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Construction Work and Utilities in Historic Centers: Strategies for a Transition towards Fuel-Free Construction Sites

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Abstract: In historic centers, construction works consist of complex activities that must balance the operative requirements and lower the impacts on a delicate and sensible environment. In this urban system, especially regarding relevant reconstruction processes such as post-natural disaster scenarios, construction operations are performed through the traditional construction processes, using fuel-based generators and vehicles with limited efficiency and with relevant impacts in terms of the consumed energy, noise and vibrations. In the global transition of the construction sectors towards a zero-emission and fuel-free future, construction sites in historic centers represent a particular opportunity where the application of fuel-free strategies is particularly feasible and can provide additional value in terms of the environmental impact, productivity and health and safety. This work addresses the need for a framework to provide the basis for the application of fuel-free principles in construction within historic city centers dealing with two major concepts: the adaptive construction site as a way to reduce the energy demand and the potential adoption of fuel-free machines. The former is derived from the analysis of a real project in the historic city of L'Aquila, while the latter is defined through the identification and categorization of the applicable electric machines, equipment and vehicles and the discussion of the limits, opportunities and added value of the fuel-free strategies.

Keywords: construction site; historic centers; fuel-free transition; zero-emissions strategy; electric construction machinery

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1. Introduction

As expressed by the recent report "Slow life, Slow city" [1], an average of 15% of the European population lives in small cities and historic centers, where energy-related utilities such as gas or electricity networks often present many complex criticalities due to the multiple interventions, inefficiencies and performance reductions due to the technologies and materials and the lack of service flexibility. In this context, two major problems arise in terms of energy management. On one side, there is a general inefficiency in the networks with a relevant waste of fossil-fuel energy and often with poor service levels (i.e., frequent interruptions, instability of energy provision, high costs per inhabitant). On the other side, the continuous maintenance operations, such as excavations, installations or substitutions of the network elements, are often performed in reduced spaces, such as small roads in historic centers, with the use of fuel-driven machinery that further impacts the delicate micro-environment of small cities. Although it is always difficult and costly to reconfigure entire utility networks in historic centers, in many cases the different public administrations collaborating with the different energy providers and network owners/managers, show increasing interest in renewing them. The recent energy crises, resulting in higher energy costs and the interest in sustainability at a city level, are among the major causes for this increased attention, as observed in various European countries [2]. In particular cases, the opportunity arose to integrate utility networks and services with energy-effective operations and management. For example, the Abruzzo municipalities involved in the 2009 L'Aquila earthquake [3] adopted prefab, unified utility tunnels and multi-hole banks which allowed for a reduction in work and ensured a high level of continuity of the electrical and energy services as well as the flexibility and the gradual progression of intervention. This process of underground utility reconfiguration positively impacted the energy efficiency and environmental quality of small historic centers at different levels, including (a) the optimization of the utilities with a limited waste of energy or gas; (b) the long-term maintenance efficacy, reducing the duration of work and the impact of the interventions; (c) the redundancy and adaptability of the networks and the provided services, allowing for only local, limited service interruption; (d) the potential distribution of electrical power to serve public and private work in different areas of the historic center, reducing the use of fuel-based generators; (e) the possibility of centralized control of the system in terms of management, consumption and safety [3]. These strategies were then integrated within a framework for an adaptive, fuel-free construction site in small historic centers, providing advantages and strategies to remove the fuel-consuming vehicles, machinery and generators currently used in this kind of work. This issue still receives little attention from the scientific community, which is more sensitive to the definition of the strategies and processes aimed at reducing emissions from the building materials production and supply industries [4]. Especially in historic city centers, construction site emissions can lead to significant negative impacts on the environment and public health [5]. However, such issues do not receive much attention [6,7] despite the city air quality regulations to control and minimize pollution. Exploring the opportunities to transition to zero-emission construction sites is important not only to achieve the environmental goals but to allow for the additional benefits, including reduced local air and noise pollution, lower operating and maintenance costs with a consequent increase in energy efficiency, a reduced dependence on foreign fuels and increased use of locally produced renewable energy [8]. In addition to the environmental issues focused primarily on reducing emissions [9], fuel-free construction sites are of recent interest to the international scientific community. However, this issue needs further investigation, especially in light of the recent agreement between the European Parliament and the European Commission (end of October 2022) that banned new combustion cars from 2035 onwards. It is the first agreement of the "Fit for 55" package [10] to reduce emissions in the European Union (EU) by 55% by 2030. This decision will presumably incite a real technological revolution in the construction vehicle and machinery industry since there is currently no EU policy on CO_2 emissions from construction machinery that addresses climate targets. The only relevant regulations [11] are aimed at improving air quality [8]. While much of the research has focused on the development of electric/fuel-free machinery and vehicles, only a few works have discussed the perspective of an entire fuel-free construction site systemically. As shown in the following section, some of the research looked at this topic from a programmatic view while almost no contribution was present regarding a framework for its implementation.

Furthermore, there is a lack of common knowledge or understanding between the different stakeholders on the definition, scope and strategies needed for fossil-free and emission-free construction sites, even in precursor contexts on the topic [12]. In particular, no analyzed research refers to historic city centers. The research gap that we address in this paper is related to the need for a framework for the implementation of fuel-free construction in historic centers, where environmental advantages are enriched by those related to the delicacy of this context. This work aims to provide a basis for fuel-free construction in historic centers by dealing with two major concepts: the adaptive construction site as a way to reduce the energy demand and the potential adoption of fuel-free machinery, vehicles and plants. This work is intended to support both researchers and professionals by providing a clearer view of the potential and issues that can arise during the implementation of fuel-free strategies for projects within a historic city center. At the same time, these bases can act as a reference for the policymakers, administrators and technical offices in various municipalities to favor the implementation of fuel-free principles in the upcoming tenders and works.

With this objective in mind, after the literature review (Section 2) organized and exploited the existing research and highlighted the research gap, the generalization of an adaptive construction site was derived by the direct analysis of a real case study (presented in Section 3.1) in the historic center of L'Aquila. Section 3 discusses the potential of fuel-free shifting for the different energy-demanding operators usually presented on-site. A classification is provided and data were collected for each identified category to depict the potential and the feasibility of such shifting. Based on the research presented in Sections 2–4 collects, categorizes, and assesses the different strategies that can be adopted to reach a fuel-free construction site, analyzing the potential applications for the specific intervention in historic cities and identifying the limits and added value.

