical explanation for this correlation: the more the density increases, the less the dimensions of the mean cell of territory occupied by the inhabitant decreases. This typical length is proportional to the reverse of the root of the urban density: a preliminary power law.

In this paper is presented notably some scale invariants for annual average car displacements by inhabitants. Secondly, the study establishes the relationship between urban density and the mean surface of territory virtually allocated for each inhabitant. Consequently, considering a broad diffusion of renewable energies (BCG, 2008), and more specifically of solar technologies whose collective surface is more or less a horizontal plane, low density implies the increase of the potential production by renewable energies.

On these bases, the present paper reveals a new type of behaviour pattern of the density-energy curve, as a function of the average producibility of the considered urban land. We define producibility as the average annual production of renewable energy converted into primary energy per urban hectare ($MJ.ha^{-1}.yr^{-1}$) The next part evokes some orders of magnitude of producibility for various renewable energies: solar, wind, geothermal power and biomass (Lhomme, 2001; MacKay, 2009). This paper develops the feasibility of large scale integration in urban situations of these renewable energies: which ones are the most likely to balance energy consumption caused by the use of the automobile? For synthesis, the last part proposes several scenarios up until 2050 on the implementation of renewable energies, associated with the prospects for evolution of the average consumption of the automobile fleet.

Limit and assumptions of the study

In the projected scenarios, we have considered that the relationship binding annual displacements and urban density is constant: it is possible obviously that this correlation may evolve according to circumstances and the economic future. The formulas developed in the following section must be considered as a global trend and a probable change of scatter plot. One might also bear in mind that the estimation of producibility – and in particular for solar technology- is based on typical solar gain in Europe around 50 ° of latitude (global horizontal ~1100kWh.m^{-2}.yr^{-1}).

A preliminary theoretical approach

GENERAL PRINCIPLE

Basic equation

The framework of this article consists in evaluating the sum (as annual primary energy consumption per person) of the two following contributions, and then to exhibit the relationship with urban density, *d* ([E1] and [E2])

$$\varepsilon^{TOT} \equiv \varepsilon^{MOB} + \varepsilon^{ENR}$$

$$\varepsilon^{TOT} \equiv \varepsilon^{TOT}(d)$$

- ε^{MOB} corresponds to the annual consumption, related to personal use of car (in MJ.pers^{-1}.yr^{-1}). The dependence with urban density will be based on the results from Newman and Kenworthy's work. When the final energy is electricity, one retains the national coefficient selected to translate the content in primary energy delivered energy (2,58 units of primary energy for 1 unit of electricity delivered as French coefficient for example)
- ε^{ENR} is the annual renewable energy production per person (in MJ.pers^{-1}.yr^{-1}). When the production is electricity, this value is multiplied by the coefficient of the national mix: it is considered that this production avoids the equivalent drain to the electricity network.

Power law definition

Mobility

The aim of this study consists in writing [E3]:

$$\varepsilon^{MOB} \propto d^{\alpha} \equiv L.c.\left(\frac{d}{d_0}\right)^{\alpha}$$

With:

- *L*, annual distance per year and per person for the density of reference (in km.pers^{-1}.yr^{-1})
- d_0, urban density of reference (in pers.ha^{-1})
- *c*, average consumption of the car fleet, translated into primary energy (in MJ.km^{-1}). We note that energy density is 36 MJ for one litre of gasoline (resp. 33 MJ for fuel) and α as power law exponent.

Renewable energy production

For the energy production, we expect to fit into the following power law definition [E4]:

$$\varepsilon^{ENR} \propto d^{\beta} \equiv -p.\left(\frac{d}{d_0}\right)^{\beta}$$

Note that the minus sign. The convention is: >0 corresponds to an energy debit; <0 an energy credit. With:

- *p*, average urban land producibility for urban density of reference (in MJ.pers^{-1}.yr^{-1});
- *β*, power law exponent of the fitting curve.

Basic equation in power law [E5]

$$\varepsilon^{TOT} \equiv K\mu^{\alpha} - p\mu^{\beta}$$

With the unitless parameter $\mu = \frac{d}{d_0}$, we write down the extrema μ_{cr} and the zero μ_{neutre}

$$\mu_{cr} = \left(\frac{K\alpha}{p\beta}\right)^{\frac{1}{\beta-\alpha}}$$

$$\mu_{neutre} = \left(\frac{K}{p}\right)^{\frac{1}{\beta-\alpha}}$$

TRAVEL AND MOBILITY MODEL

Pudding and density

To popularize the cosmic expansion after the Big-bang, astrophysicists frequently employ the metaphoric image of raisins in a fruit cake (Stephen Hawking in *A Brief History of Time*, 1988): stellar galaxies move away from one another, not so different from the raisins moving away from one another as the cake rises during baking time. The same applies to urban density: the more sprawled the city, the more specific the distance separating myself to the others increases. Let us call *a*, the typical length of the personal cell (if urban ground is equally shared between all users). For example, if urban density is 100 personas per hectare, the typical distance between the nearest inhabitants is 10 meters. We note [E6], with *a* is in meter:

