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# Energy and underground

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A B S T R A C T

Driven by urbanization growth, in recent years, the relationships among energy systems and underground space are becoming more and more intense for many reasons: the severe competition in the land use, the security of energy commodities management, the need of huge infrastructures for mass and energy transportation (e.g. pipelines), the safety requirements against seismic events and eventually, economic and environmental considerations.

For such reasons, nowadays underground space is becoming an extremely important as an alternative for urban areas expansion, if properly planned. In fact, a correct underground space planning strategy, together with the progressive developments of suitable integrated connections between surface and subsurface can increase the livability of cities and improve public health.

Population in urban areas is expected to grow, in particular in developing economies (such as China); this phenomenon leads to an increasing pressure on urban areas to supply the growing energy needs. In fact, several end-use services should be fulfilled to provide indoor comfort in buildings, for mobility of people and goods, etc. Anyway, only a very limited amount of energy can be generated inside urban areas (from municipal solid wastes, from thermal/solar PV and heat pumps installations); as a consequence, the majority of the energy commodities are produced, converted and stored in power plants located far from cities and require huge transport infrastructures.

In this paper, the cost/benefit relationship between underground and energy use is explained by reviewing main application of existing underground space utilizations for energy processes (distribution, storage and generation), as well as other innovative opportunities. From the analysis of past experiences analysis, the main conclusion is that a rational approach in urban energy planning procedures, integrating both over- and below-ground space utilizations, could help to raise the quality of energy services and it is fundamental for reaching a smarter and more resilient society. In such a new Underground Urbanism approach, the need for long-term Integrated Master Plans that propose suitable Guidelines is highlighted.



## 1. Introduction

In recent years, underground space development has become more attractive. The main similar reasons among the different countries are the need of an improved environment (Working Group No. 4, International Tunnelling Association, 2000), reducing high traffic density and land conservation (Wang et al., 2013). The growing urbanization level, expected to be over 75% in 2050 (Buhaug and Urdal, 2013), has highly contributed, especially in developing economies such as China (Delmastro et al., 2015), to the underground space exploitation. Many problems arise in this intensive underground space development (e.g. lack of suitable planning strategies, overlapping in layout and management), making the situation unsustainable with a high waste of the underground non-renewable resources.

Underground space can play a significant role either to guarantee the energy systems operation (for manufactured or natural gas pipes, electricity grids, district heating and cooling networks), as well as to offer suitable opportunities for everyday life, from the economic and environment point of view.

Underground is a possible solution also for indirectly energy related applications (e.g. water supply and sewage management networks, mobility systems for people – metro lines – and goods, storage and parking facilities, road and rail tunnel, for tele-communication lines); these solutions are often more sustainable (Lavagno and Schranz, 2007; Bobylev, 2010; Curiel-Esparza and Canto-Perello, 2012; Rogers and Knight, 2014), resilient (Sterling and Nelson, 2013), reliable and secure (Canto-Perello

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et al., 2013; Izumi et al., 2014; Augutis et al., 2015) than those above-ground and, sometimes, also less energy expensive (ITA Working Group Number 13, 2004).

Outside urban areas, the underground siting of medium and large energy plants and related auxiliary facilities has always been a viable solution for a large set of applications in places where the competition for land use or local adverse conditions were present. Pipelines are the most common corridors for long distance energy commodities transportation, from the oil and gas source extraction sites until the final users (REACCES summary report, 2011). The solution of an underground siting of pipes and auxiliaries, as well as of the storage facilities (in man-made devices, cavern or abandoned mines) is largely adopted for the multiple advantages from both the design and management points of view. Underground solutions for nuclear waste temporary depository have been the main choice in all the countries where nuclear plants are present (MIT, 2003). Anyway, finding a solution for the disposal of high-level waste or spent fuel final repository is still a great challenge.

Differently, only small or medium size power plants (mainly associated to district heating/cooling networks) can be located in urban areas. In this case, a particular attention for a rational and safe siting of plants and infrastructures in the urban underground might be required. Among the large infrastructures of urban public services, some of them have been located underground since many decades: the networks for water supply and sewage removal, the metro-lines for mass transit systems and more recently, the telecommunication system connections. Sometimes, the progressive installation of different infrastructures has produced overlapping of systems with huge management problems. In order to find suitable solutions to this criticality, in several urban areas of developed countries, the so-called utility tunnels (Swamidurai and Seerappalli, 2014) has been designed and applied (these large tunnels, excavated in rock-beds or dug in less hard soils, allow a suitable access for inspections and material supply and consequently several networks can be hosted in a very rational arrangement).