2. Literature Review

The literature search was carried out by the Web of Science database, using the keywords "construction site", "fuel free", "zero-emission" and "construction machinery" in combination with each other. The resulting bibliography appeared to be extremely limited in the number of articles present. The existing research only covers the last five years at most and primarily concentrated within the last two, from 2020 to 2022. Moreover, most of the items identified were not related to construction sites. The main research papers of interest are summarized in Table 1. All the selected studies are inherent to construction sites that focus on the problem of consumption, carbon neutrality and the fossil-free approach. Table 1 critically identifies the purpose of the research and the main results obtained, highlighting the type of approach followed by the authors and the specific scope of the construction process.

Table 1. Main references reporting the aim of the research, results, search area and approach.

Reference, Year	Aim of the Research	Results	Search Area	Approach
[13], 2022	Study of five cases in green public procurement to conceptually model an ecosystem for a zero-emission construction site	A collaborative framework for procurement oriented to zero-emission construction	Procurement/ Infrastructures	Theoretical
[14], 2022	Investigating zero-emission construction site feasibility	Comparison of different scenarios for the adoption of electric machinery and vehicles	Energy/Machinery	Analytical
[15], 2022	Presenting a holistic sustainability assessment framework designed for construction logistics activities based on life cycle approaches	Off-site zero-emission construction vehicles are the way forward if cities want to achieve environmental goals by 2035	Energy/Machinery	Theoretical/Analytical
[16], 2022	Presenting a study that aims to lay a foundation for carbon-neutral construction sites	The largest share of emissions is attributed to transport during the construction of new buildings, followed by emissions from demolition and building processes	Energy, CO_2eq emissions	Theoretical/Analytical

Table 1. *Cont.*

Reference, Year	Aim of the Research	Results	Search Area	Approach
[8], 2022	Investigating possible pathways for decarbonising construction equipment and machinery used at construction sites, in line with Lendlease's target of Absolute Zero Carbon by 2040	The report will compare and analyze how fossil-free and emission-free construction sites are being implemented internationally, as well as consideration of any transitional issues. An international policy review is also included.	Construction machinery	Theoretical
[17], 2021	Creating a framework aiming to estimate the fuel consumption of construction trucks	The viability of the method provides important insight into the advantages associated with the combination of sensorization and machine learning.	Energy consumption	Theoretical/Analytical
[18], 2020	Assessing the potential for reducing the climate impact of road construction	With today's best available technologies and practices, it is possible to abate more than three-quarters of the emissions by 2030 and achieve close to net zero emissions by 2045	Road construction	Theoretical/Analytical
[19], 2018	Study of direct and indirect CO_2 emissions in the construction sector	Gasoline, diesel, OTHPETRO and LFO are the four main energy sources for direct CO_2 emission in the global construction sector	Energy/Machinery	Analytical
[20], 2017	Presenting a set of criteria for the adoption of sustainable management practices on construction sites	Identification of solutions and development of indicators as well as a set of recommendations for the deployment of sustainable practices on construction sites	Construction site management	Theoretical
[21], 2016	Describing the environmental impact of the material production, transportation and construction phases from the construction site perspective	CO_2 emissions from material transportation and on-site construction account for 2.4% and 4.2% of the total CO_2 emissions, respectively	Construction site	Analytical
[12], 2019	Presenting the main challenges and opportunities from the construction phase of two Norwegian zero-emission construction sites	Suggesting lessons learned for reducing GHG emissions from Norwegian zero-emission construction sites	Construction site management of two case studies	Theoretical

Stokke proposed a construction site ecosystem for zero-emission construction sites in the green public procurement scope, highlighting the importance of a collaborative framework that includes municipalities, contractors and energy providers [13]. Some research in the Nordic countries [14] assessed that the major impact on the emissions of construction sites is linked to the use of fossil fuels for vehicles and machinery. The same argument applies to Huang [19], who identified that the construction industry produces 23% of the total carbon emissions and about 5.5% of these were primarily generated from the combustion of fossil fuels to power machinery and equipment. Kjendseth [14] argued that the fully electrified sites currently incurred additional costs related to the availability of the electric machinery and the services for the provision of electricity. At the same time, this research predicted that the progressive production increase in the electrical industrial vehicle sectors and the shifts in the energy typologies costs will produce a cost balance between fully-electric and fossil-fuel-based construction sites by 2025. Huang [19], calculated that the direct CO_2 emissions represent 6–10% of the total CO_2 amount globally produced in the construction sector and that the main energy sources causing them are gasoline, diesel, light fuel oils (LFO) and other petroleum products (OTHPETRO). Bellona group described a construction site where the construction activities were carried out exclusively with zero-emission construction machinery or equipment, just as zero-emission vehicles were also used to transport goods and people [22]. Thomas and Costa [20] dealt with the general topic of sustainable and low-impact construction sites, highlighting how the current BREAAM, LEED and AQUA-HQE certification systems define the guidelines that need to be applied to the construction phase. These systems follow different criteria but they refer to the same macro-areas of interest, including resource consumption, which is a top priority in their research based on online surveys. Concerning the specific strategies of the "reduction of electric energy consumption during the production activities on construction sites" and the "use of alternative energy sources, including renewable energy," the researchers pointed out that they are scarcely applied, at 18% and 0%, respectively. Brusselaers [15] analyzed how to mitigate the negative impacts of construction site logistics using the life-cycle approach and applied the framework to a pilot case in Belgium. Among the main results, they realized how off-site zero-emission construction vehicles are needed to achieve environmental targets by 2035. The study [16] aimed to identify useful strategies to achieve a zero-emission construction site by developing three steps, namely the evaluation of the processes using the life-cycle approach, the definition of the possible solutions for reducing emissions and the verification of the real cases. In particular, the CO_2eq emissions from the on-site construction processes were developed in the article. The results revealed that most of the emissions were attributable to transport and demolition work. In this regard, Pereira [17] also focused their studies on heavy construction machinery, defining a framework aimed at estimating the fuel consumption of trucks as a function of the transported load, slope, distance and type of pavement. They also employed sensors for real-time monitoring and machine learning algorithms. Similar research was conducted by Seo [21] that showed how the CO_2 emissions for the transport of materials represent 2.4% of the total CO_2 emissions on a construction site of a complex building. In particular, the transport of ready-mix concrete accounts for 63.4% of the total emissions. Karlsson [18], evaluating the climate impact reduction potential for road construction, identified that more than half of this potential came from replacing the use of diesel with biofuel for transport. However, they only consider biofuels which are sustainably produced (e.g., hydrogenated vegetable oil, HVO). They highlighted the fact that while the use of biofuels in the transport and industrial sectors is a prerequisite for successful decarbonization, there are limits to the available supply of truly sustainable biomass [23–25]. Therefore, they point out that more attention should be paid to the development and dissemination of hybrid and electric technologies for vehicles, crushing plants and cement kilns [26], given the prerequisite of low-carbon electricity [27]. Furthermore, Karlsson [18] discussed how hybrid and electric machines are already available on the market and how greater electrification of the transport and industrial sectors is a promising alternative. However, their wider adoption would require collective agreements or incentive structures to repay the initial investment costs and strategies to overcome the barriers to change [28]. Finally, another aspect argued by Karlsson [18] was significant for this study and identified the optimization of logistics as a measure with a high potential for reducing the impacts.), In a specific Australian context, Smith [8] produced a report where they compared fossil-free construction sites internationally, searching for possible pathways for decarbonizing the construction equipment and machinery used at construction sites.