$$a \equiv \frac{100}{\sqrt{d}}$$

First theoretical power law definition for mobility

This characteristic distance separating two individuals (or two functions of the city) seems able to provide the typical scale of any displacement and thus, the temporal sum of those individual displacements. According to this logic, it is not unreasonable to suppose $\alpha \approx -.5$. Using [E3] and [E6], one writes [E7] as:

$$\varepsilon^{MOB} \cong K\mu^{-0,5} \equiv L.c.\sqrt{\frac{d_0}{d}}$$

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RENEWABLE ENERGY PRODUCTION: A FIRST MODEL

Flow energies

As introduced previously, the development of a decentralized energy production proposes a simplistic relationship with density. As non-concentrated energy but distributed along the surface (Lhomme, 2006), the horizontal plan determines the annual production for solar production (resp. vertical plan for wind power). The denser the city, the more the horizontal surface offered to the elements by user decreases; consequently the potential energy output per individual decreases.

First theoretical power law definition for renewable energy production

The reverse of the density characterizes the quantity of urban territory per inhabitant. Also, by taking as a first assumption a low correlation between density and urban form, the reverse of the density is then proportional to the average roof surface per user. According to this preliminary axiom, one concludes [E8]:

$$\varepsilon^{ENR} \equiv -p.\left({}^{d}\!/\!_{d_0}\right)^{\beta} = p.{}^{d_0}\!/\!_{d}$$

FIRST GLOBAL ENERGY EQUATION

Combining [E7] and [E8], we find [E9] as:

$$\varepsilon^{TOT} \equiv K\mu^{\alpha} - p\mu^{\beta} = \frac{K}{\sqrt{\mu}} - \frac{p}{\mu}$$

Characteristic values and relationships

From this preliminary equation, one can note (and the inequality [E10]):

$$\mu_{neutral} = \left(\frac{p}{K}\right)^2$$

$$\mu_{cr} = \left(\frac{2p}{K}\right)^2 = 4\mu_{neutral}$$

$$\varepsilon^{TOT} \leq \varepsilon^{TOT}_{MAX} \equiv \varepsilon^{TOT}(\mu_{cr}) \equiv \frac{K^2}{4p}$$

The first value refers to the reduced density which allows the objective of neutral energy urban land. The second relationship corresponds to the critical reduced density: it represents the maximal energy consumption per person and per year. From [E10], one can notice the energy consumption is limited by a maximum value for any scenario of evolution of urban density. This maximum (ε^{TOT}_{MAX}) depends in a stronger way on specific consumption of the car fleet (*K*) rather than the typical producibility of renewable energies (*p*).

Cars

CAR FLEET AND PROSPECTIVE OF EVOLUTION

Example of the French car fleet

Table 1 shows the drop in average fleet specific consumption in the French car fleet between 1990 and 2005. Under the effect of the tax incentive via the bonus-malus, it is probable that this decrease will be more important for 2010–2020 decade. For example, the average emissions from personal vehicles sold in France in 2008 were 139 grams per kilometre: that means for petrol an average consumption of 5,9 litres per 100 km and 5,3 for gaseous fuel.

The electric car

After a stumbling start (Paine, 2006), it is to be noted that the car industry has recently initiated its conversion to electrification, and envisages the integration of this offer in a not too distant future: plug-in hybrid, the Prius III at Toyota, the Volt at Chevrolet for 2011, and 100 % electric (arrivals on the market in 2011 of Peugeot Ion, Citroen C-Zéro, Renault Kangoo ZE, …), etc. Beyond the obvious advantages in terms of noise and pollution, the electric car presents an inherent energetic efficiency (the output tends to up 90 % of mechanical conversion of the electricity) with the following arguments:

- The thermodynamic machine of the thermal vehicle has its maximum output on a reduced range of power.
- The electric motor delivers its maximal torque at 0 rpm: a real advantage in city driving.
- The electric motor (and hybrid devices also) authorizes recuperation of energy in deceleration or braking.

The question of the autonomy and the infrastructure of charging stay problematic for the electric vehicle.

However:

- The cars available on the market in 2010, promise a range about 100 to 200 kilometres: it is well adapted to daily displacements home to work, since at least one of these places proposes a terminal of charge. For this reason, a terminal at individual residences allows undoubtedly a better optimization, with the assumption that charging takes place during the off-peak hours for the electricity grid. Low density will eventually help the diffusion of charging points in individual garages.
- One awaits the imminent launch of plug-in hybrids (which have a thermal engine as an autonomy extender).
- The houses in low density statistically increase the potential rate of equipment with PV-roof on individual parking: a chance for the installation of individual terminals.

