Key infrastructure metric

In a global scenario of rapid urban growth and climate change, **energy supply** (i.e. generation, storage, distribution of energy) becomes an highly sensible matter from which will depend the quality and efficiency of future dense urban settlements. On one side, the current global environmental awareness roused the necessity to change radically the energy supply system, abandoning the non-renewable sources as main power sources. On the other side, the growth and densification of the contemporary cities will require in the future an increased resiliency. Among different aspects to be considered, this reflects in the necessity to provide a more stable power supply, that currently can't be guaranteed relying exclusively on renewable power sources. In a global scenario for 2050, where 70 % of the 7.1 billion people in the world will live in urban environments[1], a reduced capacity in providing a stable power supply will reflect in an higher fault risk for services and infrastructures, with increased economic losses in case of temporary blackouts, and possible catastrophic situations for the cities in case of prolonged blackouts.

Approach to the problem

Why a change in the energy supply system is needed?

Energy supply, from the industrial revolution to date, has been mainly based on fossil fuels exploitation. Fossil fuel combustion accounted in 2010 for 76 % of the total anthropogenic Green House Gasses (GHG) emissions, which have been recognised as the main cause of Global Warming (GW) in the last 250 years[2].

Urbanization is the major driving force of the contemporary scenario, in fact, as per 2006 data, energy demand in urban areas was around **71 % of the Global energy demand**, and CO2 emissions from these areas were around 73% of the Global energy-related emissions[3].

The actual global consciousness of the problems and risks related to GW, with the subsequent intake of responsibility for the consequences of anthropic GHG emissions, is leading stakeholders at all levels, from policymakers till final users, toward an epochal change of the energy supply system, from fossil-fuel based, to renewable-sources based. The COP21 agreement, signed by 195 countries in 2015, is just the last striking proof of the consolidation of this trajectory in the global policies. The increasing stock quotes value of private companies as Tesla Motors® [4], and similar, could be interpreted as a further evidence of the current growing confidence of the market toward the development of tangible alternatives to fossil-fuel based systems.

Is urbanization an obstacle or an opportunity to enhance the change?

Accounting for **positive scenarios of economic and demographic growth**, i.e. excluding catastrophic scenarios for the world's population, urbanization is unlikely a problem that could be excluded from the equation[5]. If urbanization can't be avoided in a positive scenario, then a **smart densification of the cities is a most desirable urbanization trend**, in order to mitigate its effects on GW. Smart densification means:

- an optimization of the land use to not compromise food-productive grounds and water sources

[1] IPCC, Fifth Assessment Report (AR5), 2014
[2] ibidem
[3] "In 2006, urban areas accounted for 67 – 76 % of energy use and 71 – 76 % of energy-related CO2 emissions" cit. IPCC AR5, Mitigation Measures: Summary of Policymakers, 2014, p.25
[4] Tesla Motors Inc (TSLA:US) stock quotes raised from around 25-35$ in 2012-2013, to 200-250$ in 2015-2016 (http://www.bloomberg.com/quote/TSLA:US)
[5] For global scenarios of urban growth and climate change see IPCC AR5 Mitigation Measures Summary of Policymakers, 2014

- an improvement of efficiency of transport systems, particularly of mass transport systems, in order to reduce the energy use while increasing people's mobility in the most dense environments
- an improvement of energy efficiency of buildings through all their life cycle (e.g. through passive design, re-use or improvement of existing buildings, improvement of construction technologies and construction processes, etc.)

While these mitigation measures are main objects of discussion in the current debates of urban policymakers, the possibility to use **urbanization as a catalyst of positive effects** toward the change of energy supply systems is a minor object of debate, and still fairly unexplored as realistic possibility of development. Cities and energy supply systems are usually considered as physically separate systems, where the seconds can be considered an extension of the firsts, but not vice versa. In fact, is it possible think a city as an extension of an energy infrastructure? Is it possible to inhabit a power plant?

To date, projects to implement a large scale renewable-energy generation capacity inside the cities has been discussed worldwide mainly as theoretical scenarios[6], with few isolated examples of practical applications, still at an early stage of development (e.g. Masdar City, Sonnenschiff and Solarsiedlung, Dongtan City, etc.). The impact of those projects in a global scenario is still minor and not comparable with the impact of big power plants harvesting the renewable-energies of sun and wind, installed in the countryside or in the deserts, or offshore, promoted in the last years by regional planning policies worldwide.

Power-plant city

In 10 years, in the United States, the construction of big solar and wind harvesting plants, plus hydroelectric, geothermal and biomass plants, allowed an increasing of renewable electricity capacity from 9,4% (2004) to 15,5% (2014) of the total electricity capacity, with a generation, in 2014, of 554,040 GWh[7].

Are these efforts still enough?

