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S1. Sustainability and Decarbonization

CONTENTS

ON THE POLITICS OF HYDROGEN ECONOMY, POWER-TO-X, AND DECARBONIZATION

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ABSTRACT

Since the 1970s, hydrogen has been considered an essential element of a future energy economy. Recently, within the framework of decarbonization in the energy sector, many countries have developed national plans to address the establishment of a hydrogen-based economy in the *near* future. To achieve complete decarbonization, electric power must be generated exclusively from renewable sources. Power-to-X (PtX) technologies refer to hydrogen generation from electricity and its subsequent conversion to another energy carrier for storage or transportation. Thus, the challenges associated with establishing a green hydrogen-based economy include those associated with expanding renewable energies and the production, transportation, and storage of the energy carriers denoted by X in the PtX.

A prerequisite for decarbonization enabled by the hydrogen economy is the availability of large quantities of excess "green" electricity. In the coming decades, we will be far from reaching this goal. Thus, almost all current efforts toward establishing a hydrogen economy tend to increase CO2 emissions globally instead of decreasing them because the incremental electricity generation required for hydrogen production is accomplished using fossil fuels.

As long as fossil fuels are used on a large scale to cover the demand for electricity in a country, the implementation of a hydrogen economy will lead to a significant increase in the inefficiencies, costs, and CO2 emissions in the energy sector of the same country compared to other options that either are or could easily become available. As long as the conditions for generating large additional amounts of green electricity are not met, a hydrogen economy is counterproductive to the decarbonization efforts.

Therefore, national energy policies should focus in the coming years on the expansion of the use of renewable energy sources, as well as on the expansion of the electric grids and of the interconnections among countries, which are very important for achieving the decarbonization goals faster and in a sustainable way. The use of hydrogen and PtX technologies should not be promoted now with taxpayers money (to maximize decarbonization per unit of invested capital), but in later years, when the share of green electricity in a country reaches very high levels. Finally policymakers, scientists and engineeres should (a) expand and reconsider the existing measures for reducing CO2 emissions in the energy sector, (b) objectively inform the public about the available options, and
(c) stop misleading the public about the role of hydrogen in decarbonization in the near future.

Keywords: Energy policy; Decarbonization; Hydrogen economy; Power-to-X (PtX).

1. INTRODUCTION

Despite a series of international meetings since the beginning of the 1990s, international agreements (e.g., in Rio de Janeiro, Kyoto, and Paris), and continuous warnings by experts in climate change, the worldwide CO_2 emissions have been continuously increasing practically every year until today, with the exception of the short-time effects of the financial crises and the COVID pandemic. As a matter of fact, global CO_2 emissions are today almost twice as high compared with those in the beginning of the 1990s. In the time period 2012 - 2021, the CO_2 emissions increased on average by 0.6% per year [1]. This shows that the measures undertaken so far are insufficient for tackling the problem.

To mitigate the CO_2 impact on climate change, mankind is expected to significantly reduce the net CO_2 emissions from the energy sector to the atmosphere within a few decades in the future. Countries have developed a series of measures aiming at this goal. The most important measures focus on the expansion of the use of renewable energy systems, the reduction in the use of fossil fuels, and the establishment of a hydrogen economy, but not directly on the reduction of the per capita energy use or on the reduction in the rate of increase of world population. The reduction of the worldwide energy demand is extremely important for the reduction of the net CO_2 emissions to the atmosphere. As a result of the continuous increase in the global energy demand, the primary energy supplied by fossil fuels more than doubled between 1990 and today. The failure of most of the industrialized countries that use decarbonization mechanisms (e.g., CO_2 certificates) to significantly reduce their overall CO_2 emissions in the last years shows that additional, more effective measures than the already applied mechanisms are required to mitigate the CO_2 impact on climate change.

All energy plans developed after the first energy crisis in 1973 include hydrogen as an important pilar *of a future* energy economy. Almost every known process of producing hydrogen has therefore been extensively investigated in the last 50 years and continues to be scrutinized today. The results have never been very encouraging, but hydrogen has nonetheless always been regarded as one of the most important future fuels in all these years. Since pure hydrogen is not provided directly by nature, it is important to consider the primary energy form and the process used for its production, because they both affect efficiency, costs and associated CO_2 emissions. The primary energy sources used for hydrogen production include natural gas, coal, oil, biomass, nuclear energy, solar energy, and wind energy. Every energy resource currently available can theoretically be used for hydrogen production. Today a steam reforming process is still one of the most cost-effective processes, responsible for over 70% of the worldwide hydrogen production.