As presented by Fufa [12], it is also relevant to report that in Norway the research on fossil-free and emission-free construction sites has developed rapidly since 2017. Public administrations have started to demand fossil-free construction sites through public procurement and, within a few years, they have started to target emission-free construction sites. Finally, it was useful to cite the Big Buyers Initiative [29] which led to the creation of working groups on zero-emission construction sites that were aware of the important impacts that the construction industry has on cities and the quality of life of citizens. This action is gaining a lot of attention among the communities, another demonstration that the "bottom-up drive" can bring about significant change. Other examples were the cities of Oslo, Los Angeles, Mexico City and Budapest. Since November 2020. leading companies and innovative business communities have been working together with the mayors to achieve the goal of reducing emissions by half in all the construction and fuel-free activities in their cities by 2030 [12].

3. Fuel-Free Construction Sites in Historic Cities: Rethinking the Utility Grids and the Construction Site

As explained in the introductory section, the objective of this research is to provide the basis for fuel-free construction in historic centers. Given the lack of significant references deriving from previous research, this objective was achieved by the authors through an in-depth study of an adaptive construction site in the historical center of L'Aquila (Italy) and its peculiar needs in terms of space, transport and supply. In particular, the focus of this research was placed on energy demand reduction and the potential adoption of fuel-free machinery, vehicles and plants. For this reason, Section 3 is organized into two parts: the presentation and analysis of the case study (Section 3.1) and the extrapolation of the general elements (Section 3.2), which can be replicated in other historical contexts and those with high critical conditions.

3.1. Design of New Underground Utility Solutions for Historic Centers

In small historic cities, utility reconfiguration is a complex process of design and construction activities that, occurring in consolidated and inhabited centers, has particularly strict requirements in terms of its impacts on the life and the activities of the city inhabitants. Service continuity is a key requirement, among others, that deeply affects how construction operations and logistics are managed and conducted. The continuity requirements apply to roads, building accessibility and the functions of the services provided by the networks under reconfiguration. Long road closures can hinder access to public and private services, such as municipal offices, banks and stores, while service interruptions can cause difficulties for residents or other service providers to carry out their normal activities. In this case, the design of the new utilities is particularly important since it can ensure the rapidness of installation, a reduction in traffic interferences and reduced impacts caused by future maintenance interventions. In the smart tunnel project, carried out during the L'Aquila reconstruction in Italy following the 2009 earthquake, the service infrastructure system was completely rethought to rationalize and optimize the service networks of the entire historic city [3] with economic, environmental and safety benefits. The entire existing system, composed of independent lines placed underground, an irrational result of the continuous and impromptu remodeling over the years, was replaced by a set of prefabricated elements that could be removed over time. In general, the underground sub-services were reconfigured using two design solutions, each with a specific realization methodology (Figures 1 and 2):

- in the multifunctional underground structures or walkable tunnels where the tunnel will be composed of prefabricated elements to be assembled on-site
- in the multi-hole duct banks or, more precisely, the underground artefacts arranged for the insertion of the cables.

Figure 1. (**Left**), reconstruction of the duct in a street in the historic center of L'Aquila; (**right**), 3D view of the duct.

Figure 2. Positioning and assembly of the prefabricated elements to host the utility networks along Corso Vittorio Emanuele in L'Aquila.

Depending on the type of duct, wastewater drainage conduits, water supply networks, public lighting networks, and networks serving the tunnels, such as lighting, monitoring and medium Voltage Enel networks, low Voltage Enel networks, telecom networks and optical fiber networks are normally allocated. The choice between tunnels and multi-hole duct banks is mainly influenced by the width of the roads and the presence of the existing sub-services which cannot be removed or terminated. The intervention also requires the implementation of stormwater drainage conduits in the roads that are subject to the realization of the tunnels and multi-hole duct banks.

The construction of the smart tunnel was carried out through an integrated contract divided into two parts or "excerpts". The first part was practically completed. The second part was divided into five lots and, currently, about 10% of the total work has been performed only on the second lot. Gran Sasso Acqua Spa played the role of the project implementing entity, which was considered the most important public order of the post-earthquake period. The integrated contract was foreseen by Italian law (Legislative Decree 50.2016) in particular cases, for example when the work was very complex. The realization of the contract can benefit from the high specialization of the technicians and workers of the construction companies. This type of contract involves a joint award from the contracting authority of the executive design and the execution of the work based on the final design.

3.2. The Adaptive Construction Site

The construction of the first section, which, was practically completed to date, was burdened with many interferences, criticalities and continuous variations that often interfered with the activities that characterized the daily life of the urban center. In general, when complex work has to be carried out in contexts similar to those presented in the previous paragraph, the main critical issues include [30] the limited availability of space, the presence of multiple typologies of the inhabitants with different needs (e.g., residents, tourists, workers and elderly people) and the proximity of the sensitive receptors (e.g., hospitals, schools, kindergartens and nursing homes). These conditions can negatively influence the process of construction site planning and it is necessary to tailor the specific strategies. In the specific case of the smart tunnel, the critical issues intrinsic to the context, such as those listed above, and the extrinsic causes were identified, i.e., they were dependent on the lack of proper planning of the construction site, of the collaboration between the entities and of the last involvement of all the stakeholders involved in the post-earthquake reconstruction of the city. All these issues were fully analyzed [3] thanks to a direct relationship with the project implementing entity and the construction company that carried out the work. Therefore, the research was subsequently deepened, believing that the "adaptive" approach was the most functional for resolving the critical issues and interferences. The subdivision of the work in local, distributed sites [31] with different execution phases was an effective solution that allowed for optimizing the operations, better control of the health and safety aspects, avoiding the blockage of entire sectors in the historic center with relevant impacts on the social life of the inhabitants (Figure 3). Each construction site is usually conceived with a dedicated border, access and exit routes and a set-up area. The latter is a space allocated specifically for the instalment of the auxiliary factors to guarantee the correct and efficient implementation of the various activities on site.