In France, consumption in primary energy of an electric car (with a typical 15 kWh for 100 km and a specific primary energy-electricity ratio of 2,58) is identical to a gaseous fuel run vehicle consuming 3,5 liters/100 km: very few petrol-driven cars provide this performance. It is also important to keep in mind the advantages of the electric car in terms of noise, air pollution and hydrocarbon pollution. Also let us note the potential

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Table 1: Evolution of the French car fleet specific consumption.

		1990	1995	2000	2005
Average fuel consumption	*l / 100km*	8,25	7,76 *(-6%)*	7,49 *(-4%)*	7,09 *(-5%)*

Left, the Bell PV-car park in Albuquerque (New Mexico, USA): 1,600,000kWh of electricity a year on 2 hectares of parking area. In the middle, a plug-in hybrid, the Prius 3, connected to PV-panels for reload. Right, a 2"wheel car", X-Prize winner 2008 during the Zero Race in 2010: the shape as a lever for efficiency.

Figure 1: From renewable electricity to friction efficiency.

Table 2: Scenario of evolution of the average car fleet consumption in primary energy.

		2000	2010	scenario 2020	scenario 2030	scenario 2040	scenario 2050
Average fuel consumption	*litres / 100km*	7,5	6,5	5,5	5	4,5	4
Average electric consumption	*kWhelec / 100km*	20	17	15	14	12	10
Equipment of electric car	*%*	~0%	~0%	1%	10%	20%	35%
□ **c**	*MJ.km^{-1}*	2,6	2,2	1,9	1,7	1,5	1,2
□ **K**	*MJ.pers^{-1}.yr^{-1}*	25 628	22 211	18 745	16 677	14 530	12 135

consequences of the broad diffusion of the electric cars on dimensioning at a peak of production for national electricity. It is necessary also to point out the symbioses awaited between electric mobility (as potential decentralized storage), smart grids and the renewable energies.

Scenarios of fleet evolution

The French National Strategy for the deployment of the infrastructures for recharging the electric vehicles and plug-in hybrid estimates 100,000 vehicles by 2015 in order to launch the market. While based on the Ademe document and by assuming that as from 2020, 10 % of new cars shall be electric, one then projects the scenario summarized in the table below: we retain however a lower value in the 2020.

> By 2020, the inertia of the vehicle fleet in France (2 million new vehicles sold per year, on more than 30 million light vehicles) will not allow to imagine a "tsunami" of electric vehicles. If the options of development evoked in the various works in progress are reached, they are a little more than one million electric vehicles which are conceivable at this horizon, that is to say approximately 3 % of the fleet. (Ademe, 2009)

This scenario also projects a continuous fall of the average fuel consumption of ICE vehicles of one half-litre less in each decade after 2020: the current trend is about double that. However, the optimization of sobriety will be confronted with an asymptote of friction: a very good shaped car (with S.Cx=0,5m^2) needs 5 kW of power to oppose aerodynamic forces at 100 km per hour.

UPDATE OF THE CORRELATION BETWEEN URBAN DENSITY AND ENERGY CONSUMPTION

Newman and Kenworthy (1995)

As expressed in energy consumption, the paper of Newman and Kenworthy (1989) unveiled the link with urban density without taking into account local specificities of car fleet and in particular the average automobile consumption. American cars are well known for consuming more fuel than European and Asian ones. In their article of 1995, Newman and Kenworthy mitigated this difficulty, to highlight the distance covered on average by town dwellers. The power law found by Newman (Newman 1995) was [E11]:

$$L(d) \equiv L\left({d}/{d_0} \right)^{\alpha} \equiv 105866 d^{-0,6612} \equiv {\varepsilon^{MOB}}/{c}$$

With $\alpha \equiv -0,6612$, this exponent is close to theoretical result (-0,5, as found in last section). One could also interpret this coefficient as a 'virtual' fractal dimension of the automotive infrastructure: it will be thus equal to 1,32.

Update of equation [E3]

We define urban density d_0 as Ld_0 equals 10000 km. With [E11] and [E3], we have:

$$d_0 \equiv 36$$

$$L(d) \equiv 10000\left(d/36\right)^{-0,6612}$$

For this density, the specific length of the cell is 17 meters (remember [E6]). We could also interpret ([E12]):

$$L \approx 10000.\sqrt{\frac{d_0}{d}} \equiv 10000.\frac{a}{a_0} \approx 6.10^5.a$$

It means the typical annual distance is almost 60,000 times the length of the typical length of individual urban cell.