While carbon capture appears to theoretically be a promising and essential technology for reducing greenhouse gas emissions, there are several challenges and obstacles, including high investment and operating costs, high energy requirements, the lack of public acceptance of transportation of large CO_2 amounts, and the need for identifying and using suitable sites for storing the captured CO_2. Therefore, carbon capture could not yet reach the status of wide commercialization, although Carbon Capture and Storage (CCS) and Carbon Capture and Use (CCU) are based on conventional technology. Many countries with large resources of fossil fuels emphasize the CCS/CCU solution, as long as they want to continue exploiting fossil fuels. In the author's opinion, however, CCS and CCU will not have a large contribution to decarbonization in the future because very few industrialized countries (e.g., Norway) will finally employ CCS technologies. Therefore, the use of fossil fuels for hydrogen production should be avoided and is not further considered in this paper.

2. PLANS FOR HYDROGEN

Recently many mainly industrialized countries (among them the USA, Norway, Germany and some other countries of the European Union) decided to proceed with a hydrogen-based energy economy, in order to fight climate change. To achieve this, the hydrogen should be produced using renewable energies, mainly electricity generated by renewable sources (the so-called *green electricity* that leads to the production of *green hydrogen*). In many studies (e.g., [2]), hydrogen is presented as the most practical alternative to reach net-zero CO_2 emissions in the coming decades. It is hoped that by creating a high demand for green hydrogen, water-electrolysis technologies will be adopted rapidly by many countries and, thus, the production costs will be reduced. According to these plans (see also [3]), hydrogen will be produced in regions rich in renewable energy and part of the hydrogen will be transported to other regions, which have a high energy demand. The so obtained hydrogen and its derivatives will be initially used in energy sectors that are hard to decarbonize (for example, steel or cement production and aviation). Plans for establishing a hydrogen pipeline network, based on the existing natural gas pipeline network, are currently under discussion in Europe.

It is true that hydrogen is a fuel which theoretically can be produced in almost any country. This "democratization" of the energy sector is appealing, particularly for countries that depend on fossil fuel imports from other countries. If a hydrogen economy is established, this energy dependence could be reduced, but not eliminated for most countries. In Germany, for example, approximately 90% of the predicted future demand for hydrogen would be covered by imports from other countries (35% from European countries and 55% from countries outside Europe) according to recent studies [4].

Since it is not expected that all industrialized countries will be able to generate all the green hydrogen required for decarbonizing their energy sectors within their geographical areas, large quantities of hydrogen will need to be transported over long distances and transport and storage of hydrogen will be essential in the realization of the above plans. Because transportation and storage of *gaseous* hydrogen is associated with some problems, and the use of pipelines is not always possible, so-called Power-to-X (PtX) concepts have been developed. These concepts refer to the generation of green gaseous hydrogen from green electricity and its subsequent conversion to an energy carrier X which can be further stored and transported over long distances (for example, liquid hydrogen, methanol, or ammonia). The significant thermodynamic inefficiencies and costs associated with the large-scale liquefaction and regasification of hydrogen are discussed in [5] and [6]. The inefficiencies and costs of the conversion of gaseous hydrogen to another substance (methanol, or ammonia) are however also significant. Ref. [7] provides a comprehensive review and assessment of the state of the art, challenges, and recent developments associated with all these processes.

It is apparent that, when evaluating PtX processes, the inefficiencies and costs of these processes must be added to those of water electrolysis, resulting in relatively low overall efficiencies and a high cost of the hydrogen available at the consumer site. The efficiencies of the overall process starting from electricity used to produce the hydrogen to the final product delivered at its destination are well bellow 50% [7], making the meaningfulness of applying these solutions at least questionable because the potential for increasing all these efficiencies is not very large. Despite all these points, a significant amount of research funds are currently allocated to PtX processes.

Finally, current plans call for the generation of large amounts of hydrogen in dry areas (e.g., northern Africa). In this case, the inefficiencies and cost of PtX processes, transportation of X, and water desalination (even if small compared to the total product cost), must be added to those of the electrolytic process for hydrogen generation, making such an overall process even less attractive. It should be noted here that the required quality of water used in electrolysis is, in general, relatively high. When analyzing plans referring to the production and use of hydrogen, the question arises, whether all these plans maximize decarbonization and, if not, under what conditions maximization of decarbonization can be achieved. These points are discussed in the next section.

