COMBATTING MODERN CITY PROBLEMS WITH THE USAGE OF UNDERGROUND SPACE: THE CASE STUDY OF GREECE

Dimitrios Papadomarkakis[1]

Abstract: By the year 2030, the global population is projected to reach 8.6 billion, with further growth expected to 9.8 billion by 2050. Presently, over half of the world's population resides in cities and urban areas. This rapid population increase, coupled with the global trend of urbanization, has precipitated numerous transportation and environmental challenges. Among the proposed solutions to address these issues is the development of Urban Underground Space (UUS). The strategic utilization of subterranean spaces can significantly contribute to meeting the escalating demands of urban areas by providing reliable transportation, harnessing green energy sources, and promoting environmental sustainability. This study investigates the current use of underground space in the region of Attica, Greece, serving as a case study to elucidate how urban underground spaces can alleviate traffic congestion, foster sustainable urban development, support the creation of compact cities, and address various related concerns.

Keywords: Urban Underground Space (UUS), Metro Lines, Underground Parking Facilities, Underground Hazardous Waste Repository.

1. INTRODUCTION

Many cities worldwide are confronting rapid population growth, leading to a higher concentration of individuals in urban areas (Cui et al., 2021). By 2050, it is projected that 70% of the global population will reside in cities, with the urban population more than doubling since the turn of the century (United Nations, 2007, 2013; Broere, 2016). Cities experiencing uncontrolled population growth will inevitably encounter significant challenges regarding efficient transportation infrastructure. If these infrastructures are not adequately upgraded to meet the demands of future "mega" cities, traffic congestion will increase exponentially, resulting in prolonged travel times. Moreover, the daily number of vehicles in circulation will rise, exacerbating the already critical issue of CO_2 emissions. Additionally, urban expansion to accommodate growing populations will capture valuable farmland, leading to substantial losses. As urban populations augment, the energy demands of cities will escalate dramatically, raising critical questions about the optimal placement of power suppliers to ensure comprehensive coverage. Over the past 40 years, the development of Urban Underground Space (UUS) has significantly contributed to addressing transportation, environmental, and land use challenges that typically arise during urban development (Cui et al., 2021). Generally, the development of the latter in order to combat modern city problems has been studied by various researchers (e.g. Hurtado and Perello, 1999; Bobylev, 2009; Broere, 2016; Li et al., 2016; Qian, 2016; Vahaaho, 2016; Yu et al., 2023).

Prominent examples of underground space utilization include Shanghai's extensive subway system, Tokyo's intricate underground shopping complexes (Cui et al., 2021), Toronto's subterranean parking structure beneath Nathan Phillips Square, and the Wierzchowice underground gas storage facility in the Wrocław province of Poland. Since the dawn of the 21st century, Greece, particularly the region of Attica, has witnessed a significant surge in the use of underground spaces. Notably, on January 29, 2000, the first two lines of the Athens metro, Lines 2 and 3, were inaugurated, encompassing a total length of 13 kilometers and 14 stations (Elliniko Metro A.E., 2025). Nearly 24 years later, the Athens metro has expanded to include two operational lines with a combined

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[1] Undergraduate Student, Laboratory of Tunnelling, School of Mining and Metallurgical Engineering, National Technical University of Athens, 9 Iroon Polytechneiou Str., GR 15780, Zografou Campus, Athens, Greece. E-mail address: papadomarkakisdimitrios@gmail.com

length of 59,7 kilometers and 40 stations (Elliniko Metro A.E., 2025). Furthermore, a third line, Line 4, is currently under construction, projected to span approximately 12,8 kilometers with 15 new stations, and further expansions of this line are in the preliminary stages of development (Elliniko Metro A.E., 2025). Furthermore, in recent years, numerous underground parking structures have been established, such as the Siggrou-Fix underground parking facility, which provides 640 parking spaces distributed across six underground levels and is directly connected to Line 2 of the Athens metro. Additionally, in 2010, new underground storage facilities were constructed at the Lavrion Technological and Cultural Park (LTCP) for the purpose of storing hazardous toxic wastes, with the repository reaching a depth of 40 meters.