Conclusion for mobility equation

We note then [E13]:

$$\varepsilon^{MOB} \approx K\mu^{-\frac{2}{3}} \equiv L.c.\left(\frac{d_0}{d}\right)^{\frac{2}{3}} \equiv 10000.c.\left(\frac{36}{d}\right)^{\frac{2}{3}}$$

Renewable energies

PROSPECTIVE

Evolution of photovoltaic technologies

From an economical point of view, one expects a coincidence between the marginal production cost of photovoltaic with the sales price of the electricity network operators. The sweet-spot (or grid parity) is hoped for by 2015–2020 (BCG, 2008). The probable development of tracking device will also permit to maximize the annual productivity. In addition, we can note the potential evolution of photovoltaic combined with heat production: pre-heating beneath the photovoltaic panel (and thus a reduction of the building heating needs), combination of wafers with optical concentration (Fresnel lens, parabolic mirrors etc.) and collection of the heat generated.

Large scale technologies into city?

Within the framework of the consultation for Grand Paris (2008), a proposal consisted of integrating renewable energies in an urban situation on a large scale definition: great urban voids (parks, parking …) could participate in the metropolitan energy production. A further development of this proposal could consist of the adaptation on a large scale of the CSP technologies into the urban landscape: the output of the annual solar gain would be maximized by developing production of electricity, of heat even also of chilled production.

SCENARIO OF PHOTOVOLTAIC INTEGRATION IN URBAN AREAS

Table 4 synthesizes a possible scheme of integration of urban producibility. In order to evaluate a typical potential of production, we chose here to equip mainly the roofs with photovoltaic panels, and estimate a possible evolution of equipment of the roofs linked with the increase of the typical output in future years.

Synthesis of scenarios

We approach in this last part of the synthesis, highlighting the total energy balance based on:

1. The scenario of the car fleet evolution and the power law curve of annual distance [E13];
2. The scenario of the potential energy urban production, based essentially on photovoltaics technology.

GLOBAL ENERGY EQUATION

The update of the energy balance can thus be written [E14]:

$$\varepsilon^{TOT} \approx K\mu^{-\frac{2}{3}} - p\mu^{-1}$$

In this case, we have:

$$\mu_{neutral} = \left(\frac{p}{K}\right)^3$$

$$\mu_{cr} = \left(\frac{3p}{2K}\right)^3 = \frac{27}{8}\mu_{neutral} \approx 3,4\mu_{neutral}$$

$$\varepsilon^{TOT} \le \varepsilon^{TOT}_{MAX} \equiv \varepsilon^{TOT}(\mu_{cr}) \equiv \frac{4K^3}{27p^2}$$

Like the first theoretical case (recall [E10]), the last inequity [E15] revealed a stronger dependence toward the typical car consumption (*K*) rather than the average producibility (*p*).

A FIRST PARAMETRIC SCENARIO

We investigate in this paragraph the effect of renewable integration (see Figure 4). As a first step, the car fleet corresponds to the one in France in 2010. The basic scenario presents thus the consequences of a volunteer program which would strongly encourage investment into urban renewable technologies.

p~0 MJ.ha^{-1}.yr^{-1}

The left curve shows the contemporary total balance in France (negligible integration in urban context). The shape fits with the Newman's asymptote.

p~500 000 MJ.ha^{-1}.yr^{-1}

The graph in the middle simulates a reasonable integration of eco-energies: it corresponds to the average electric productivity of 5 kWh per m² of urban land and per year (and equivalent also 1/20 of urban landscape covered with PV-panels with a typical productivity of 100 kWh.m^{-2}.yr^{-1}). We also note that the curve is much flatter: the dependence to density is lowered. At low density, the curve lost a maximum to infinite. But urban land keeps a global negative-energy behaviour: personal use of automobile require energy out of the considered urban area.

p~1 000 000 MJ.ha^{-1}.yr^{-1}

For a double quantity of producibility, the curve takes an opposite shape. At low density, the production exceeds the consumption of cars. Beyond 100 persons per hectare, the dependence with the density becomes very weak: there is a relative balance between the reduction in consumption associated with individual displacements and reduction with the production per capita.

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Table 3: A brief panorama of renewable energies and their capacity to integrate into cities.