3. CHALLENGES ASSOCIATED WITH A GREEN HYDROGEN ECONOMY

We must always keep in mind that the selection of hydrogen (generated using electrical energy) as an energy carrier results more from our inability in the past years to find other more attractive solutions to decarbonize the energy supply and less from hydrogen's attractiveness to be produced, transported, and used as an energy carrier.

First, we must recognize that from the thermodynamic viewpoint it is not meaningful to invest money and accept significant thermodynamic inefficiencies to convert electricity (which has the highest thermodynamic quality, as expressed by the exergy concept) into an inferior energy carrier (hydrogen) in an electrolytic unit. Thermodynamics shows that the theoretical capability of hydrogen to generate work (the exergy of hydrogen) is 83% of its higher heating value (the energy of hydrogen), whereas the exergy to energy ratio for electricity is 100%. This point becomes particularly clear, when the generated hydrogen is subsequently used to produce electricity. In this case, hydrogen is just used to store electricity with an expected roundtrip efficiency well below 50%. There are other concepts (e.g., batteries and, particularly, pumped storage power plants) that may offer a storage capability for electricity which is more attractive from both the thermodynamic and the economic viewpoints. In addition, from the decarbonization viewpoint, the storage of excess electricity in the form of hydrogen is only required when the electricity has been entirely generated from *intermittent* renewable resources, i.e., solar or wind. Regarding the production of green hydrogen, the main problems have always been the relatively low thermodynamic efficiency of all known processes and the high production cost.

Considering the way electricity generation units are dispatched with the renewable energy units using solar and wind energy being dispatched first, any *additional demand* for electricity for the production of supposedly green hydrogen will be covered in the next decades mainly using other energy forms: nuclear energy or, in the large majority of countries, fossil fuels. Policymakers, who are frequently in favor of establishing a hydrogen economy, base their arguments on the *average* energy mix used in a country for electricity generation, but what really matters is which energy sources are used to supply the *additional* (*marginal*) electricity required for an electrolytic unit to generate hydrogen. If at least one fossil-fuel power plant is in operation when an electrolytic unit is in use, then the electricity used to produce hydrogen comes exclusively from fossil-fuel energy and is definitely *not green* independently of the average amount of electricity generated from renewable sources at that time.

The hydrogen generated in this way leads to an increase in the associated costs and the overall CO_2 emissions (compared to the case without hydrogen generation) and has a negative effect on the decarbonization efforts, particularly when PtX technologies are further involved. Here we should also consider that, once electrolytic units, which are capital-intensive energy converters, have been installed, to ensure economic viability, they might be operated more or less independently of whether green excess electricity is available at a given time. Such operation would definitely not contribute to decarbonization efforts for the great majority of countries in the coming years.

Let us now consider a different aspect and assume that in a specific region A there is a given amount of excess electricity generated exclusively from renewable sources. In one option (*option I*) this excess electricity could be used for hydrogen production. The hydrogen would then be transported to and used in another region B to reduce the amount of fossil fuels used in B, e.g., in industry or in power production. A second option (*option II*) for using the excess electricity might be to directly transfer the electricity to a neighboring region C that uses fossil fuels for electricity generation at the time being considered. In *option II*, the transferred energy would be used directly in C to reduce the electricity production from fossil fuels and, thus, the CO_2 emissions in the same time period, whereas the required energy in region B would be covered by continuing to use fossil fuels. The energy demands in regions B and C are independent of the amount of excess electricity generated in region A.

Option II leads to a more efficient and cost-effective use of the excess electricity in region A and simultaneously to lower *overall* CO_2 emissions, because the potentially avoided CO_2 emissions in region B in *option I* are smaller than the potentially avoided CO_2 emissions in region C (*option II*), due to the additional inefficiencies in generating and transporting hydrogen in *option I*. If the excess green electricity generated in region A is significant and it is anticipated that fossil fuels would be used for a long time in region C, it might even be more cost effective to connect the two regions with an electric line (assuming they are not already connected) than to generate hydrogen. This comparison demonstrates that investments in green electricity generation used exclusively for hydrogen production might not be using the invested money in the most effective way to maximize decarbonization. It is apparent, however, that there are exceptions to that, for example in the cases of an island that is far away from the mainland (e.g., Island and Canary islands), where the production and storage of green hydrogen to be used later for electricity generation might be the preferred solution for decarbonization.