Despite numerous discussions highlighting the potential of underground spaces to address urban challenges, general awareness remains low (Broere, 2016). Consequently, this study aims to analyze the current and prospective utilization of UUS in the region of Attica, Greece, with a focus on the examples previously mentioned. Specifically, the main uses of UUS in the area of interest are the Athens metro, underground parking facilities, and an underground hazardous waste repository. Ultimately, this study intents to elucidate how the development of UUS can deliver sustainable solutions for mitigating traffic congestion and CO_2 emissions, enhancing parking space availability, and safely storing hazardous wastes.

2. METHODOLOGY

The study will examine the three major current usages of UUS in the region of Attica, Greece, which are the following:
- The Athens metro,
- Underground parking facilities, and an
- Underground hazardous waste repository.

To accurately assess the positive impact of the Athens metro on the daily lives of citizens, the results from two questionnaires conducted over the past 20 years (e.g. Golias, 2002; Mitoula and Papavasileiou, 2023) were utilized. The first survey of Golias (2002) was conducted during the inaugural year of the Athens metro's operation, while the second survey of Mitoula and Papavasileiou (2023) was carried out nearly 18 years later. This approach allowed for an examination of the metro's initial impact and also investigated its long-term significance after almost two decades of operation.

As for the underground parking stations in Athens, numerous such structures have been constructed over the past two decades to alleviate the scarcity of parking relative to the increasing number of registered vehicles. Details regarding the capacities and number of floors of the largest facilities in Athens were provided. Additionally, due to the complete absence of primary surveys that examine the social impact of underground car parks in the city of Athens, studies that have been conducted on other large urban centers such as Sydney and Boston were utilized. As a result, the positive contribution of such structures was investigated, particularly towards their effectiveness in combatting the growing issue of limited parking spaces.

Finally, a brief historical background of the area currently occupied by the Lavrion Technological and Cultural Park (LTCP) will be provided to elucidate the environmental contamination issues that have plagued the region. Then the study conducted by Benardos and Kaliampakos (2006), in which they proposed the creation of an underground repository to manage the significant amount of waste in the area will then be thoroughly presented. This analysis will highlight the advantages of such facilities compared to other waste management methods, such as landfilling and incineration. Furthermore, the creation of this underground repository showcased how historical industrial sites could be rehabilitated and repurposed to meet modern environmental and technological needs while preserving cultural heritage, through the sustainable utilization of underground space.
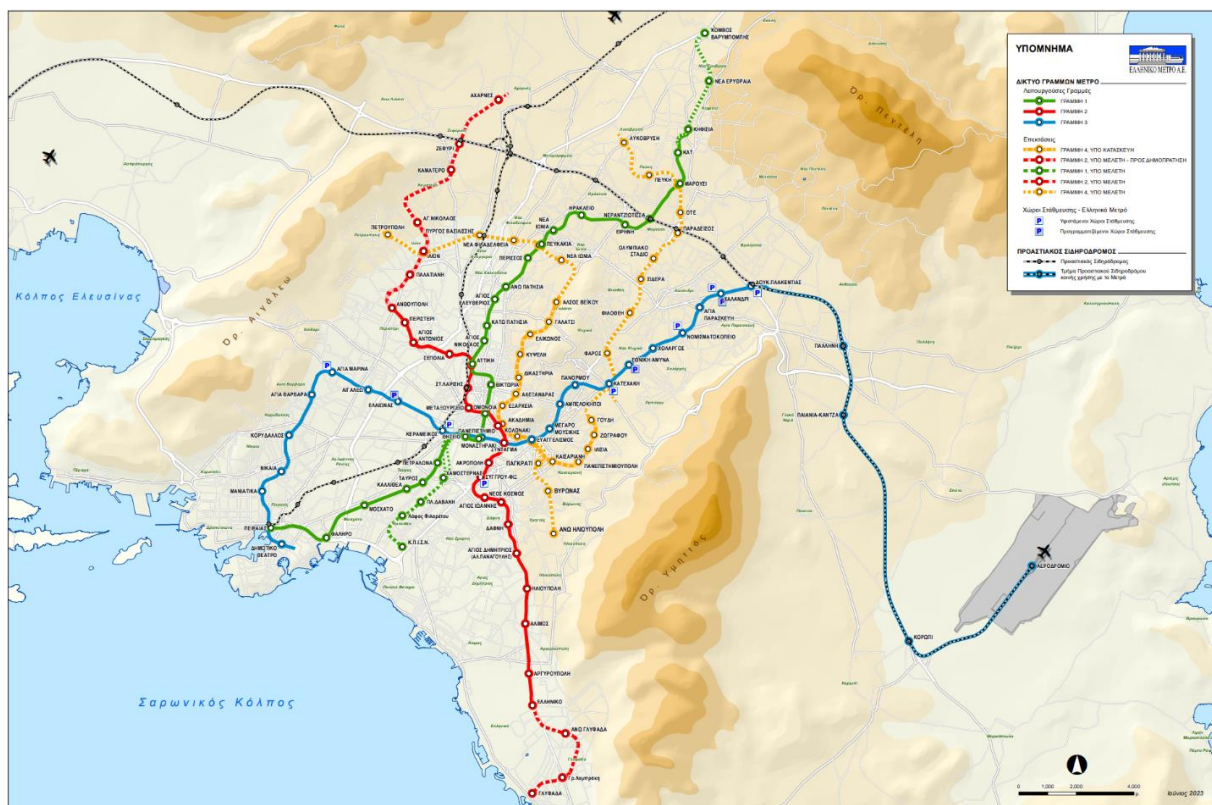
3. THE ATHENS METRO