The IRENA REmap study[8] enlighten how, to achieve significant results in terms of GW prevention and economic benefits in terms of reduced energy costs and employment, the worldwide **renewable energy share should double the current 18%, reaching the 36% of the total global power capacity in 2030**. However, the same authority, analysing the single countries involved, showed how US current policies will only achieve, by 2030, a generation capacity from renewables "far below the 27%" over the total, which is the optimal US goal, to r identified in the study[9].

As known, today **US are one of the most urbanized countries in the world**, with 81.6% of its total population living in urban areas[10]. Then the question is, if were possible to implement a similar electric capacity per square meter of a renewable energy power plant in US urban areas, wouldn't be possible to meet or to go beyond the goal stated by REmap?

The NREL recently published a study [11] that shows how, **in the USA, rooftop photovoltaic (PV) could generate 39% of the current annual electric energy demand**. This is considering an installed PV technology with 16% efficiency. Taking into account more efficient PV technologies and not just the rooftops as suitable surface for the installation of PV technologies but also building facades[12], urban canopies, or even the paved

[6] Jeremy Rifkin, The Third Industrial Revolution, 2011
[7] NREL, Renewable Energy Data Book, 2014
[8] IRENA, Remap: global report, 2016
[9] IRENA, REmap: United States of America - Executive Summary, 2015
[10] US Central Intelligence Agency, The World Factbook, 2015 https://www.cia.gov/library/publications/the-world-factbook/fields/2212.html
[11] NREL, Rooftop Solar Photovoltaic Technical Potential in the United States: A Detailed Assessment, 2016 http://www.nrel.gov/news/press/2016/24662
[12] International Energy Agency, Photovoltaics in Buildings, Paris (FR), 1999

surfaces, U.S. cities could generate a consistent surplus compared to the objective suggested by the REmap study.

Following these observations, then the answer is yes, power-plant cities would be more than a concrete possibility of making the change to the renewables effective in the USA.

Energy supply stabilization problem

The “power-plant city” hypothesis is still far from a possible application nationwide. At the state of the art, there are many limitations in this idea. First of all, as discussed, the hypothesis relies mainly on the harvesting of solar energy through PV technologies, but solar energy is a discontinuous source and the production patterns don’t match the patterns of the electric demand. Therefore, a backup energy production from other sources would be needed, to cover completely the electric demand (e.g. during the nights, when solar energy production is null, or during the winters and the overcast days, when production is reduced). But, if on one side the solar potential of US cities could cover more than 40% of the national electric demand, on the other side this limitation implies that would be more effective not to rely as much as possible on solar. In that case, would make more sense to have a reduced investment on PV installations, to be able to invest on other sources, to have a balanced national energy production.

There is another possibility, that is invest enough to take the maximum advantage of the solar resource from the cities, to **provide a large scale energy generation capacity and at the same time an adequate energy storage capacity**, to distribute better over time the energy generated. Now, the storage of electric power requires processes of transformation that not only cause an additional cost to the implementation of PV in the cities, but also imply a certain amount of energy losses, in fact, none of the current storage technologies is 100% efficient[13].

Therefore the question remains: even if the renewable energy potential of the cities is acknowledged, is it worth to transform radically the urban environment to try to make the most of it despite the current state of the technology?

Win-win strategy

The city works as an hyper-connected system of anthropic processes where different human ideas and actions influence each other as in an ecosystem. Differently from the development of a power plant on the desert, the development of a power-plant city would affect not just the national energy generation but also the qualities of the urban environment. If we **take advantage of the diversity and the interconnection of the urban environment**, then there would be the possibility to balance the current technological inefficiencies of the renewable-energy supply system with the indirect benefits that the city could gain, in the long-term, from the transformation into power-plant.

Because the technology efficiency is constantly increasing (with different growing rates over time though) becomes a secondary objective in a long-term perspective, whereas the main objective should be to **amplify the benefits of the change** and create new “ecological niches” in the urban ecosystem.

Therefore the research question is: Acknowledging the renewable-energy potential of the cities, how to provide a base for the transformation of the city into a power-plant city, which would allow to make the most of these resources, without being limited by the inefficiency of the current technologies and enhancing instead the evolution of the renewable energy supply system?