The above observations demonstrate the need to (a) increase the capacity of electrical interconnections among regions and countries, (b) establish new or expand existing electric grids and (c) keep the largest possible boundaries when evaluating the effects of decarbonization measures involving hydrogen. Thus, decarbonization of a city or a small geographical region through hydrogen might increase the overall CO_2 emissions, compared with the option in which the electricity used for the hydrogen production would have been used to reduce the use of fossil fuels for electricity generation in a neighboring region. Therefore, plans to decarbonize single cities, regions, or industries must be carefully evaluated considering the above facts.

The term *neo-colonization* has been used in conjunction with the efforts of some industrialized countries to speed up their decarbonization by importing hydrogen from developing countries, while the latter are still using fossil fuels to generate electricity. In these cases, part of the exported hydrogen might be generated from fossil fuels in a rather inefficient way that does not reduce the overall CO_2 emissions in the fastest and least expensive possible way. Even if the generated hydrogen is 100% green, the electricity used for its production could have been used instead to eliminate the use of fossil fuels in the exporting country before the first hydrogen for export is produced. We have not achieved much if an industrialized country manages to decarbonize its energy sector “at the expense” of one or more developing countries that are denied the maximum potential for reducing their CO_2 emissions. All future partnerships of countries in the energy area must ensure that all the countries are at the same level (at eye level).

Since the available financial resources for decarbonization are limited, an important criterion for evaluating decarbonization options and establishing priorities is the amount of CO_2 emissions avoided per dollar invested in each option considered. In such comparisons, the system boundaries should not be local, but should include the entire Earth. Under these conditions, many decarbonization projects currently being considered should be rejected.

When establishing priorities for the use of hydrogen, hydrogen should be initially used in the sectors and processes that are the most difficult to decarbonize. Examples include the use of hydrogen in the steel, cement and glass industries, or in fuel cells used in heavy trucks as well as the use of hydrogen derivatives in the aviation sector. Plans calling for mixing green hydrogen with natural gas to use the existing pipeline network for hydrogen transportation should be abandoned because in this case hydrogen would also be used in processes and sectors that could be decarbonized more easily from the technical and economic viewpoints, like production of electricity or heat.

We must further recognize that the goal is not, and cannot be, the establishment of a hydrogen economy, as some studies suggest. *The goal is the decarbonization* of human-related operations on Earth (the largest possible boundaries). Thus, as long as the conditions for generating large *excess amounts of green electricity* in large areas are not met, a hydrogen economy would be counterproductive to the decarbonization efforts.

From the above discussion we might conclude, that as long as fossil fuels are used on a large scale to cover the demand for electricity (here we must also include the expected increases in this demand for purposes such as artificial intelligence, transportation and decarbonization of industry and the heating sector) in a country, the implementation of a hydrogen economy will lead to a significant increase in the inefficiencies, costs, and CO_2 emissions in the energy sector of the same country compared to other options that either are already or could easily become available. This becomes particularly important for decarbonization, when the additional electricity for hydrogen production is generated using coal and subsequently PtX technologies are used. Generating hydrogen from electricity produced using coal or natural gas is costlier and leads to higher CO_2 emissions compared with the option of generating the hydrogen directly from the same fossil fuels.

A hydrogen economy can only be meaningfully implemented when worldwide large quantities of excess green electricity will be available. Unfortunately, this requirement cannot be realistically achieved in the next two to three decades while ensuring economic, social and political stability, because of the following significant challenges associated with this required increase in providing green electricity [8]:

1. The capital required for new investments in renewable energies and for establishing new infrastructures (e.g., power lines) is very large. Only a relatively small portion of this capital can realistically be supplied by governments. Moreover, these investments are not yet attractive enough compared to other investment options for private investors to invest in rapidly decarbonizing the electricity generation.
2. The energy sectors of electricity generation, heat supply, transportation and industry will compete among themselves for the same decarbonization options, leaving not all options available for green electricity generation.
3. Political calculation (see for example [9]),lobbying efforts, populism (one of the main dangers and obstacles in the author's opinion), and corruption often make the implementation of required policies impossible or cause a regression in the decarbonization process.
4. The world population, which continues to rapidly increase, is not yet ready for the changes in prices, use of energy, or lifestyle that are essential for reducing the demand for energy (at least on a per capita basis) and particularly for green electricity. The public has not been educated adequately or is misinformed about what needs to be done.