	Type of energy	Urban situation for integration	Potential	Difficulties	Typical annual production
Biomass	Food Fuel Wood for heating	· Garden plots · Vegetable plots · Small market gardens in or on the outskirts of the town	· For food production, decrease the global carbon footprint (reduction of transport) · Storage possible · Low investment	· Very low output of solar energy: less than 1% (and more generally comprised between 0,2 and 0,5%) · Smoke and air pollution generated by wood combustion	· Maximum of 360000MJ.ha^{-1}.yr^{-1}, field of Miscanthus, (MacKay, 2009)
Photovoltaic	Electricity	· Roofs (and facades) of buildings · Photovoltaic covers on carparks · Large urban voids · Prospective: road covers	· Quiet, safe and easy to maintain · Intermittency relatively foreseeable · Improvement of the technology : typical conversion into electricity is 10% (varies between 5% and almost 20%). Output expected in next decade : 15 to 25% · Architectural integration relatively simple · Perenniality is interesting (the outputs are in general guaranteed for a total value of 80% over a life-span of 20 years)	· Cost and difficulties for electricity storage in 2010 · Cost of production and investment in 2010 · Decrease of the albedo and consequence on local heating islands · Sensible to partial solar shading	· 70 to 150 kWh of electricity per m² of panel and per year (Weller, 2010) · 600 000 MJ.ha^{-1}.yr^{-} (typical annual production for BedZed neighbourhood) · 6 200 000 MJ.ha^{-1}.yr^{-1} for the PV parking cover of the Bell Group Headquarters in New Mexico (USA)
Solar thermal	Heat (generally hot water <70°)	· Roof, facade of buildings	· Rudimentary technology · Direct consumption · Easy to mix with traditional fossil fuel driven heating device	· Creation of a hot loop in interface with the building · Few examples of mid to long term heat storage · Unable to generate electricity	· 200 to 400 kWh of heat per m² of panel and per year
Geothermal	Heat Cooling	· Slab and ground under and around buildings	· Low investment for a new construction · Discrete integration · Direct consumption · Reversible for cooling production	· Require installation of heat pump · Ground warming · Weakness of heat flow ~ 0,06W per m² of ground · Unable to generate electricity (only few examples in very specific areas: Iceland, French Caribbean islands, …)	· From 15000 to 41000 MJ.ha^{-1}.yr^{-1}
Wind power	Electricity	· Roof of building · Light candelabra · Large wind turbines in big urban voids	· Availability of new design of vertical axis wind turbine dedicated to urban integration · Huge wind turbines (with horizontal axis) sometimes compatible with urban context (offshore wind turbines near Copenhagen)	· Turbulent layer of wind in urban situations : consequences on productivity of wind turbines uncertain · Difficulties for building integration (vibrations, noise, aesthetics, ..) · Weakness of swept areas in urban context · Intermittency of the production	· 600000 MJ.ha^{-1}.yr^{-1} (MacKay, 2009) to 1 800 000 MJ.ha^{-1}.yr^{-1} (classical wind farm)
Hydraulic power	Electricity	· Rivers in city · Bridges	· Local opportunity · Merely dedicated for hamlets or villages · Production constant	· , Urban rivers generally strongly regulated : their stream is lower than in outer situation (due in part to water risk management) · Very low captured area (cross section of the urban river) compared to the urban land	
CSP (Concentrated Solar Power)	Electricity Heat (Cooling)	· Buildings · Urban voids	· Capacity of storage for heat generated (via molten salts) : the electricity production can thus be adapted, and smoothed on the rhythm of the day · .On a smaller scale, one will note a prototype devoted to individual integration: recent Solar Decathlon with the Napevomo project (2010) · High output of solar conversion	· Contemporary examples of large scale confined to extra-urban situations · Dedicated to zones where the direct solar availability is very important (Solar Paces, 2009)	8000000 MJ.ha^{-1}.yr^{-1} (PS10 Solucar in Spain near Seville) 7500000 MJ.ha^{-1}.yr^{-1} (Nevada One)

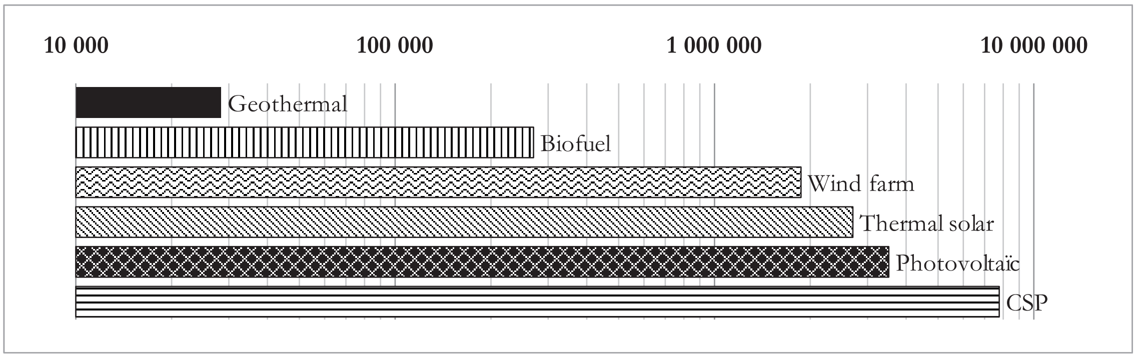
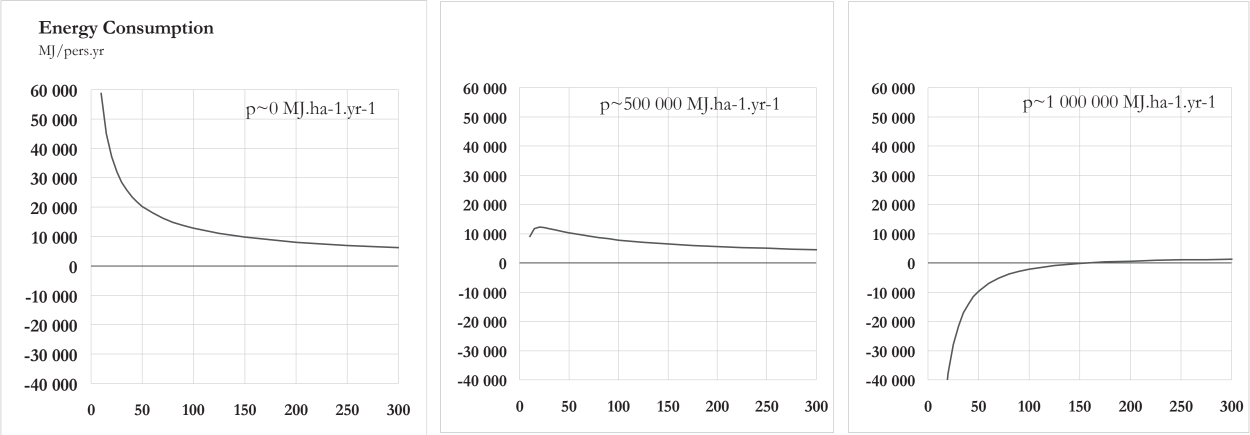