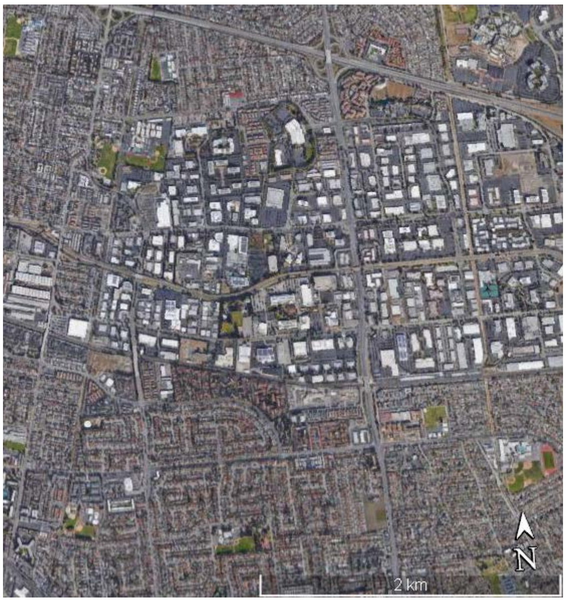
[13] I. Hadjipaschalis et al., Overview of current and future energy storage technologies for electric power applications, 2008

Proposal

Here a schematic urban model that, leveraging the transformation of industrial/commercial areas and the improvement of the mass transport systems in the city, aims to provide a basic infrastructure for the production, storage and distribution of renewable energy inside the city.

<u>Urban transformation and generation of energy</u>

Cities' industrial/commercial areas are typically planned as mono-functional zones, occupying extensively portions of land with low rise buildings, large asphalt surfaces dedicated to the mobility on wheels and to open air storage of goods, scarce presence of vegetation, scarce walkability. These characteristics makes them hardly embeddable in a dense urban environment and the city usually grows around them as a discontinuous structure.



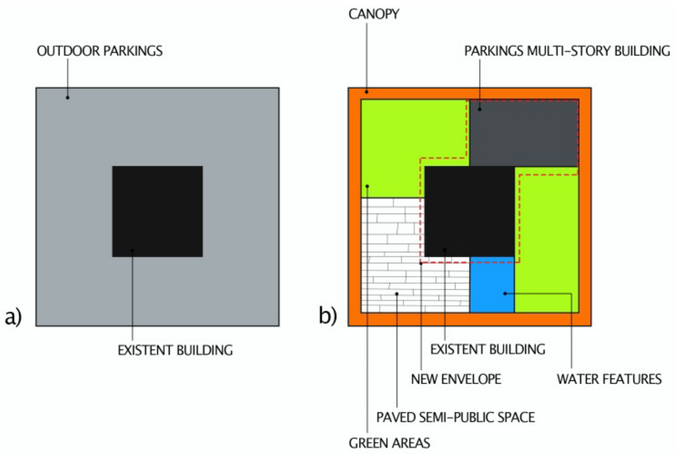


Fig.1 Clear distinction between industrial/commercial (I/C) areas and residential (R) areas in San Francisco
Fig.2 Typical configuration of industrial/commercial urban block (a) and proposed scheme of urban reform (b)

When the pressure of the city around these areas increases, and the values of the land rise, the industrial activities starts to be dislocated and replaced by mixed-use medium to high rise buildings. The willingness to improve the quality of the existing industrial/commercial environment to fit the standards of the mixed use urban fabric and to enhance the value of the new buildings causes an additional cost of urban structure reform.

Moreover, the current typical characteristics of these areas, plus the residual anthropogenic heat of industrial and commercial buildings increases the overall Heat Island effect of the city (UHI), affecting the cooling loads for the buildings surrounding the industrial areas[14].

Nevertheless the large roofs and walls of the industrial/commercial buildings (usually concrete or steel opaque structures) are optimal surfaces for the installation of PV mono-crystalline Si panels, which currently is one of the most affordable and efficient solar cell technologies[15]. The opacity of the cells, which is a weakness for some building integrated PV applications, in these buildings would reduce the exposed surfaces with high thermal inertia, therefore would help to counteract the UHI effects discussed before.

[14] S. Kato, Y. Yamaguchi, Analysis of urban heat-island effect using ASTER and ETM+ Data: separation of anthropogenic heat dischargeand natural heat radiation from sensible heat flux, 2005
[15] M.A. Green et al., Solar cell efficiency tables (version 45), 2014

In a recent study, developed by the author in collaboration with the University of Auckland[16], is analysed a possible implementation of this technology within a scenario of urban reform of the industrial areas of Christchurch (New Zealand), which are very close to the structure and form of the industrial/commercial areas of the American cities. The study proposes and tests the energy output of an hypothetic future urban scenario informed by a series of **planning measures to improve the quality of the urban environment** (Fig.2).

The measures aim at a more articulated strategy of mitigation of UHI effects, which would have immediate impacts on the city. On the long term, in a future perspective of city growth, the measures would allow a densification of these areas with a reduced cost for urban reconversion from industrial/commercial to mixed use.

These planning measures include:

-the reconversion of the paved areas for parking to green areas

-the relocation of the existing parking spaces in multi-storey structures that could be reconverted to other functions (e.g. small commercial or residential) with minimal efforts

-the implementation of energy-generating skins in the existing buildings and in the proposed multi-storey parking buildings

-the development of energy-generating canopies as urban visual features, able to optimize the direct sun radiation over the outdoor paved surfaces while increasing the walkability of the area through sheltering from wind and rain.