A very important and still unresolved issue refers to the cost of energy in the future. We cannot expect that the decarbonization goals will be achieved in the coming 3 to 4 decades without a significant reduction in the per capita energy use in industrialized countries. The two energy crises in the 1970s and the recent price increases in Europe as a result of the Russian war against Ukraine have clearly demonstrated that an increase in energy prices leads to a reduction of the per capita energy use. These experiences have shown that a price increase above a given threshold is the most effective way for reducing this use. Here the author refers to a price increase that will not come through a war, fuel shortage, or thermodynamic inefficiencies, but through thoughtful deliberations and agreement among main players to fight climate change. Needless to say, that no matter how well designed such a price increase will be (e.g., gradual introduction, and support of socially disadvantaged and low- income groups), it will be used for political gains by populist political parties seeking to capitalize on the economic anxieties of working people, so that even a government serious about decarbonization will likely not proceed with such required price increases. Here, an objective education of the public on decarbonization issues and solutions that contain important elements of social justice could improve the situation, but not solve the basic problem.

Since there is no realistic solution to this problem, we cannot expect that the per capita energy use will decrease and decarbonization will proceed with the speed required to avoid serious climate change effects. Here we should make two notes: (1) a well-designed energy price increase would provide the much-needed planning security in the energy-intensive industry, and (2) the goal of “affordable energy”, as formulated in the Sustainable Development Goal number 7 by the United Nations (2022), is well-intentioned, but not necessarily consistent with the decarbonization goals, because the more affordable energy is, the lower the expected efforts to save energy, and, consequently, the larger the energy use (and “waste”) per capita will be. This, combined with the continuous increase in the world population results in a continuous increase in the world demand for energy. It is obvious that each additional unit of energy required in a not fully decarbonized country (assuming it does not use nuclear energy) comes, in general, from fossil fuels and this leads to an increase in CO_2 emissions worldwide.

Finally, in the planned projects on hydrogen there seems to be an imbalance between supply and demand: on one side, many plans for supplying hydrogen exist, whereas fewer projects deal with the subsequent use of hydrogen. This imbalance is certainly also the result of all the challenges associated with the use of hydrogen. Any subsidies that might be used to change this imbalance in the very near future would mean a non-effective use of the corresponding financial resources for decarbonization purposes. No liquid market for green hydrogen exists to date and few renewable hydrogen financing deals have been closed. More than 1,400 renewable and low-carbon hydrogen projects representing $570 billions of investment by the end of 2030 have been announced globally, although less than 7% have reached a final investment decision [10]:This last reference also provides a detailed assessment of the risks associated with green hydrogen projects and the corresponding risk mitigation strategies.

4. WHAT MUST BE DONE AND AVOIDED IN ENERGY POLICIES

Possible applications of hydrogen in various energy sectors include those in electric power generation, heat supply, transportation, and several industrial applications (e.g., production of steel, cement, synthetic fuels, and fertilizers). Prioritizing the use of hydrogen, particularly in the first decades of the establishment of a hydrogen economy, and initially focusing on the sectors that are more difficult to decarbonize are of paramount importance for the success of the hydrogen plans. With that in mind, and contrary to the current plans of many electric utilities, we should not be talking about the use of hydrogen for electricity production or heat supply in the very near future. (Christidis et al, 2023) provides a comprehensive discussion of the challenges associated with the use of hydrogen in power plants.

Calls to “double the energy efficiency”, as mentioned in documents of the European Union, mislead the public, because they are very far from being realistic for electricity generation, and are still very exaggerated, when they refer to the use of electricity. This is true not only when we consider the economic sides (costs), but also thermodynamic boundaries imposed by the second law of thermodynamics. For example, with the latest improvements achieved in combined-cycle power plants (efficiencies above 63%), we approach these boundaries, i.e., the largest part of the remaining thermodynamic inefficiencies (exergy destructions) in the production of electricity is unavoidable. Similarly, efficiencies above 48% in the conversion of coal energy in electricity will remain economically unfeasible in the coming decades.

Some priorities and some actions that need to be established possible include the following:

1. Absolute priority in the coming years and perhaps the coming decade should be given to the expansion of the use of renewable energy sources, as well as to the expansion of the electricity grids and of the interconnections among countries, which are very important for achieving the decarbonization goals faster and in a sustainable way.
2. The public must be objectively educated on the necessity of decarbonization and the real challenges associated with it and should be persuaded to accept and support higher energy prices to reduce the “energy waste”. The way we all think about energy must be changed, if we want to succeed.