Figure 2: Histograms with estimates for maximal annual producibility (in MJ per hectare and per year).

On left, photo of a solar thermal plant in the desert of Mojave: mirrors focus solar rays on the tower and produce heat at high temperature and then electricity with a steam turbine (BrightSource Energy) On the right (Menard, 2010), heliostats (mirrors which turn so as to keep reflecting sunlight toward a t arget) are installed on existing roofs and focus to the tower: the hub for the heating district network and electrical plant.

Figure 3: Prospective drawings with in particular urban CSP-integration.



Curves of density-energy: possible evolution of the correlation shape between density and energy with large integration of renewable energies. On the left: no production of energy. In middle: development of urban-integrated energies. On the right, voluntary and strong development of renewable energies: low densities become positive energy territories.

Figure 4: Curves of density-energy.

Table 4: Synthetic scenario of car fleet evolution and integration of renewable technologies.

		2000	2010	scenario 2020	scenario 2030	scenario 2040	scenario 2050
Equipment of electric car	%	~0%	~0%	1%	10%	20%	35%
□ **K**	$MJ.pers^{-1}.yr^{-1}$	25 628	22 211	18 745	16 677	14 530	12 135
Land use by building	%	30%	30%	30%	30%	30%	30%
Roof equipped with PV-panels	%	0,01%	0,01%	1%	5%	10%	25%
Average output of photovoltaic	$kWhelec.m^{-2}.yr^{-1}$	50	60	80	100	125	150
□ **Producibility of urban land**	MJ per ha a yr	139	167	22 291	139 320	348 300	1 044 900
□ **p**	$MJ.pers^{-1}.yr^{-1}$	4	5	628	3 928	9 820	29 460
□ **p/K**	_	0,0002	0,0002	0,03	0,24	0,68	2,43
→ **Max. annual consumption**	$MJ.pers^{-1}.yr^{-1}$	59 192	51 300	43 295	38 519	4 713	305
→ **Critical urban density**	person/hectare	_	_	_	2	37	1 713
→ **Neutral energy density**	person/hectare	_	_	_	_	11	507

GLOBAL SCENARIO: A CHANCE FOR CORRECTING THE EFFECTS OF URBAN SPRAWL?

Figure 5 zooms in on urban densities lower than 150 persons per hectare. A quick reference to the curve of Newman and colleagues, it is not unreasonable to imagine a ranking inversion of the efficiency between American, European and Asian cities in 2050. Let us note that on the eve of 2030 the dependence with density becomes weaker. In 2040, it is possible that the correlation is reversed.

Low densities make the diffusion of eco-technologies easier on an individual level: quote as example the decentralized production of electricity by biomass (example of Volkswagen Blue Power). In this last case, it is useful to recall that the quantity of heat rejected by a fuel driven car during 20,000 kilometres, corresponds more or less to the annual heating needs for a house of 100 m². With the electric car and this type of individual cogeneration, consumption in primary energy could then be almost divided by two: tomorrow, whereas the power unit reloads the car at night, its heating "waste" will warm the house and generate hot water.