The scheduling methodologies also play an important role in the organization of a construction site and, more precisely, in the planning of all the activities to be implemented within it. They help identify in advance what needs to be achieved (i.e., the working phases, qualified events, elementary events), the actions to be carried out (i.e., the activities necessary for the implementation of the work) and the usable resources (i.e., the workers, tools, auxiliary factors). Therefore, the scheduling techniques highlight the aspects which are crucial to controlling the construction process as a whole and in its single parts. The use of a correct work breakdown structure (Figure 4) allows for the decomposition of the complex activities into smaller items, considering the works that need to be performed in each distributed site and controlling the general granularity of the operations.

This approach was extensively applied to the described case study and suggested that a non-traditional construction site planning process should be put in place to exploit the electrical energy provided by the urban networks or produced by the renewable systems as a key energy source for the vehicles and equipment. The use of electric vehicles was particularly indicated in the historic centers due to the limited distances they can travel and the limited available space, avoiding the common diesel-fueled vehicles that operate with low efficiencies in these areas, often with large fuel waste in idle mode and a high rate of CO_2 emissions, noise and vibrations. The strategies hereby described and derived from the case study presented in Section 3.1 are preliminary but relevant in the implementation of fuel-free construction sites in historic city centers. They contribute to the optimization of logistics and machinery usage, generating a crucial reduction in energy demand and, consequently, increasing the applicability of fuel-free choices in the execution of construction work. In addition, the optimization of the utility networks in historic city centers further increases the potential adoption of fuel-free technologies, since it ensures an energy provision for all the electric machines and equipment used to reduce emissions and allows for the implementation of temporary charging stations for medium and heavy-duty vehicles.

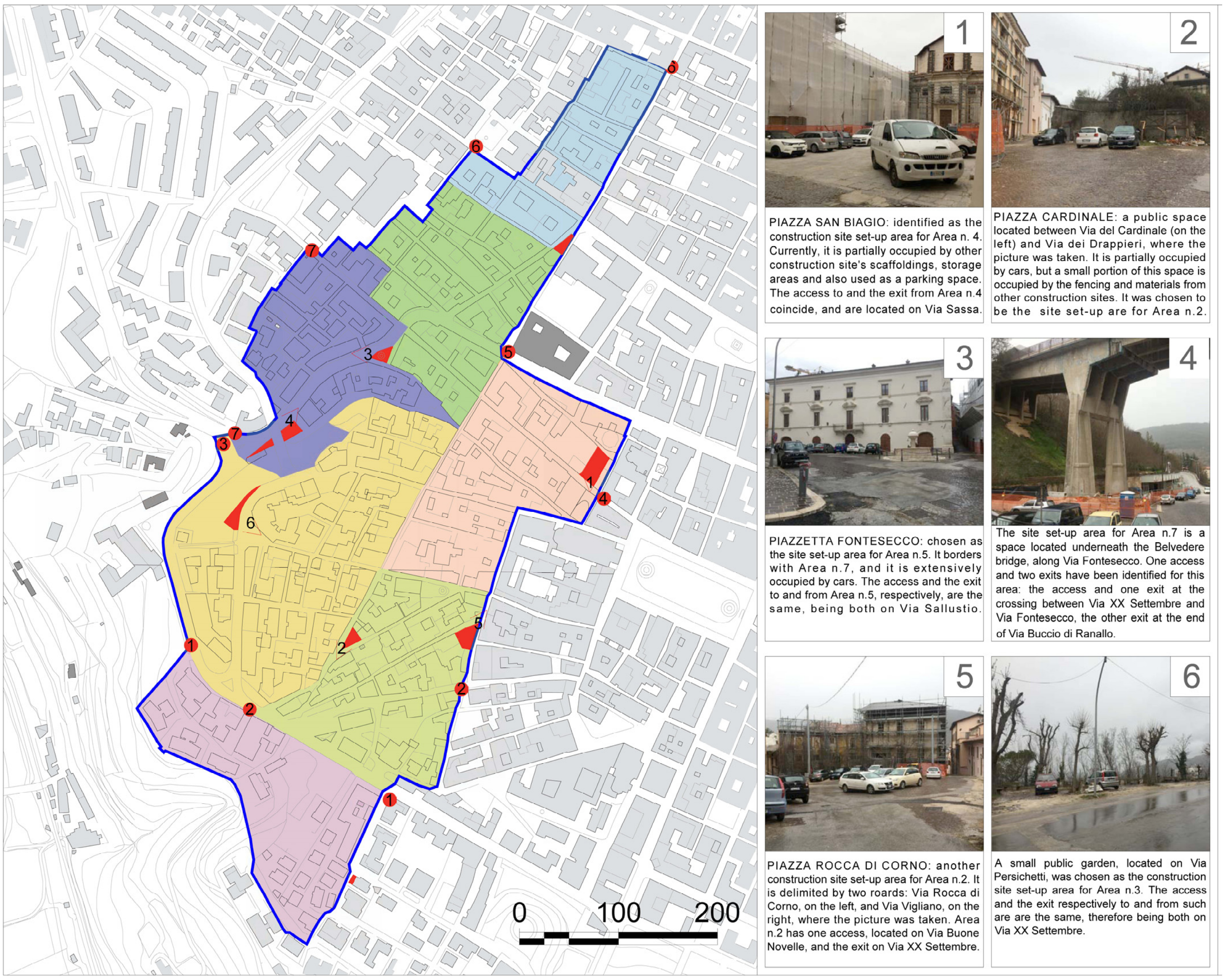

Figure 3. Organization of construction sites within the historic center of L'Aquila, aimed at the optimization of the phases for the utility reconfiguration. In the subfigures there is an analysis of the main public spaces that can be used to allocate each set-up area for the instalment of the auxiliary factors.

Figure 4. Detailed work phasing for the realization of the utility smart tunnel in L'Aquila. Thirteen working phases have been identified and each of them was subdivided in sub-phases (or activities). These phases stretch from the construction site set-up (phase n. 1) to its dismantling (phase n. 13). In the figure, photographic documentation of some of the sub-phases has been provided.The coordination between this construction plan and the site subdivision strategy allowed for parallel execution of the work (Figure 5) to reduce the project duration and reduce the laydown areas. At the same time, the adoption of the prefabricated elements further sped up the process, reducing the on-site energy demand with a lower impact on the urban environment.