3. The use of hydrogen and PtX technologies should not be promoted now, but in later years, when the share of green electricity in a country reaches very high levels. When evaluating the role of hydrogen in the decarbonization of any sector, we should use the largest possible system boundaries and not evaluate isolated industries or cities.
4. Later, the initial goal should be to generate hydrogen for internal use or export mainly in countries where the electricity generation from renewable energy sources exceeds a given high percentage, for example, 90%, and only if it is not possible/required to export the excess green electricity to neighboring countries to reduce their use of fossil fuels.
5. The design of an *efficient* carbon pricing scheme (e.g., carbon tax) that could be implemented initially in many mainly industrialized countries has the potential to speed up the production of green electricity and to facilitate the transition to a hydrogen economy. International cooperation is of paramount importance also in this case.

Regarding the required actions for decarbonization, policymakers (as well as scientists and engineers) carry a heavy burden: They must ensure that (a) international collaboration in the energy area is maximized, (b) the profitability of private investments in the production of green electricity remains high, (c) the electric grids and the interconnections among different regions are sufficient to transfer large amounts of electricity from one region to the other, and (d) the electricity is sold to the other region at a fair price. In addition, policymakers, scientists and engineers must (1) get objectively informed and further educate the public about the necessity of all required measures (incl. higher energy prices) to combat climate change and to minimize waste, (2) prioritize these measures to maximize the benefits per invested dollar, and (3) effectively respond to misinformation and the arguments by populists. Finally, most policymakers must reconsider some of their until now advocated policies, in particular the hydrogen-related ones, while research organizations must reconsider their research priorities and the allocation of research funds.

It is understandable that each country has as one of its highest priorities to safely provide as much green energy as possible to meet its total energy demand and we cannot realistically expect an industrialized country to finance the energy transition of a developing country without the former gaining something useful out of the deal. However, deals in which a developing country agrees to provide hydrogen to an industrialized country should not be celebrated as significant contributions to decarbonization, because they are not maximizing decarbonization worldwide, and often represent some of the very expensive contributions to decarbonization, when significantly less money could be invested in other projects that would provide the same or larger long-term decarbonization effects.

Finally, at the international level there is a need for a transparent exchange of information and data. The discrepancies between nations' pledges and reality should be reduced. Also, the environmental policies of countries must become more consistent. Approvals of large new projects involving the use of fossil fuels and the continuing use of subsidies for such fuels are certainly not consistent with long- term decarbonization efforts.

5. CONCLUSIONS

Decarbonization faces many challenges associated with political, technical, economic, and social issues. The decisions we make today will affect what is going to happen in the decades ahead. For the very near future, it is important to select the most cost effective decarbonization options; these do not yet include the establishment of a hydrogen economy.

All decarbonization options involving the generation of hydrogen should be evaluated very carefully. Hydrogen will undoubtfully play a role in the very long term energy supply. The size of this role at a given time point will depend on the ability of our society to provide large amounts of green electricity in excess of the current demand. It is not a matter of our willingness; it is a matter of the realistic capability of a democratic society to reliably provide and use green hydrogen while continuously reducing the CO_2 emissions. As long as both of the following conditions exist: (a) the hydrogen is expected to be generated mainly through electrolysis, and (b) large amounts of fossil fuels are still used for electricity (and consequently for hydrogen) generation, a hydrogen economy should not be established.

Unfortunately, when considering the energy plans of some countries, it appears that fossil fuels will continue to be heavily used to generate electricity for several more decades. For decarbonization purposes it is important to distinguish between average and additional (marginal) energies used to produce electricity. Theoretically, and to maximize the decarbonization effect, each country should first cover practically its entire electricity demand using renewable sources and then use the generated excess electricity to produce hydrogen for internal use or for export. Therefore, absolute priority should be given to the further development of green electricity generation as well as to the expansion of the electricity grids and of the interconnections among countries before) the introduction of a hydrogen economy. It is apparent that there can be exceptions to this when, for example, the required electricity interconnections are not in place and/or the existing electrical grid is not capable of transferring large amounts of additional electricity, then local hydrogen production might become meaningful.

Decarbonization and the hydrogen economy will be realized faster with a significant designed increase in fossil-fuel prices. The existing emission trading mechanisms do not appear to be sufficient for achieving the decarbonization goals. An appropriate carbon-pricing scheme established through political decisions might be necessary but is difficult to realize.

Given all these challenges, it seems unrealistic that a hydrogen economy would significantly contribute to decarbonization within the timeframe suggested by many recent studies. The main reason for this is that a prerequisite for decarbonization enabled by the hydrogen economy is the availability of large quantities of *excess "green" electricity*. In the coming decades we will be far from reaching this goal worldwide. Thus, the introduction of a hydrogen economy in some industrialized countries should perhaps, contrary to current plans, not be currently supported by taxpayers' money. This money would be better invested in the expansion of the green electricity generation and the electric grids.