The following tables describe with few parameters the formal impact of these planning measures over an industrial/commercial **test area**, of around 4.8 hectares (ha), in the city of Christchurch (New Zealand) [17]:

TABLE 1: urban transformation

	Existing	Proposal
Floor/Area ratio	0.46	0.99
Outdoor paved surfaces	2.77 ha	0.57 ha
Green areas	0.33 ha	1.98 ha
Building Envelopes (roof+walls)	2.76 ha	3.88 ha
Canopies	-	1.14 ha

TABLE 2: resources for new urban niches

Electricity harvested in a year (calculated through a computer analysis of the annual solar radiation in the area, and considering a PV technology 20% efficient, covering 90% of the roof surfaces and 40% of the facades surfaces)	70.26 GWh (total) 14.64 GWh/ha
Water harvested in a year (considering an annual total precipitation of 648 mm/m^2)	216,000 m^3 (total) 45,000 m^3/ha

[16] A. Melis, A. Figg, E. Lisci, T. Auer, Urban strategies for achieving positive development in Christchurch (New Zealand) through a new infrastructure system for a region of the inner city, 2015

[17] The data are extrapolated from the dataset of the Christchurch model; see Melis et. al. for a detailed explanation of the calculations methodologies.

How to make the most of the harvested resources?

Looking at the data of the test area, 10 ha of a similar intervention would be able to generate as much as a 17MW coal power plant running 24h/day all year and emitting 49 Gt of CO_2 in the atmosphere[18].

This is just considering the installation of a PV layer, i.e. without considering the possibility to harvest other types of renewable sources e.g. the wind energy, through a technology as Windbelt™ or similar, or the piezoelectric energy, through a technology as Pavgen™ or similar. But the question is how to stabilize this amount of energy generated to evenly distribute it during the year.

The idea is to take advantage of electricity and water harvested from the roofs at the same time, to store the energy. Water is a perfect renewable medium for storage on a medium-large scale.

The first possibility would be to pump, with the produced energy, the harvested water on large dams and generate energy when needed through hydroelectric plants. However this option would imply to dislocate large amounts of water outside the cities, in places suitable to such hydroelectric dams, which are difficult to find everywhere, e.g. in regions which are almost flat. And also not from all the cities is possible to harvest large amounts of water.

The second possibility would be to split, with the PV electricity, the water molecules through water-electrolysis, producing Hydrogen. At the state of the art of the technology **water electrolysis systems can reach an efficiency of 45-50 % in the production of the hydrogen**[19], which means that around 66 kWh are required to produce 1kgH[20]. However, in all the cities can be harvested even little amounts of water (theoretically, around 9 litres of H_2O are required to produce 1 kg of H), and all the places are suitable to store hydrogen, even the flatlands.

Hydrogen as energy storage medium

There are **limitations** in the use of Hydrogen as an energy storage medium, in fact the technologies to reconvert H to electricity add a further energy loss. **Hydrogen fuel cells have today an average efficiency of that ranges between 50% and 85%**[21]. This means that after the water electrolysis, the compression and stocking, and the reconversion to electricity through fuel cells, we can get just approx. ¼ of the electricity that we have tried to store[22]. This makes it not competitive in small applications, because batteries are much more efficient. But on medium-scale applications, **where batteries can't be used**, because they don't have enough electric capacity, or because they recharge too slowly, H produced through water electrolysis becomes the most sustainable alternative to fossil fuels.

Medium-scale applications are e.g. on-site distributed generation, for buildings and industrial plants, fuelling for space, aviation and naval industry, on ground transportation with heavy vehicles. Power capacity and reliability makes Hydrogen an interesting opportunity to develop a **public mass transport system for dense cities**, where medium-large vehicles are required to run sometimes uninterruptedly 24h/day. Having "clean" public transport fleets in the cities would be a double goal toward the GW problem discussed initially. In fact not only the overall energy needing on the city for the mobility will be diminished, using few common vehicles instead of an infinity of individual vehicles, but also the GHGs emissions and the air pollution in the urban environment, both caused by fossil fuel alimented engines, would be reduced dramatically.

[18] Based on U.S. data, the carbon intensity coal combustion is 334.5 kg/MWh (https://www.eia.gov)

[19] Houcheng Zhang et al. , Configuration design and performance optimum analysis of a solar-driven high temperature steam electrolysis system for hydrogen production, 2012

[20] A theoretical electrolytic transformation, 100% efficient, would require 2.94 kWh to produce 1m^2H_2 at a temp of 273 K and 1bar pressure, which would be 0.08988 kg H_2. This means 32.71 kWh/ kg H_2 are required in an electrolytic process 100% efficient.