3.1. Historical background

The urban area of Athens, the capital of Greece, encompasses 1,470 km² (Golias, 2002). In 2020, the total number of vehicles in Athens reached 4,4 million, 69% of which were private vehicles (Chaziris and Yannis, 2023). Traffic in Athens has steadily increased since the advent of motorization in the 1960s (Chaziris and Yannis, 2023), culminating in the implementation of restrictions in 1982 to limit the use of private vehicles within the city center. Specifically, on even-numbered days of the month, only vehicles with an even last digit on their license plate are permitted to enter, while those with an odd last digit are prohibited. In the 1980s, the concept of constructing a metro system began to gain traction, but serious efforts did not materialize until the early 1990s. Consequently, the construction of the Athens metro commenced in November 1992 with the deployment of Tunnel

Boring Machines (TBMs). The planned Lines 2 and 3 were gradually delivered, encountering significant delays in certain excavation segments. In 1997, it was announced that the two lines would be operational by December 1999, but last-minute technical issues delayed the opening by one month (Elliniko Metro A.E., 2025). Finally, on January 29, 2000, the initial sections of Lines 2 and 3 were inaugurated. Line 2, connecting Sepolia with Syntagma, and Line 3, connecting Syntagma with Ethniki Amyna, each comprising of seven stations. Additionally, on November 15, 2000, five additional kilometers and five more stations were added to Line 2, completing the originally planned 12-station line. In April 2003, one more station, extending Line 3 by 1,4 kilometers, was added.

Over the past 20 years, Lines 2 and 3 of the Athens metro have continuously expanded, with the latest addition being three new stations on Line 3, delivered on October 10, 2022. Since its inception, the Athens metro has significantly contributed to reducing traffic congestion, thereby decreasing CO_2 emissions and noise levels. The system has a recorded daily ridership of approximately 938.000 passengers (Elliniko Metro A.E., 2025), a figure expected to rise dramatically to around 1,278 million passengers with the completion of Line 4 (Klontza, 2021). Fig. 1 illustrates the routes of the train (green line) and metro Lines 2, 3 (red and blue line respectively), and the planned route of metro Line 4 (yellow line).

Figure 1. Map of the Athens metro (Elliniko Metro A.E., 2025).