The purpose of this paper is to add to the warnings demanding significant adjustments to the energy policy referring to hydrogen of at least the countries responsible for the largest energy use. It appears that many policymakers in industrialized countries have not yet received all the pertinent information. Many current discussions and actions in political parties, the media, and scientific journals referring to hydrogen are, in the author's opinion, giving the general public the wrong message that the decarbonization problem can be easily solved by imminently establishing a hydrogen economy, an impression that is certainly wrong. In addition, the proposed decarbonization time schedules appear unrealistic at least from today's perspective. By misleading the public, policymakers, engineers and scientists do not ensure its full cooperation. The public must be adequately, objectively, and transparently informed about the realistic options for decarbonization and their consequences. The way we all think about energy must be changed, if we want to succeed in decarbonization.

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SUSTAINABLE ENERGY FOR INSULAR ENVIROMENTS

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ABSTRACT

Lately, there has been a lot of talk about a future “hydrogen economy”, based on hydrogen (H_2) in "green" or, alternatively, in "blue" form. Despite its claimed advantages and the significant investments and research efforts, the practical impact of hydrogen technologies is, to date, negligible. The reason lies in the formidable challenges related to the H_2 transport, storage and distribution:

Hydrogen is extremely dangerous: in the presence of O_2 it ignites (even self-ignite) explosively. It is the inadvertent production, release and ignition of hydrogen that has caused some of the worst accidents globally, most famously that of the nuclear disaster at Chernobyl. Moreover, potential leaks into the atmosphere have very negative environmental impacts, worse than either CO_2 or methane.

The present paper aims at an innovative underwater compressed hydrogen storage method, part of offshore wind farms, of fixed foundation or floating. Such method can be used also in insular windfarms, relatively close to the seaside. Hydrogen would be produced by electrolysis during periods of low electricity demand, stored in innovative underwater pressure tanks and used for producing electricity during periods of high demand. The proposed method, having all the H_2 components underwater, hopes to overcome most of the H_2 issues, particularly those concerning safety. Two variants of the system are proposed and their pros and cons analysed:

1. A centralised underwater hydrogen storage, in the form of a long tubular pressurised vessel, connected through small pressure tubes to the electrolysers and fuel cells located underwater at the base of each offshore windmill.
2. The electrolysis and fuel cells modules are located underwater at the proximity of the hydrogen storage, in a unique underwater complex which is connected to the windmills exclusively via electric power cables, while the hydrogen is produced, stored and consumed locally underwater.

Essentially, the system, in both above variants, would act as a large battery. According to the implemented electrolysis and fuel-cell technologies, at the current state of things, it promises a 35-40% overall (electricity → H_2 → electricity) efficiency and cannot compete with the Lithium batteries. Its main advantage lies in its extremely low environmental footprint, much lower than any other storage method, battery or hydrocarbon-based.

Keywords: Sustainability, Energy, Hydrogen, Wind, Underwater

1. INTRODUCTION

Lately, there has been a lot of talk about a future “hydrogen economy”, based on hydrogen produced by carbon-free methods (blue hydrogen). The product of hydrogen combustion is none other than pure water. Unfortunately, although it is the most widespread element in nature, it is very rarely found in pure form (H_2). For this reason, hydrogen is not considered a primary energy source but a mean for energy storage and transport.

To date, hydrogen is produced almost exclusively from natural gas, i.e. in "grey" form, primarily for the petrochemical and fertilizer industry. As a fuel, grey hydrogen is overall less efficient and dirtier than the hydrocarbons from which it is produced.

Hydrogen can also be used for direct electricity generation in fuel cells, with efficiency comparable to that of thermal engines. However, the cost of hydrogen cell-based systems is prohibitively high. Despite its claimed advantages and the significant investments and research efforts, the practical impact of hydrogen technologies is, to date, negligible. The reason lies in the formidable challenges, mainly related to the H_2 transport, storage and distribution.

Hydrogen is extremely dangerous: in the presence of O_2 it ignites (even self-ignites) explosively. In fact, it is the inadvertent production, release and ignition of hydrogen that has caused some of the worst accidents globally, most famously that of the nuclear disaster at Chernobyl. Moreover, potential leaks into the atmosphere have very negative environmental impacts, worse than either CO_2 or methane.

That is why, despite the significant investments and subsidies, “green” hydrogen technologies have yet to have a noticeable penetration, not only in the energy market but also in the chemical and fertiliser industries.