[21] US Department of Energy, Hydrogen Fuel Cells factsheet, October 2006 https://www.hydrogen.energy.gov/pdfs/doe_fuelcell_factsheet.pdf

[22] Hydrogen have an energy density of 33.3 kWh/kg (Zittel, Werner & Wurster, Reinhold & Bolkow, Ludwig. Advantages and Disadvantages of Hydrogen. Hydrogen in the Energy Sector. Systemtechnik Gmbitt. 1996.). A fuel cell which is 50% efficient could generate 16.65 kWh/kgH, which is only the 25% of the previously discussed energy to generate 1kg of H (66 kWh/kgH).

Hypothesis of implementation in San Francisco

U.S. government is already financing research programs and projects of implementation of FCV for the mass transport in the cities. The ZEBA bus project, in San Francisco is one of these projects[23].

The following table summarizes with few data how would that be if the energy generated through an urban intervention in San Francisco's industrial areas, with characteristics similar to the test area previously discussed, was used to aliment a bus fleet in the city.

TABLE 3: hydrogen generation and use

If electricity and water harvested in the test area were converted in hydrogen and stored (considering the inefficiencies previously discussed):	hydrogen: 221,800 kgH / ha water surplus: 43,000 m^3/ha
If the hydrogen produced were used only to aliment the ZEBA busses (considering a current average annual consumption of 5040 kgH/bus):	44 bus/ha
If the entire bus fleet of San Francisco (800 busses) were FCV, could be possible to aliment them with:	18.2 hectar of intervention
If the hydrogen produced were reconverted to electricity for on-site distributed generation, with a system 50% efficient, would be possible to generate:	16.65 kWh / kgH 3.73 GWh / ha 17.9 GWh (over the 4.8 ha model)
If the hydrogen produced were reconverted to electricity for on-site distributed generation, with a system 85% efficient, would be possible to generate:	28.30 kWh / kgH 6.28 GWh / ha 30.14 GWh (over the 4.8 ha model)

A new building typology

Following the considerations on the use of hydrogen as an energy storage medium for medium-scale applications, the proposal concludes with the idea of include in the urban transformation of industrial areas structures to generate hydrogen in loco from the harvested resources. **These structures will work as building-batteries**, with the possibility either to redistribute H as fuel for a clean fleet of mass transport vehicles, or to provide back-up energy to the city through the reconversion of H in electricity.

The structures will be distributed inside the urban industrial/commercial areas according to the amount of resources produced by the surrounding resource-harvesting installation capacity. The energy generating skins and the urban canopies, will be connected to these structures to transfer the resources in the "urban batteries" with the shortest possible distance, in order to minimize the dispersion due to the grid inefficiencies.

Varies examples of hydrogen filling stations or medium-large scale fuel cells, sized to fit an urban scale, could be mentioned, e.g the 1.1 MW Fuel Cell System at Toyota's Sales and Marketing Headquarters, in California, or the hydrogen generating/filling station built in Nevada by Proton Energy Systems® [24]. However is still unexplored the possibility to integrate these types of structures within a wider urban intervention which aims to improve the quality of the urban environment, as the urban model discussed before. Also is unexplored the possibility to integrate the technology of projects similar to the cited examples, within buildings which could host other functions, and would be experienced as city landmarks or collective places. The possibility to integrate a new building typology that mixes the functionality of a medium-scale battery with architectural qualities not only would stabilize an energy supply system of a power plant city, but would also enhance the effects of a large scale urban intervention on industrial areas, facilitating the reintegration of those areas within a dense city. This idea is part of the urban win-win strategy previously discussed.

[23] NREL, Zero Emission Bay Area (ZEBA) Fuel Cell Bus Demonstration: First Results Report, 2011
[24] Mark R. Campbell et al., A Solar Powered Hydrogen Generation and Filling Station, 2008