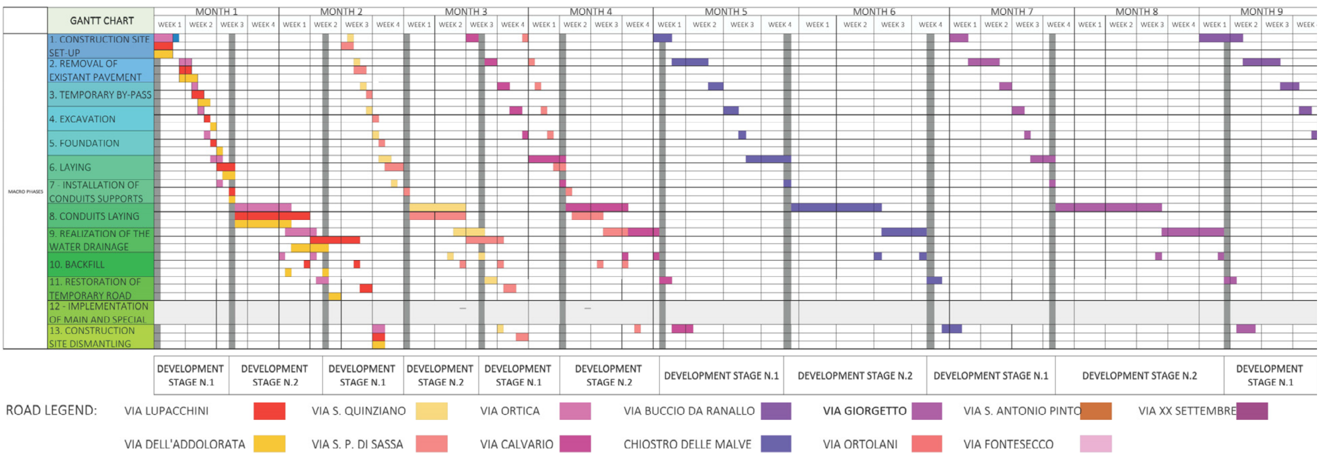

Figure 5. Parallel planning of construction works in a historic center, where the activities path indicates the execution of the works for each distributed construction site and the colors indicate the streets affected by the works.

On these bases, the following section elaborates on the fuel-free scenario for construction work in historic centers, relying on the extensive use of electricity as the main energy source and assessing its operative and environmental impacts.

4. The Transformation toward the Fuel-Free Site

The reduction in the emissions in construction sites is deeply connected with the adoption of fuel-free strategies for vehicles, machinery and for all equipment that demands a certain amount of energy to transform or transport materials and objects. To contribute to the development of this topic, the following methodology was applied. A categorization of the principal energy-demanding operators was developed taking into account their role in the execution of the work and identifying their specific key performance indicators such as the power, runtime and autonomy (hours or kilometers depending on the operator). After each operator was included in one of the three categories, the data research on the manufacturing companies' websites and catalogues was performed to verify the existence of the fuel-free alternatives and to depict the data regarding the KPIs as well as the reduction in terms of the CO_2 produced based on the direct comparison to the comparable, conventional machinery.

The energy-demanding entities on a construction site can be classified into three major areas, depending on the objectives of their operations:

1. Transforming operators: the machinery and equipment that contribute to demolitions, excavations, material transformations, building components installations, etc. This includes machinery items such as cranes, excavators, demolitioners, stampers, wheels loaders, conveyor belts, etc.
2. Transportation operators: the vehicles in charge of transporting materials, objects, people and waste internally to the construction sites or on external roads (i.e., for soil disposal). This group includes trucks, dumpers, vans, cars, pick-ups, etc.
3. Site and logistics operators: the site installations that require energy and that act as supporting facilities for the construction operations. This group includes site offices, signals, fences, surveillance systems, gates, lighting, industrial machinery, plants, site machinery, etc.

Each of these areas is discussed more in detail to highlight the potential strategies and assess the actual impact towards a net-zero construction site for small historic centers.

4.1. Transforming Operators

Transforming operators are machines that are located on the construction site and are dedicated to transforming materials and objects, providing spaces for utilities or preparing new construction elements for installations. In the construction sites in small historic cities, these kinds of machines are usually selected by their maneuverability in small spaces and on city roads. Their required power is less than the power required by larger machinery usually used in infrastructural or construction activities in non-urban areas or outside the historic centers. This results in a particularly effective transition to fuel-free machinery. At present, it is quite difficult to find electric versions for large equipment, although the industry has already produced different electric equipment typologies for small and medium segments. The use in historic centers operations of these machinery typologies ensures their availability on the market of applicable electric machines while operating them in a spatially limited construction site reduces the distances that those machines need to travel during the day and increases the maximum advantages for transitioning to electric engines. In addition, construction works in historic centers tend to be low-intensity—with pauses, overlapping multiple actions, etc.—and the use of electric vehicles with automatic start-and-stop control can avoid the energy waste generated by continuously running engines.

If larger distances need to be travelled or if high-intensity jobs are required—or more rarely if a higher power is required—hybrid construction equipment can be used, still reducing the total amount of CO_2 produced. Generally, the construction equipment market is showing an increased availability of electric machinery, with an expected increase in production in the next few years. Table 2 identifies an electric example for the major equipment typology. The data were derived from the technical specifications of each machine. A comparison with other machines from other brands was conducted to validate the approx. CO_2 estimation.

The main advantages related to the adoption of electric equipment are the reduction in noise emissions (an average of 13 decibels for excavators and wheel loaders) and zero emissions of CO_2. These features affect not only the environmental impact of the construction site but also the safety of the workers since reduced noise helps to control risks and also allow for better communication among operators, while less CO_2 and fewer pollutants can reduce the workers' exposure to air-related risks. At the same time, the comparable operativity of electric machinery can be obtained through the different components to be fully operable through electric energy. This means not only reconfiguring the energy supply from fuel-based engines to those with electrical batteries but redesigning the hydraulic and valve-controlled systems to optimize the energy and, in some cases, even implementing the energy recovery systems [32,33]. Another important element for promoting the use of electric machinery is the expected lifetime, which is considerably higher than combustion engine machines. A recent study estimated an extension of the lifetime for electric vehicles by about 25–50% due to fewer components, less maintenance and fewer vibrations [34]. From an operational perspective, in the specific sectors where electric machines are available, the operating specifications are nearly identical, offering some benefits in terms of operating costs and the provision of instant torque during operations [35].