In this paper, the role of underground use for the main energy applications is reviewed. The first section analyses the main application for energy generation, distribution and storage while the second one is focused on energy planning procedures and on the importance of the integration of underground in long-term strategies definition and in Master Plans.

## 2. Energy generation, distribution and storage

The underground siting of energy plants and related auxiliary facilities has been very often a viable opportunity for a large set of applications, outside as well as inside urban areas: in-cavern hydro plants, Combined Heat and Power (CHP) units, geothermal heat-pumps, facilities for Syngas production and $CO_2$ storage. Similarly, long distance transport and urban distribution infrastructures as well as storage devices of energy commodities are usually located in underground for a variety of reasons tied to: cost, safety and security. In the next paragraphs a survey of such installations is presented.

### 2.1. Energy power plants

The solution of building in-cavern hydro plants has been often adopted in several situations. In fact, local land conditions around a mountain dam (gorges, steep valleys, avalanches risk, etc.) cannot be suitable for housing a power station located on the surface: the underground solution can result to be less expensive and less impacting on the environment; moreover, security issues can be a further positive incentive. Furthermore, an underground power station can be a component of a wider pumping system, with external upper and lower basins, and the in-cavern solution is very appropriate.

The first (very small, around 50 MW) underground hydro power station was built in 1899 close to Seattle; presently, one of the largest one is in Newfoundland and Labrador, with 11 turbines for a total of 5400 MW. At the time, the project was the largest civil engineering project ever undertaken in North America: a cavern that equals a 15-storey building, 300 m underground (Smith, 1975).

In Italy, where the hydroelectricity has a long tradition, the 300 MW hydro plant of Pont-Ventoux is hosted in an underground cavern obtained with an excavation volume of about 35,000 $m^3$ (IREN, 2015).

Recently, a growing interest started to be also addressed to portable hydroelectric generator systems that can be easily located also in an urban environment, exploiting small water flows and can be associated to electrical batteries for several domestic or mobility uses (Kanellos, 2009; Redfield, 2014).

Due to the very favorable rock characteristics, Nordic European Countries developed a wide experience in the sector of underground power and industrial facilities; in particular, Norway built more than 200 underground hydropower plants, in addition to storage facilities, civil and military shelters, sport facilities and public parking (NCM, Nordic Council of Ministers, 1990).

Medium and small-size energy generation plants can be located underground inside the city (or in the surroundings of urban areas) in connection with local district heating networks. However, such solutions for these facilities are not very popular. Among the few, two significant examples of underground solutions for energy generation associated to local district heating networks are: (i) the heat pump installation in Zurich (Switzerland) – in use since 1937 – located under a garden, close to the bank of Limmat River (where the "environmental" heat source is taken from) (Brodowicz et al., 1993) and (ii) the gas-driven CHP plant in Imola (Italy), located in the middle of a city park, surrounded by leisure facilities.

Concerning the use of coal, that is presently the largest available source of energy in the world (and the basic fuel for China and India), many projects have been developed for finding solutions for a more rational use of this source and, in particular, for facing the global impacts associated to the $CO_2$ emissions. All these projects involve the use of underground space. As an example, the production of Syngas through Underground Coal Gasification (UCG) systems allows to use poor quality coal resources and to obtain a useful, clean and economically exploitable source for generation of electricity or for the production of fuels and chemicals through commercially proven technology (Puri, 2006).

Integrated systems, such as Underground Coal Gasification (UCG), steam assisted gravity drainage (SAGD), syngas fueled Solid Oxide Fuel Cell (SOFC), integrated gasification combined cycle (IGCC) and an electrolyzer are proposed. The system, suitable for regions with oil sands, coal reserves and lakes such as the Alberta area, aims to produce the syngas directly underground without mining and to produce electricity (in the IGCC and the SOFC) and hydrogen (electrolyzer) (Bicer and Dincer, 2015) with estimated efficiency of about 30%.

Anyway, $CO_2$ removal is still the main challenge associated to the use of coal and the solutions for Carbon Capture and Storage (CCS), also known as Carbon Capture and Sequestration, include geologic storage as one of its key components (Benson and Cook, 2005; Benson, 2006).

### 2.2. Infrastructures for energy distribution

The supply of gaseous energy commodities started in mid 1800s, initially for street lighting purposes and – some years later