3.2. Impact assessment

As it was previously mentioned results of two separate surveys, with the first having been conducted one year after the metro's introduction (Golias, 2002) while the other 18 years later (Mitoula and Papavasileiou, 2023), were utilized in order to showcase both the initial, as well as the long-lasting positive impact of the metro on the daily lives of the citizens of Athens. The 2002 survey by Golias (2002) initially focused on the modes of transportation utilized by the new metro riders before the metro's introduction. Specifically, over 50% of the new metro users transitioned from bus usage, while 24% shifted from private modes of transport (16% from cars, 7% from taxis, and 1% from motorcycles) (Golias, 2002). Another significant finding of the study is that due to the limited network initially offered by the Athens metro in its first year of operation, 57% of its users were forced to use an additional mode of transport to complete their journeys. This issue has gradually diminished due to the extensive expansions and additions made over the past 20 years. As previously mentioned, in 2000 both metro lines had a combined length of 13 km with 14 stations, while today, the network has expanded to a combined length of 59,7 km with 40 stations (Elliniko Metro A.E., 2025).

Furthermore, it was understood that the two primary criteria influencing public transport users' choice of transport mode were travel costs and travel time (Golias, 2002). The ticket cost is uniform across buses, the metro,

and other forms of public transport. Consequently, the travel cost of the metro, or public transport in general, can only be compared with private modes of transport such as cars, motorcycles, and taxis. Undoubtedly, the metro is significantly more economical than private modes, especially given the recent surge in gas and petrol prices due to the ongoing conflicts in the Middle East and Ukraine. Regarding travel time, the Athens metro is by far the fastest mode of transport in Athens, especially during the morning and afternoon rush hours. Particularly, according to reports by Elliniko Metro A.E. (2025) the Athens metro only requires 14 minutes to cover a distance of 10km, while for the same distance in the morning and afternoon rush hours a car requires at least 45 minutes. Ultimately, the metro uniquely combines both low cost and rapid travel time, thus meeting the primary criteria sought by daily users. Almost all other available options, including buses, private vehicles, combinations of modes, and walking, fail to meet both criteria. For instance, while the bus offers low cost, it is prone to traffic congestion. Conversely, private modes of transport neither offer low cost nor quick travel times. The only other option which offers both affordability and swift travel time is the train, also known as Line 1 (see green line in Fig. 1).

Overall, the survey revealed that the two newly established metro lines, unequivocally alleviated a significant portion of the traffic issues in the serviced areas. Undoubtedly, the Athens metro, despite initially offering a limited number of stations, profoundly improved the daily lives of citizens by providing a new, sustainable, rapid, and affordable mode of transport that could directly compete with private cars. However, a critical question remains: has the Athens metro continued to positively impact the daily lives of citizens almost two decades later? The latter question was answered by examining the results of a more recent survey conducted by Mitoula and Papavasileiou (2023).

The latter survey centered its 27 questions around three key "pillars" of sustainable development: the environmental and economic impact, and the societal influence of the Athens metro. Firstly, over 75% of the surveys participants believed that the metro has positively contributed to the environment of Athens (Mitoula and Papavasileiou, 2023). It is worth noting that according to recent statistical reports by Elliniko Metro A.E. (2025) the extension of metro line 3 to Piraeus has reduced the number of vehicles by nearly 11.000 per day, consequently decreasing CO_2 emissions by 60 tonnes daily. Interestingly, more than 93% of participants observed increased trade in the vicinity of metro stations, particularly noting a surge in hotels, restaurants, coffee shops, commercial outlets, and even museums (Mitoula and Papavasileiou, 2023). Citizens have also perceive that the Athens metro has fostered commerce in surrounding districts by facilitating the creation of new businesses, thereby generating ongoing job opportunities (Mitoula and Papavasileiou, 2023). Furthermore, over 90% of participants indicated that the overall quality of life has improved due to the Athens metro, which they attributed to a combination of the aforementioned economic and environmental benefits (Mitoula and Papavasileiou, 2023). Additionally, more than 92% of the participants believed that the metro has contributed significantly to the general development of Athens (Mitoula and Papavasileiou, 2023).