Discussion

Further development 1: GHG emissions approach

This study largely concentrated on energy balance. However, it is obviously necessary to consider GHG emissions. If this point is reserved for the discussion, it is because the assessment is much more complex than the energy sum: it is largely depend on the GHG intensity of the supply for electricity production (including variation in space and time). Jointly, the taking into account or not of a life cycle analysis associated with renewable technologies is also up for debate. Table 5 shows when energy mix for electricity production provides CO_2 intensity under 500 grams, the electric car presents a more favourable balance. As the intensity reaches 700 grams, the equivalent GHG emissions of the electric car are equivalent with those of a specific fuel consumption of 5l/100 km.

Thus let us lay down the terms of future developments of this article by rewriting the equation of the total assessment: [E16]

$$GHG^{TOT} \approx L.r_{CO_2}.\mu^{-\frac{2}{3}} - \delta_{CO_2}.\mu^{-1}$$

With:

- r_{CO_2}: average rate of GHG emissions of car fleet ($grCO_2.km^{-1}$)
- δ_{CO_2}: difference in GHG emissions between traditional production (e.g. from the grid) and renewable production, at the urban reference density ($kgCO_2.ha^{-1}.km^{-1}$)

This last parameter is the most difficult to assess. It is indeed a function of:

1. Effective substitution: does self-production erase or attenuate conventional production?
2. GHG intensity of power plants distributed to electricity grid ($grCO_2.kWh^{-1}$ of electricity delivered)
3. Management of the intermit production: which capacity of storage for the producibility one is for example stored to propose an availability equivalent to the traditional resources?

While transposing the increase carried out on the assessment incorporated in energy, one can deduct: [E17]

$$GHG^{TOT} \leq GHG^{TOT}_{MAX} \equiv GHG^{TOT}(\mu'_{cr}) \equiv \frac{4(L.r_{CO_2})^3}{27\delta^2_{CO_2}}$$

$$\mu'_{cr} = \left(\frac{3\delta_{CO_2}}{2L.r_{CO_2}}\right)^3$$

In this last case, it is much more effective to bet on GHG emissions reduction of cars, for two reasons. One because of cubic dependency in the equation of GHG^{TOT} with δ_{CO_2}. The other due to uncertainties around δ_{CO_2} as explained. For those reasons, the introduction of a bonus-malus policy for the purchase of a new car showed the effectiveness of this tax incentive to decrease the global GHG impact of the French car fleet: a strategy to be amplified in a low density zone?

Further development 2: economic approach

What is the best lever to prevent energy poverty? First of all, the aim of a positive mobility would require nowadays as a first approach, an investment in photovoltaic panels of at least

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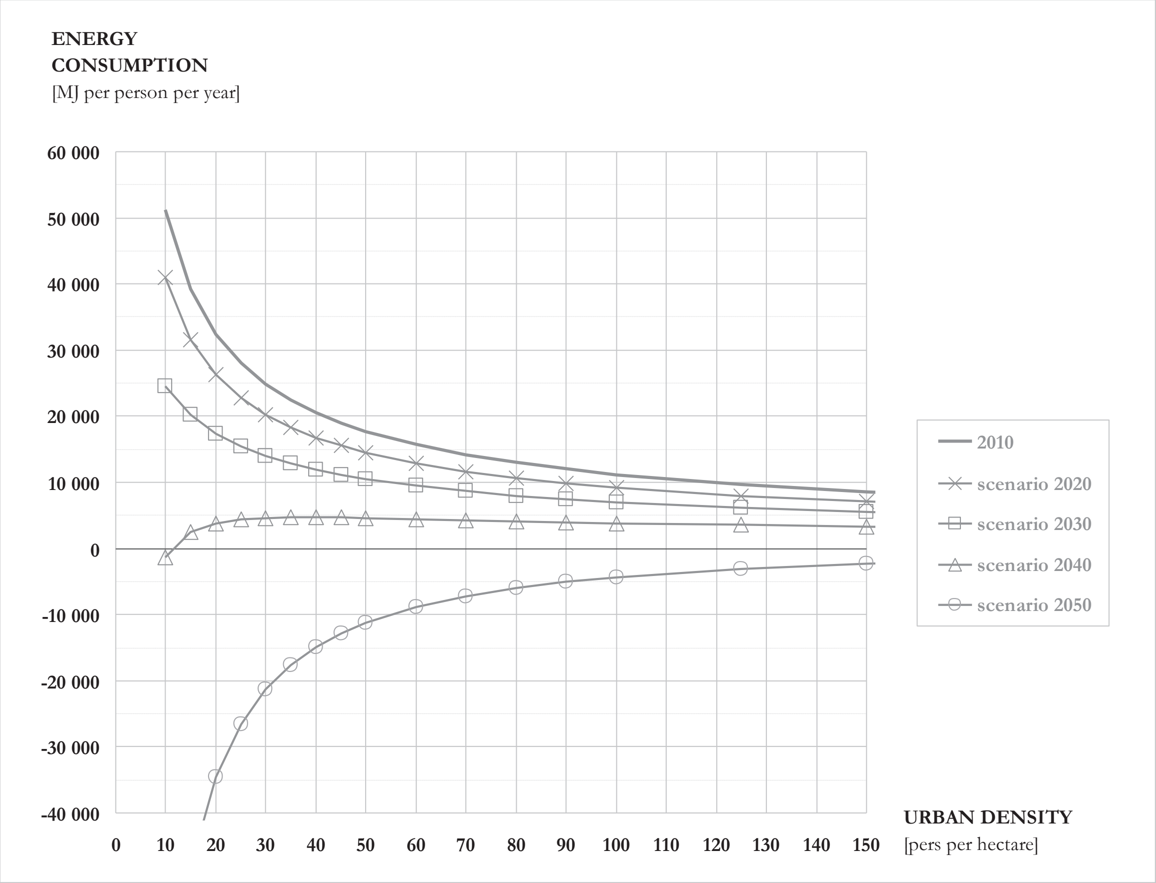