Table 2. Construction machinery key data for fuel-free transition.

Equipment Typology	Example	Power (Peak)	Indicative Runtime	Charging Time	Approx. CO_2
Compact wheel loader	Volvo l20/l25 electric	up to 40 kW	up to 6–8 h	approx. 2 h	8 kg/h
Excavator	Volvo ecr18/ecr25 electric	up to 20 kW	up to 4 h	approx. 1 h	1500 kg/y
Drilling rig	Bauer ebg 33	400 kW (drive power)	continuous (direct power supply solution)	n/a direct power supply solution	n/a
Trench cutter	Bauer mc 96	550 kW	continuous (direct power supply solution)	n/a direct power supply solution	n/a
Telehandler	Faresin 6.26 2 tons capacity	n/a	6 h	3 h	7000 kg/y

On the other side, autonomy is the main critical aspect for their extended adoption, although the optimized processes (with short recharging cycles) and the progressive increase in the battery capacity can overcome this issue. Another critical issue is the costs of these machines (about 15–25% more than the equivalent fuel-based equipment [36]), which is usually attributed to the costs of batteries and the materials necessary for the electrical components [37]. However, the progressive reduction in costs and the promotion of government policies can help with the initial investment. In addition, this equipment requires less maintenance and fewer costs (a large part of the engine is missing), which can reduce the time for the return on investment. The amount of energy required to perform the energy-demanding work, such as soil-mixing, does not allow for electric batteries to be mounted on specific machinery items, such as drilling rigs and trench cutters. In those cases, the current applicable solution, as described by the equipment producers, is the adoption of a direct power supply that requires a specific energy provision infrastructure and ensures higher efficiency in terms of the used energy.

4.2. Transportation Operators

Transportation operators include all the vehicles that transport mass, waste, bulk materials, soil, goods, construction items, machinery and workers within or outside the construction site borders, for instance from caves or suppliers to the final disposal areas or construction camps. Mobility and transportation are the two business markets related to construction sites that show greater advancements in terms of the fuel-free philosophy and, as a direct consequence, in terms of the produced CO_2.

Due to the good availability of electric vehicles, especially for the capacities required by construction work and utility interventions in historic city centers, the key topics that need to be monitored during the site planning and the actual construction phases are related to the transportation needs, the operation time and the charging infrastructure (Table 3). Several studies compared diesel, hybrid and all-electric vehicles for medium and heavy-duty transportation. Ensuring the same performances in terms of trip and transportation capabilities, these studies highlighted the necessity of increasing the battery capacities and battery rapid swapping technologies while improving adequate charging infrastructure to reduce the charging time and the risks of forced stops, preferably integrated into path optimization algorithms [38,39].

Table 3. Construction vehicle key data for fuel-free transition.

Equipment Typology	Example	Distance Autonomy	Charging Time	Approx. CO_2 Saved
Supply trucks	Volvo FM electric	300 km	2.5 h (dc)	27.5 g/ton-km
Dumpers (small size)	Ecovolve ed1500	n/a	8 h	n/a
Tipper trucks	Fiat e-Ducato	370 km	2 h 25 min	200 g/km
Truck mixers	Liebherr etm 1004 t electric truck mixer	190–380 km	1 h	960 g/km (fully loaded)
Pick-ups	Gmc hummer ev	530 km	1 h 10 min	180 g/km

The first key performance indicator is defined by the distances travelled per day—often in cycles—and the number of travels per day, which usually depicts the travelling demand of an average day in the construction site and is detailed for each transportation typology. The strategies such as earthworks balancing, the reduction in on-site waste, the reuse of materials and elements (often possible in historic centers) and the careful selection of disposal sites, caves and camp locations can positively reduce the travelling demands. Additional aspects such as the quality of the roads and the periodical maintenance of the vehicles can contribute to optimizing this parameter. The travelling time is another key element for a fuel-free construction site. Despite the increased capacity and autonomy of electric batteries, it is hard to rely on an electric vehicle to cover the high-intensity transportation caused by construction. Therefore, the actual time of travel is an important factor that can drive the selection of the right vehicles and the organization of the construction work, taking into account the periods for a partial recharging phase. The third factor, the electric infrastructure, is extremely critical. Sufficient energy on-site to recharge, the vehicles, sometimes in parallel, is necessary to ensure the construction site's autonomy and to keep the process fully operating. Due to the often rigid demands in terms of the work duration, it is not possible to consider delays for vehicle recharging, forcing the decision of adopting fuel-based vehicles. In historic city centers, electric networks are often available and, by adopting dedicated solutions such as ad hoc charging stations or modular DC fast charging systems, it is possible to make decisions towards a fuel-free philosophy. A transition towards fuel-free strategies for these kinds of vehicles is particularly effective in construction operations in small historic centers, since this context usually requires smaller vehicles, short movement paths and lower capacities, providing additional benefits such as the reduction in noise, vibrations and pollutants in the urban environment.

4.3. Site and Logistics Operators

The category of site operators embraces the large diversity of equipment and machinery that are located on-site and that support the specific operations, including elevating objects and people, mixing materials, installing components or performing specific tasks such as perforating, opening, demolishing, etc. Examples of this equipment include:

- Cranes
- Lifts
- Compactors
- Light towers
- Demolition/hydraulic hammers
- Aggregates mixers
- Concrete mixers
- Vibratory plates

These machinery items usually do not have on-board fuel engines but the energy they require is usually ensured by a central or distributed fuel generator (energy source), a site network able to reach the work area (the energy distribution), an energy distribution point and some controlling devices. For some moving equipment (i.e., wheelbarrows), electric batteries are already available on the market. Considering the general framework for the fuel-free construction site, these operators mainly contribute to the power peak and the total energy demand of the construction site to carefully address the entire duration of the project and the different phases. The right selection of new-generation equipment can sensibly reduce the energy demand, ensuring the manageability and energy autonomy of the construction site and leaving room for the additional energy demand produced by the charging systems for transforming transportation operators.

The logistics of a construction site usually require the presence of additional equipment, machinery and systems that provide the necessary mandatory services to the construction site, even if they are not directly involved in the works. These operators include:

- Site lighting
- Controlling systems (cameras, sensors, etc.)
- Plants for materials and waste management (deposits, warehouses, etc.)
- Wheels washers
- Energy provision for site offices, canteens, lavatories, first aid rooms, etc.
- Gates and other accesses

Logistics operators, similar to the site operators, rely on the energy provision of the construction site and essentially contribute to the choice and dimensions of the generators or providing systems.