Several general questions were also posed regarding potential improvements to the Athens metro. More than 53% of respondents suggested that the network of stations should be expanded (Mitoula and Papavasileiou, 2023), highlighting the metro's recognized contribution to improving daily life in multiple aspects and the public's desire for further development. Additionally, over 70% and 68% of participants, respectively, indicated that the metro's travel cost is not prohibitive and that ticket prices remain reasonable and affordable for daily users (Mitoula and Papavasileiou, 2023). These findings suggest that the metro continues to offer a cost-effective travel solution nearly 20 years later, consistent with the 2002 survey's indication that users highly value travel cost. Moreover, over 70% of participants believe the metro is well-maintained (Mitoula and Papavasileiou, 2023), reflecting its nearly 25-year longevity without significant issues. Finally, almost 85% expressed satisfaction with the metro's quality, citing clean and accessible stations throughout Athens (Mitoula and Papavasileiou, 2023). Overall, this more recent study not only confirmed the conclusions suggested by the early 2002 survey but also highlighted the Athens metro's significant contribution to the economic growth of the city. The overwhelming majority of respondents expressed strong views that the Athens metro has greatly benefited the environment, economy, and society of Athens, solidifying its status as a sustainable mode of transport that supports the three key pillars of sustainable development. Additionally, when asked about potential improvements, more than 50% of respondents immediately suggested expanding the metro network to increase the number of citizens it can serve daily.

To sum up, the Athens metro stands as the largest and most promising example of underground space utilization in the Attica region. The citizens of Athens have rightfully recognized its significant positive impact on their daily lives. This recognition is supported by two pivotal surveys: one conducted by Golias (2002), only 12 months after the metro's opening, and another by Mitoula and Papavasileiou (2023), when the metro had been in operation for nearly 18 years. By closely examining the results from the two separate surveys, a more definitive conclusion can be drawn about the effectiveness of the metro and its overall impact. The 2002 survey captured the initial positive impressions of the metro's users, who viewed it as the newest and most sustainable mode of transport, capable of directly competing with passenger vehicles. Despite these positive views, there were concerns about its long-term effectiveness due to the initially limited network. However, the 2020 survey, conducted nearly two decades later, addressed these concerns and provided comprehensive answers. It demonstrated that the metro's

positive impact is not only lasting but has also grown over time. The metro has significantly reduced noise pollution, alleviated chronic traffic congestion, and decreased CO_2 emissions. Moreover, citizens reported that the metro has contributed to the economic development of Athens, further enhancing its societal impact. When considering the low travel costs and quick travel times, two key criteria valued by daily users, the Athens metro emerges as the most sustainable mode of transport. Its network, already expanded significantly, continues to grow to better serve the city's population. The Athens metro exemplifies how effective underground space utilization can address and mitigate real-time urban challenges. This is particularly relevant as urbanization continues to rise globally, amplifying the need for sustainable and innovative transportation solutions.

4.   UNDERGROUND PARKING FACILITIES

The underground space of Athens has been utilized to create several major underground parking stations in order to combat the persistent problem of parking. As illustrated in Table 1 below, the ten largest underground parking stations for vehicles (particularly cars) in the region of Attica are listed, along with one underground bus depot. It is worth noting that the parking station in Syggrou-Fix is a particularly vital one due to its direct connection to the Athens metro and its strategic location, particularly being less than 3 km away from the city center and under 6 km away from the sea. Another significant facility with direct metro access is the Nomismatokopio underground car park, which offers 630 parking spots distributed over three floors. In Agia Paraskevi, the ninth largest underground parking station provides 360 car spots on a single floor, while also maintaining a convenient link to the metro. Lastly, the Katehaki underground bus depot stands out with its capacity to house 284 buses, all on a single floor. This facility plays a crucial role in accommodating a major part of the city's public transportation fleet, contributing to a more organized and efficient urban transit system.

Table 1. The ten largest underground parking stations of Attica for private vehicles are presented, along with one underground bus depot.