Figure 5: probable evolution of the correlation curve between urban density and energy consumption.

Table 5: GHG emission of an electric car (15 kWh/100 km) and scenario of GHG emission from car fleet in 2040.

		Sweden	France	Belgium	Spain	Germany	Ireland	Lux.
Carbon intensity of electricity	*grCO2/kWh*	40	90	290	480	600	700	1080
CO2 emission of electric car	*grCO2/km*	6	13	43	72	90	105	162
$\rightarrow r_{CO2}$ (Scenario 2040)	*grCO2/km*	91	92	98	104	107	110	122

50,000 Euros per person in low density situation: this is not achievable. As value analysis, let us imagine governmental aids of about 10,000 Euros per household, the latter living in a low density area.

- 10,000 Euros is a significant amount to encourage and even finance the replacement of an old car (which consumes 8 litres) by a new (or second hand but recent) with a specific consumption of 5 litres per 100 km. Thus, for 20,000 km a year, it represents an economy of 600 liters. With 1,50 Euros per litre, this economy represents almost 1,000 Euros a year.
- 10,000 Euros corresponds in 2010 for the typical personal investment for a photovoltaic roof of about 2kWp (~5 Euros per Wp). The forecast annual production, under European climate, will then be about 2,000 kWh. With a feed-in tariff of 0,40 Euro, this is a credit of about 800 Euros a year

This very approximate budget approach shows a relative equivalence between both strategies. One should nevertheless opt for the more reasonable choice: better in terms of GHG emissions reduction and easier to perform. Lastly, the dynamics of incentive could also encourage – starting with the registration of the building permit – to install a complete kit of autonomy integrating renewable energies, solution of storage and electric mobility: the key of automobile autonomy. In 2010 and very first estimate, the additional investment would be about 75,000 Euros: that remains obviously prohibitive for a budget of acquisition of a house of 200,000 Euros. In horizon 2020, it is extremely probable that the appreciation of this autonomous mobility corresponds to an acceptable over-investment, in particular if it is supported by inciting tax policies.

Further development 3: integration of all ground transportation

Hessi recalls works of François Asher, then Orfeuil and Soleyret: the famous "barbecue effect" recalls that high densities generate an increase in leisure outings. Therefore, it is possible that the full writing out of the power consumption of total individual mobilities highlights an asymptotic character less extremely than when only the automobile curve is taken in to account.

Further development 4: integration of building energy consumption

In a later development, it will also be crucial to integrate building energy consumption. The relationship between urban density and typical building energy consumption becomes difficult when:

- The correlation with urban density and compactness of building is weak;
- The type of construction and the efficiency of the envelope is not related to urban density;
- Climate (in particular heating degree days) is an important determinant of heat consumption (Kennedy, 2009)

In contrary, it might be possible that major effect could be due to correlation between density and the average individual surface of housing. This last point would point to a better efficiency of dense urban lands. These speculations however remain to be even confirmed to quantify.

Conclusion

This study proposes an update of the curve revealed by Newman and Kenworthy. With different scenarios, the curve of the algebraic sum of car consumption and renewable production shows a climax: it is probable that the improvement of car consumption efficiency, diffusion of the electrical car and the development of renewable production will result in a weaker relationship between energy consumption and density in the time horizon 2030–2040.

It reveals the potential in the medium-term of positive energy urban land at low densities: the latter would be finally more efficient than the high densities by compensating higher distances travelled by car with a greater potential of auto-production of energy. The conclusion of this theoretical model also shows that aggregate consumption is controlled much more by the average consumption of the car fleet than by the producibility of urban land: a good argument to encourage car efficiency and car sharing.

Also let us point out the important correlation between household incomes and density. The households with lesser means are more largely represented in suburbs: low density implies an increased risk of energy poverty. Also, with a tax incentive, it seems necessary to accelerate the technological change for households located in very low density areas: specific feed-in tariff for renewable energies, incentives for efficient car purchase and the development of smart grids in these urban areas.

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