Emanuele Lisci

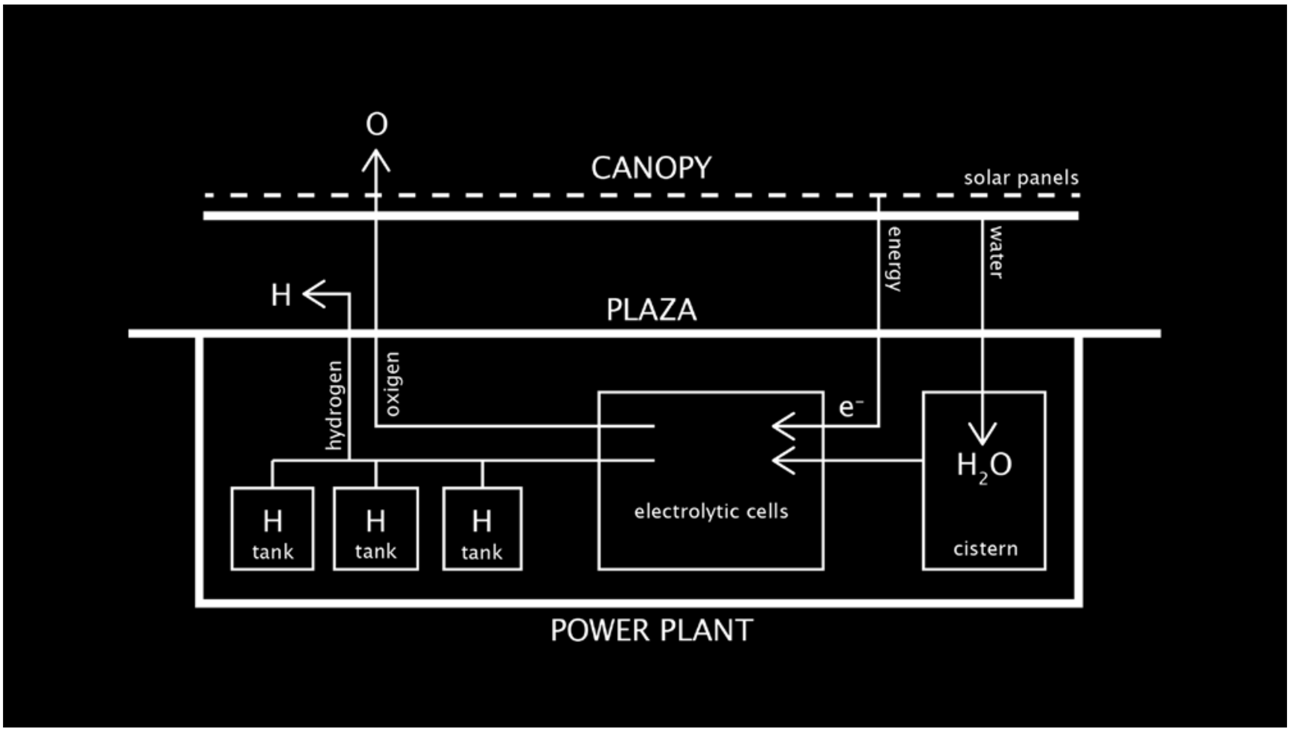


Fig.3 Scheme of building-battery

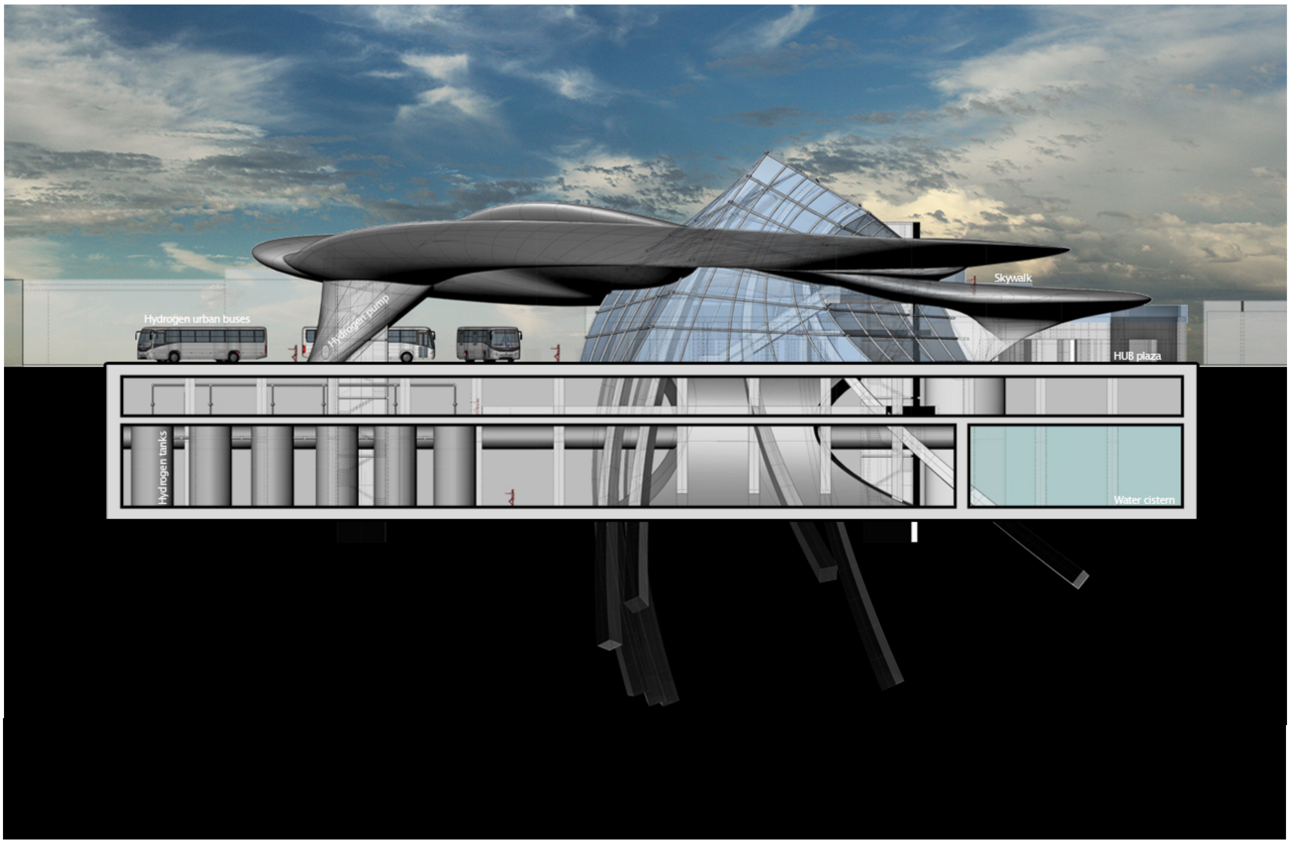


Fig.4 Functional scheme of the building-battery within an architectural form (artist impression)