Parking Station	Capacity (Parking Spots)	Number of Floors
Piraeus	727	4
Nea Smyrni Square	665	3
Rizari Street	660	4
Paidon Hospital Square	651	5
Syggrou-Fix	640	6
Nomismatokopio	630	3
Kaniggos Square	491	4
Pedion tou Areos	365	5
Agia Paraskevi	360	1
Kerameikos	270	5
Katehaki Bus Depot	284 (for buses)	1

As it was mentioned in the earlier part of the present paper there is a very large gap in the existing literature, as well as statistical data, for the assessment of the social, environmental and economic impact of the various underground parking stations that have been created in the past 25 years in the region Attica, and particularly Athens. As a result, the author will present two case studies from other large urban centers, particularly the city of Sydney in Australia and Boston in the U.S.A., where similar issues of limited parking availability were faced but were subsequently combatted using underground car parks. The Sydney Opera House is undoubtably one of the most important landmarks of the city of Sydney. The latter monument was opened in October of 1973, and according to reports of the Sydney Opera House (2025) more than 10,9 million people visit the site every year. One disadvantage of this historic building, that was clear from its first decade of operation, was its difficult accessibility due to its lack of parking facilities. However, in the early 1990s it was decided to create a large underground helical shaped car park, in order to meet the growing parking issues. The choice of the underground structure was chosen on the basis that an above-ground facility of the same magnitude would greatly affect the visual beauty of the monument. The facility has 12 different floors and approximately 1.100 parking spaces (ITA WG13, 1995). Additionally, the whole excavation of the cavern was executed without disrupting the surface, and in general the aesthetic appeal of the area, due to it being a very high-profile touristic attraction. Overall, this large underground car park under the Sydney Opera House illuminates the advantages of underground space utilization, and particularly underground parking facilities, in producing realistic solutions that can face the major environmental problems of modern cities, such as covering the basic need of accessible parking spaces.

In the early 1980s a very big concern of urban planners in downtown Boston was the lack of open spaces. Subsequently, in 1983 it was proposed to create a 1,7-acre public park as well as an underground parking facility on Post Office Square, which is located in Boston's downtown financial district. The underground car park was opened to the public in June of 1991, and had a capacity of 1.400 parking spots (ITA WG13, 1995). Generally, with the construction of the aforementioned underground structure the available parking space increased in the area by almost 50% (ITA WG13, 1995) without losing any of the valuable surface space. Moreover, the creation of the underground car park increased the overall revenues of the city of Boston, since more people could easily access its downtown. Finally, the option of placing the parking facility underground paved the way to sustainably utilize the above-ground area, transforming the Post Office Square into a much-needed green park right into the heart of Boston (ITA WG13, 1995).

These two examples of large underground car parks perfectly showcase how such underground structures can help alleviate modern issues that most large urban centers face, especially when surface areas are limited. Consequently, all of these direct and indirect benefits that are yielded from the development of underground car parks can be considered valid for the case study of the present paper, particularly the region of Attica, however no efforts have been made yet to study the extent of their social, environmental, and economic impact.

5.   UNDERGROUND HAZARDOUS WASTE REPOSITORY

In 2010, Greece opened its first, and to this day, its only underground repository, with a storage capacity of approximately 3.000 m^3 for toxic wastes, in Lavrio, Attica, within the renowned Lavrion Technological and Cultural Park (LTCP). The proposal for its construction was first put forth by Benardos and Kaliampakos (2006), using the room-and-pillar mining technique, with the excavation taking place in a competent marble formation. The room-and-pillar method was chosen for its cost-effectiveness and it essentially exploited the natural structural stability provided by the marble.

Lavrio boasts a rich mining and metallurgical history, dating back to the 5th century BC when ancient Athenians established underground operations to extract silver. These deposits were further metallurgically exploited for their high lead content from the 19th century until the early 1990s. Due to the presence of heavy industries for all almost a whole century, the buildings within the LTCP complex were highly contaminated. Efforts to preserve the area, given its significant cultural heritage, began in the early 1990s. The extent of the environmental contamination became evident when it was found that the land within the park was extensively covered in waste and slag materials, remnants of the old metallurgical processing. This resulted in the soil having excessively high levels of lead, zinc, arsenic, cadmium, copper, and other toxic substances, far exceeding the acceptable environmental standards. The more hazardous wastes, particularly those with the highest arsenic concentrations, were placed in steel drums. These drums were intended to be stored in the innovative underground repository created within the LTCP. This facility represented a significant advancement in hazardous waste management, utilizing UUS to safely contain and isolate toxic materials from the environment.