To transition the site and logistics operator categories towards a fuel-free and zero-emission approach, it is essentially necessary to:

1. Reduce the energy demand of the construction site by adopting energy-saving and high-efficiency equipment for all the aspects involved.
2. Choose the energy source, including the direct provision from the existing networks or the use of generators.

In construction operations within small historic centers (for instance in the case of utility reconfiguration) the availability of the energy networks is not an issue since the presence of the existing electrical networks with different voltages allows for the creation of an energy provision point or multiple access points depending on the extension of the construction site. A good practice for managing the multiple energy demands of a fuel-free construction site, it can be beneficial to dedicate a specific infrastructure for the vehicles recharging and a different point for the non-battery equipment. When electrical energy is not available on-site, the use of generators is essential and, although there is no way to ensure a total fuel-free process, hybrid strategies can be studied to reduce the amount of produced CO_2, even integrating renewable sources such as photovoltaic systems and batteries for energy storage.

5. Considerations about the Implementation of Zero-Emission and Fuel-Free Strategies for Construction Sites in Historic Centers

As discussed in the previous sections, a set of integrated strategies can be applied to construction sites in historic centers to promote and satisfy the fuel-free and zero-emissions objectives. From the study of the adaptive strategies for the construction sites in historic centers (Section 3) and the analysis of the transition towards the fuel-free use of machinery, equipment and vehicles (Section 4), it is possible to derive a list of principles and strategies that are potentially applicable to any construction site typology and need to be discussed in the specific context of the operations in the historic city centers. For each identified zero-emission construction principle, the limitations or requirements were considered and some notes were presented describing how well the principles can adhere to construction processes in the historic centers. After discussing the potential application of those principles in the construction sites within historic centers, this study depicted the additional values that were provided, in terms of CO_2 emissions and other domains such as the social impact, the health and safety of the operators and the overall efficiency of the construction processes. Although conceived for emission reduction, these principles and strategies produced relevant contributions to reduce other impacts of the construction operations—at least in the context of the historic cities—and even on their productivity, safety and efficiency.

The first consideration that emerged from our study was that an accurate energy plan should always be integrated into the overall construction plan, even in the preliminary phases of the project. From an energy demand-provision perspective, the key points of the construction site energy plan reside in the reduction in the overall demand, also in terms of the peaks for the specific work and the transition of all—or part—of the vehicles and machinery items from fuel-based to electrical power. The recharging of vehicles was a critical addition to the total energy demand and required specific infrastructure to be designed and to harmonize the recharging time of the vehicles with the operative sequences.

The integration between the time-based energy plan and the common construction plan allows for reduced peaks in the power demands and can help balance the energy provision during the entire project. Nevertheless, this can often increase the total duration of the work. This aspect needs to be discussed in a larger assessment of the project. One possible solution is to plan the use and charging of the machinery to alternate between short, intermittent low-energy use and continuous high-energy use, as well as using breaks and pauses as a moment to proceed with fast or partial recharging. The vehicles were another key component to be addressed when dealing with fuel-free construction sites. In this case, the typology of the construction sites in historic centers allows for the use of smaller vehicles that are already available in fully electric or hybrid typologies, while external recharging infrastructures and specific time for charging (i.e., during the night) must be defined following the energy plan vision. The optimization strategies for material handling, such as balancing the excavations and fills, favoring the re-use of the materials on-site, reducing the waste disposal and material supply travels and adopting two-way journeys, can reduce the impact of the construction transportation on the overall demand of the site. In the historic centers, the connection to existing electricity networks with dedicated infrastructures for the site equipment and vehicle recharging can favor the transformation towards fuel-free construction. When generators are needed, hybrid strategies should be pursued to reduce the total emissions of CO_2. The use of battery containers and the adoption of battery exchanging stations integrated with photovoltaic systems where applicable can contribute to an increase in the fuel-free component of construction sites. This study clarified the positive impact of these strategies, specifically conceived to reach the fuel-free objective, on the other aspects of the construction site in historic centers in terms of operational optimization, environmental impact and health and safety. The result was a new vision for construction activities where the fuel-free strategies are not an additional requirement to address but part of an integrated strategy with multiple advantages in the construction process. Table 4 clarifies the applicability and the advantages of the zero-emission construction principles to the work, in particular the utility reconfiguration, within historic centers.

Relying on the applicability of the zero-emission construction principles described in Table 4, it is possible to recognize the additional values for each strategy provided on the processes and impacts on the construction operations in historic centers. As expressed in Table 5, the different areas are positively affected by those strategies. The acoustic and vibration pollution can be sensitively reduced, while the use of smaller, electric vehicles—combined with the smaller area occupied by the adaptive site—allows for minor interferences in the operation of roads and city paths. Productivity and cost monitoring are also affected. Electric vehicles do not need to move away from the construction site for refuelling, while the use of electrical energy reduces the cost fluctuations related to the cost of gasoline. The health and safety of the workers are also improved, with a reduction in the risks related to explosions, noises and vehicle accidents. For this aspect, it was necessary to consider adequate signaling systems due to the general quietness of electric vehicles.

Table 4. Zero-emissions strategies and their applicability to construction sites in historic centers.

Sector	Zero-Emission Construction Principles	Requirements/Limitations	Notes on the Applicability for Construction Sites in Historic Centers
Machinery and vehicles	Use of electric machinery	Currently, electrical vehicles have limitations in operating power	Utility works in historic centers require the use of small-to-medium machinery (bob-cats, small excavators, etc.)
Machinery and vehicles	Use of electric vehicles for materials/waste transportation	Electrical vehicles for material movements are effective only for medium size and short to medium distances.	Small electric vehicles are preferable in historic centers (noise and pollution). External supply chains may reduce the advantages of electrical vehicles
Material handling	Reduction in emissions caused by material/ waste transportation	Materials provisions and waste disposal requires many trips to and from the construction site	Construction and utility work in historic centers rely on large reuse of materials and building components to favor coherence with the existing context
Energy provision	Use of fossil-free energy sources	On-site equipment (cranes, mixers, etc.) already rely on electricity but are usually produced through fuel-based generators	In historic centers, the presence of electricity networks—if their continuity is ensured—can provide energy to the site
Energy provision	Avoid the use of fossil carburants	Vehicles have to be frequently charged	The presence of electrical networks allows for the placement of temporary/removable charging stations. Charging can occur at night, increasing day productivity and with lower energy costs. No need for re-fueling trips
Machinery and vehicles	Avoid engines in the idle state	During work, vehicles are often idle consuming fuel and producing noise and CO_2	Electric vehicles and machinery have energy-saving protocols that automatically turn off or on the engines, saving energy
Energy provision	Use fuel-free energy for site installation	Site installations such as offices, fences, gates, site lighting, surveillance cameras and signals require some energy usually produced by fuel-based generators	Ensuring network service continuity, it is possible to avoid the use of fuel-based generators. Where applicable (sun radiation accessibility), removable photovoltaic systems can be used in site offices and/or covered laydown areas
Energy provision	Battery containers and exchanging stations with photovoltaic systems	Additional batteries are needed (two cycles); the necessity of photovoltaic panels	Changing batteries can ensure continuity for operating machines. Photovoltaic systems are difficult to be temporarily installed in historic centers.
Site installation and logistics	Reduce the dimension of construction sites to reduce the energy demand	Larger construction sites require more installations, equipment and an increased number of vehicles and machinery, with higher energy demands	Adaptive construction sites in historic centers are usually optimized to have a minor quantity of area occupied and machinery and operating vehicles
Machinery and vehicles	Charging/required electrical power	Usually, charging stations and equipment require 400 v energy	Temporary converters can be easily installed if sufficient electricity provision is available