Emanuele Lisci

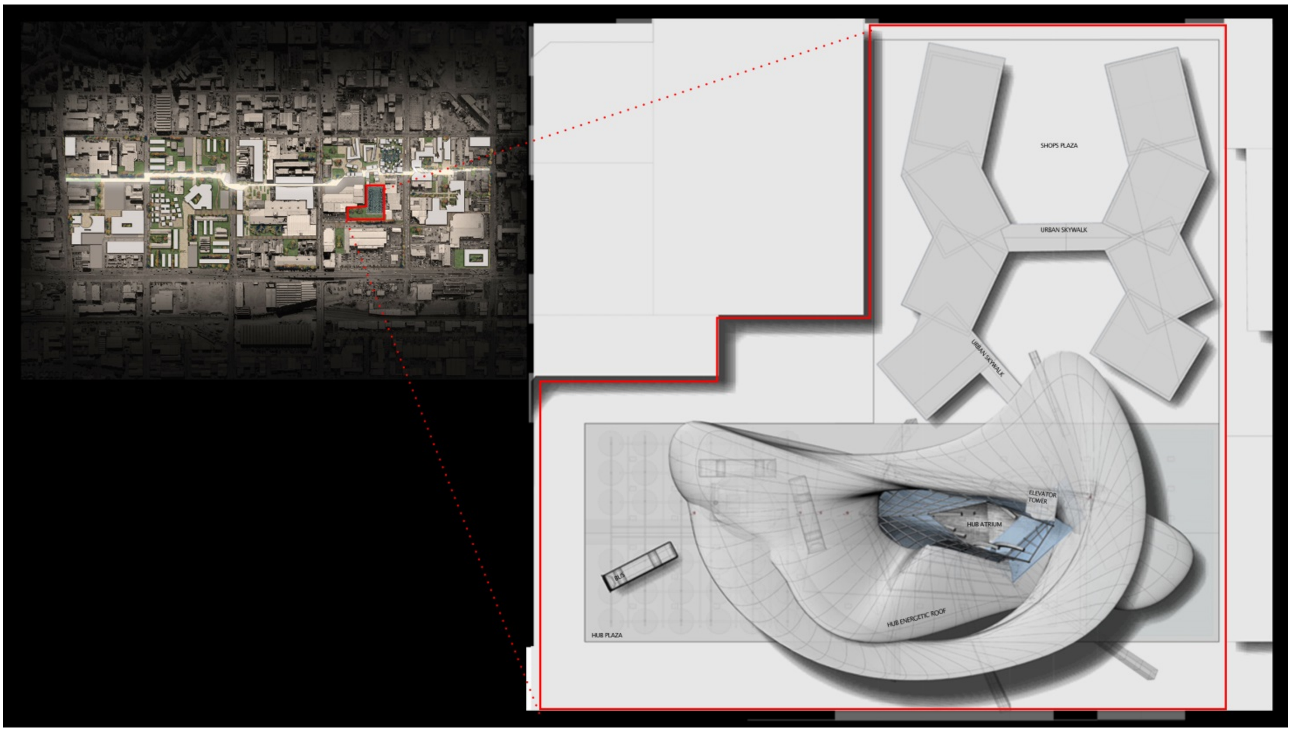


Fig.5 Integration of the proposed building typology within a commercial/industrial urban scenario (artist impression)