The establishment of the underground repository in Lavrio not only addressed the immediate environmental hazards but also marked a significant step forward in sustainable waste management practices in Greece. It demonstrated that managing hazardous wastes through the use of underground space offers clear advantages over commonly used remediation techniques. Additionally, this project showcased how historical industrial sites could be rehabilitated and repurposed to meet modern environmental and technological needs while preserving cultural heritage, through the sustainable utilization of underground space. This approach not only mitigated the environmental risks, but also revitalized the historically significant area of Lavrio. To summarize, the underground repository in Lavrio has significantly improved the safe storage of hazardous wastes. However, the development of such facilities has not yet been widely adopted in Greece, as evidenced by the fact that no other such repositories have been established since then. In contrast, other European countries have recognized the sustainability and cost-effectiveness of underground storage solutions and continue to develop them. With studies such as the one conducted by Benardos and Kaliampakos (2006) nearly two decades ago, and studies like the present, the perpetual and invaluable benefits of underground repositories for storing highly toxic wastes, which pose extreme risks to public health, should be emphasized and made clear to the public.

6.   FUTURE UNDERGROUND PROJECTS

The most prominent future developments for the utilization of UUS in the Attica region primarily involve extensions to the two existing metro lines, particularly Line 2, and the creation of Line 4. Line 4 is expected to be fully operational by 2029 and will connect Petroupoli with Ano-Ilioupoli and Likobrisi (Elliniko Metro A.E., 2025). As illustrated in Fig. 1, this new line will feature 35 new stations. Early estimations suggest that it will serve

more than 340.000 passengers daily and reduce the number of circulating cars by 53.000 (Klontza, 2021). This development will address the increasing demand from citizens to expand the metro network, providing a cheaper and faster transport alternative compared to other modes of travel. Regarding Line 2, there are plans for 9 new stations. Three of these will extend the current terminus at Elliniko towards Glyfada, and six will extend the Anthoupoli terminus towards Axarnes. Additionally, it is under consideration to incorporate underground parking facilities near these new stations to alleviate the persistent parking problems and reduce visual and noise pollution (Elliniko Metro A.E., 2025). Lastly, there have been proposals to expand the underground repository in Lavrio, though these plans have yet to materialize.

7. CONCLUSIONS

The constant increase in urbanization has created significant challenges in modern cities. These issues range from extreme traffic congestion and severe environmental pollution in all its forms, resulting in unhealthy living conditions for citizens, to a lack of sufficient parking spaces and difficulties in managing the uncontrollably increasing hazardous wastes. Given the limited availability of surface space, the utilization of subsurface areas has become a necessity in modern urban planning. This study, focusing on the region of Attica, Greece, demonstrated that large underground projects, such as the creation of the metro, have a lasting positive impact on citizens. The benefits of the Athens metro were confirmed by two separate surveys: one conducted during its inaugural year and another almost 18 years later. Both surveys indicated that citizens recognized the environmental, economic, and societal contributions of the metro, with a strong demand for network expansion. Additionally, the utilization of underground space has proven to be a sustainable solution for creating parking stations, offering numerous advantages over surface car parks. However, the extent of the impact of the latter underground structures has not yet been assessed in the region of Attica, and particularly Athens, hence making their overall evaluation difficult. Furthermore, the case of Lavrio decisively demonstrated that the utilization of underground space can effectively manage hazardous waste. Creating underground repositories for various types of waste (toxic, nuclear, etc.) significantly lowers monitoring costs and mitigates the risk of leakage or environmental contamination, thanks to the impenetrable geological formations used in their construction. The room-and-pillar mining technique also reduces construction costs, making these repositories a superior choice over traditional methods like landfilling or incineration. In summary, while the future development of Athens' subsurface looks promising with the ongoing expansion of existing metro lines and the construction of a new Line 4, many opportunities remain to fully exploit the city's underground potential. Initiatives should focus on creating more underground car parks and especially underground repositories to enhance urban sustainability and effectively address the pressing challenges posed by urbanization.

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