Table 5. Additional impacts of zero-emissions strategies on construction sites.

Sector	Zero-Emission Construction Strategy	Added Value	Impacted Construction Area
Machinery and vehicles	Use of electric machinery	Reduction in noise due to the use of electrical engines with low DBs emission	Acoustic pollution
Machinery and vehicles	Use of electric vehicles for materials/waste transportation	Smaller vehicles moving on the roads of the historic center, with less impact on their use by citizens	Social impact—transportation
Material handling	Reduction in the emissions caused by material/waste transportation	Fewer trips of vehicles to supply materials or to transport waste and soil to disposal areas, with reduced impact on traffic and road use	Social impact—transportation Environmental impact
Machinery and vehicles	Use of electric vehicles and machinery	Reduction in the explosions risks due to the presence of gas networks near the combustion engines	Health and Safety
Machinery and vehicles	Use of electric machinery	Reduction in the noise risks for workers and improved awareness of the construction occurrences	Health and Safety
Machinery and vehicles	Avoid engines in the idle state	No vibrations during the idle state of vehicles	Environmental impact Health and Safety
Machinery and vehicles	Use of electric vehicles and machinery	Silent machinery and vehicles increase communication between workers	Productivity/efficiency on site
Energy	Vehicles charging at night	No time wasted for vehicle refuelling. Acquisition of electrical energy with minor costs.	Productivity Works costs
Energy	Electrical energy driving the construction site	More stable energy costs without oil fluctuance	Costs monitoring
Adaptive site	Road occupancy and interruptions	Reduced area occupied by the construction site with fewer road closures	Social impact
Adaptive site	Utility service continuity	Reduced interruption of services	Social impact
Machinery and vehicles	Maintenance	Reduced maintenance costs due to no engine-related maintenance	Costs monitoring

Although Table 5 is not exhaustive of all the principles of the strategies that are applicable to pursue a zero-emissions construction site in historic city centers, the discussed applicability and the identified added value provided in the other areas different from the emissions-control perspective show how the relevant potentials can be activated by shifting this type of construction towards a fuel-free implementation. The reduced costs of those interventions and the good availability of electric machinery and vehicles allow for a rapid transition with a high social and environmental impact, leading to further transitions in other construction project typologies such as large infrastructures or new large buildings.

6. Conclusions

In this study, we discussed the possibility of a fuel-free construction site in the context of historic centers, discussing the potential implementation strategies and identifying the limits, advantages and impacts not only in terms of the emissions but also considering the other relevant effects on the operations and the urban environment. In particular, the study relied on a real project for utility network reconfiguration in the historic city of L'Aquila, deriving the necessary features for the future implementation of fuel-free work. This study highlighted the relevance of rethinking the construction site by integrating the strategies that control not only the machinery typologies but the entire site infrastructure and operational processes, including the work schedules and execution methodologies. The zero-emissions construction strategies in the small historic centers passed through the integration of strategies in terms of:

- A design that ensures the effective provision of the services and that allows for the utility configurations to favor net-zero construction and maintenance works
- Construction planning and logistics optimization by defining the construction processes that allow for the adoption of net-zero strategies, reducing the material and waste transportation and optimizing the resource involvement.
- Fuel-free work execution, relying on the use of electric vehicles and machinery and managing their use to allow for efficient recharging cycles.

In historic centers, the peculiarities of the work and the presence of the existing utility networks represented the major aspects that result in a more effective fuel-free approach. The sensitivity of the historic center context, the narrowness of the roads, the general scarcity of the operating spaces and the service continuity requirements favor the use of adaptive strategies for the construction site based on the limited occupied areas with a gradual progression to the other parts of the historic city and the use of smaller, easy electrifiable equipment, machinery and vehicles. The presence of the existing utilities was another critical point in adopting fuel-free principles to the construction sites in historic centers. By keeping the utility networks operating, even partially, it is possible to provide the construction activities with the necessary electrical infrastructure, ensuring that the site equipment functions and providing the energy for the recharging stations for the vehicles and machinery with a consequent limitation of the use of fuel and gas generators.

When dealing with the electrification of the construction sites, it is important to consider not only those activities that are directly performed on the building or the infrastructure but also the indirect industrial actions related to the production of the materials, transportation and waste disposal that are activated by a construction project. This scenario was considered promising by different authors (e.g., [18]). However, to generate a meaningful impact, it was necessary to assess the dense systems of the connections and interactions between the different industrial sectors. In addition, a long-term strategy was required to plan and assess the economical investments for the realization of the supporting infrastructures, embracing electrification and renewable energies. The ongoing process of transitioning the construction industry towards fuel-free operations has an optimal experimentation field in the construction work within historic centers due to the controllable operations, the sensitivity of the context and the measurability of the actions and the effects. From these experiments, those principles can be extended to the entire sector, favoring the positive reduction in emissions and the fulfilment of the Sustainable Development Goals of the UN Agenda 2030 [40], suggesting new approaches and solutions to politicians and administrators [25]. Historic centers are complex systems by definition due to the often overlapping relationships between the urban fabric, networks and facilities, routes, uses, users, services, physical components, administration, management, etc. Moreover, in historic centers, the complexity also lies in balancing the aspects of conservation and the use of the centers towards a continuous search for compatible solutions. Therefore, the strategies valid in historical contexts are exportable and replicable in different and less complex contexts.

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