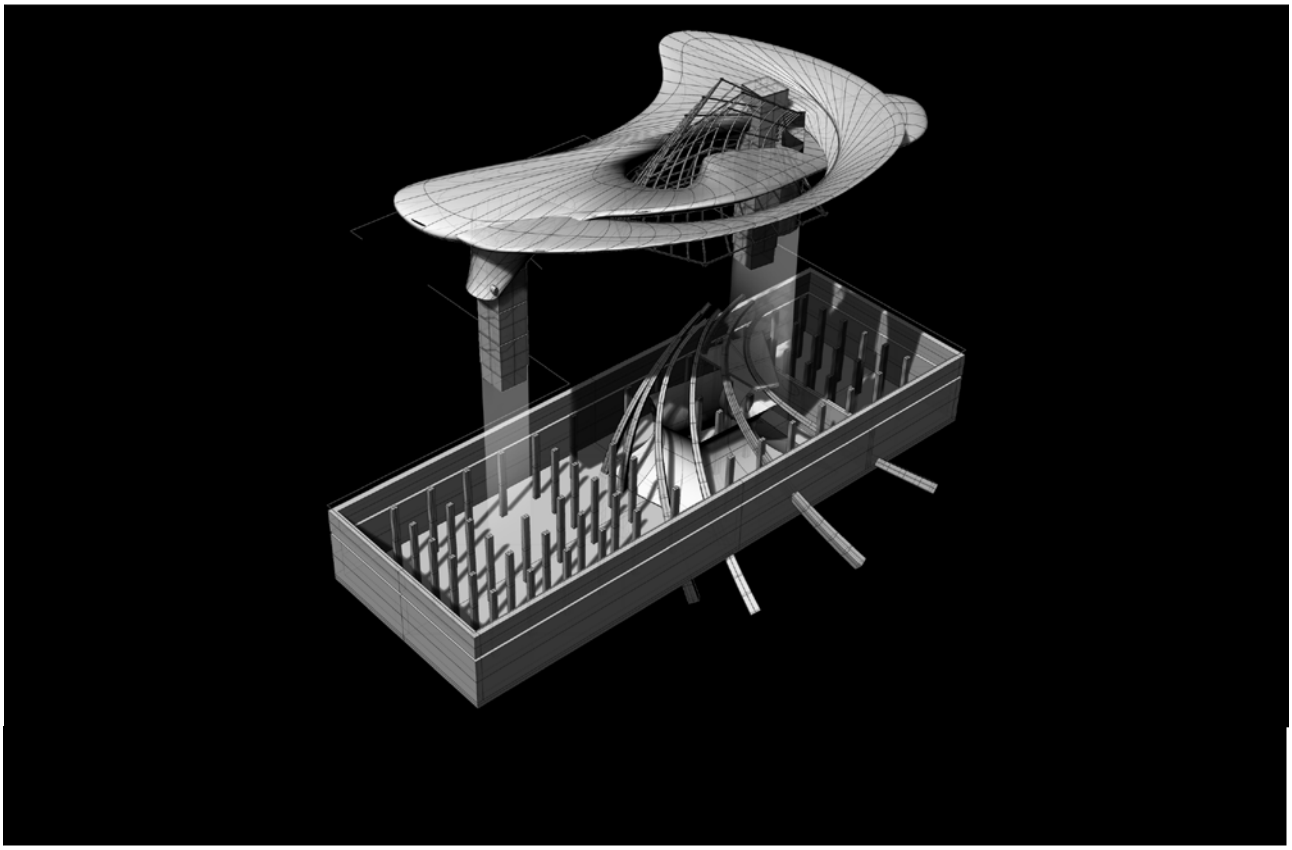


Fig.6 3D structural concept of the proposed building typology (artist impression)

Limitation of the current study and further development

The idea here proposed and the related discussion is presented in general terms which would require a further investigation in relation to real case studies.

This general proposal has the potential to be actuated in different U.S. cities, particularly those cities where the densification of the urban environment is already demanding for a reform of old industrial/commercial areas and for the improvement of a mass transport system, as well as for measures to contrast air pollution and the Urban Heat Island effects.

Once the opportunity for the development of this proposal has been found (San Francisco could be a good first case study, where an urban intervention could be developed in conjunction with the institutions and stakeholders already involved in the ZEBA bus project) the scheme of planning measures here discussed has to be expanded and adapted to meet the existing planning standards of the city.

Because this is a proposal to be developed with a long-term planning action, and because the energy harvesting technologies, as well as the hydrogen-based technologies, are being improved with an increasingly speed, the systems to be implemented as "urban batteries" needs to be discussed with specialized consultants once the project has reached an operative phase, for an overall costing and for an estimate of the energy supply scenario, expanding the data here presented as indicative only.

To conclude, the design of the buildings that will work as urban batteries will need to be discussed and adapted to the related urban context. The spatial configurations of the typology may vary to the necessities of public or private developers. If projects compatible with the idea of the building typology here proposed are already programmed, a possible integration of the "urban battery" scheme should be considered, as a strategy to amplify the benefits of the change while reducing its impacts, e.g. in terms of realization costs, land use, etc.