In the next sections, an application that can overcome most of the hydrogen safety issues will be outlined. It is about the use of hydrogen, instead of batteries, as energy buffer in offshore or coastal windmills. In such an application hydrogen is produced, stored and consumed locally. It is stored underwater, at intermediate pressures, thus overcoming the risk of fire and explosion. An additional advantage is that the hydrostatic pressure adds to the pressure vessel structural containment capacity.

2. HYDROGEN REALITY

Lately, colourless hydrogen has acquired many colours, according to its production method: "Green" is the name given to hydrogen produced from water using exclusively clean electricity (e.g. from solar, wind or hydraulic systems) or nuclear power. When produced from fossil hydrocarbons, it is called "blue” when accompanied by full carbon capture or "grey" when we do not have carbon capture. Hydrogen in "green" or, alternatively, in "blue" form, is supposed to become an important component of the future, carbon-less economy.

The product of hydrogen combustion is none other than pure water. Unfortunately, hydrogen, although it is the most widespread element in nature, is very rarely found in pure form (H_2). Its production can be done either by electrolysis (from water) or from natural gas or other hydrocarbons. For this reason, hydrogen is not considered a primary energy source but a means of energy storage and transport. Today, the production of hydrogen, mainly for use in the chemical industry, is done almost exclusively from natural gas, i.e. in "grey" form. Grey hydrogen has a significantly less efficient and clean life cycle than the hydrocarbons from which it is produced. In other words, it is in our interest to burn natural gas directly rather than use it as a raw material to produce hydrogen fuel. "Blue" hydrogen does not have clear environmental advantages either, compared to the use of natural gas. In fact, the total amount of CO_2 emitted during the process of CO_2 capturing, processing, transport and storage is often more than the CO_2 emitted during the direct combustion of natural gas.

Hydrogen, in addition to combustion fuel, can be used for direct electricity generation in fuel cells, with efficiency comparable to that of thermal engines. There are many types of fuel cells, the proton exchange membrane (PEM) being the most common. However, the cost of hydrogen fuel cell-based systems is prohibitively high, which is why their market penetration, despite subsidies, is negligible. The reason lies in the formidable challenges mainly related to the H_2 transport, storage and distribution. More in particular:

1. Hydrogen is a very light gas with an extremely low energy density by volume, about 0.01 MJ/L STP, 3 times less than natural gas or 3.4 thousand times less than gasoline. Consequently, to be available in usable quantities, it must be stored as:

   a. In gaseous form under extremely high pressure (typically 350 to 700 bar) or, where space is not an issue, under moderate pressure (typically 100 to 350 bar)
   b. Liquefied at impossible cryogenic temperatures (−253°C)
   c. Chemically bound in carriers such as ammonia or metal hydrides

   Each of these options presents significant energy penalties and complexities.

2. Hydrogen atoms tend to permeate the solid metal structure, increasing crack propagation and reducing their ductility. This process, known as hydrogen embrittlement, occurs in steel, iron, nickel, titanium, cobalt, and their alloys, while copper and aluminum are less susceptible. Thus, hydrogen can only be safely stored in special, internally coated pressure vessels.
3. Hydrogen is extremely dangerous because it ignites and explodes very easily. The inadvertent production, release and ignition of hydrogen has caused some of the worst accidents, most famously that of the nuclear disaster at Chernobyl.
4. Potential leaks into the atmosphere have very negative environmental impacts, much worse than either carbon dioxide or methane. The main reason is its rapid direct binding with hydroxyl (OH)T free radicals, drastically reducing the ability of the atmosphere to deal with atmospheric methane. Another risk is related to ozone chemistry and water vapor production in the troposphere.
5. The overall efficiency of “green” hydrogen life cycle (production, transport, storage and electricity generation) is extremely low (< 35%) further reduced when sea or other non-clean water is used for electrolysis.

A way to overcome some of these issues is to produce hydrogen, store it underwater and consume it locally, such as the application outlined in Sections 4 and 5.

3. OFFSHORE WIND ENERGY SYSTEMS

Offshore wind turbines can be either fixed on the seabed (in shallow waters) or floating, moored to the seabed through dedicated mooring lines. The floating maritime base (floater), on which wind turbines are erected, plays an important role since it ensures the stability of the whole system even in very rough weather conditions. This is by no means simple. There are many types of windmill floaters, some of them being depicted in Figure 1 below. They are massive structures that represent a significant part of the overall system cost, both capital and operational. They are considered maritime vessels and as such they are engineered, maintained and inspected, [1].

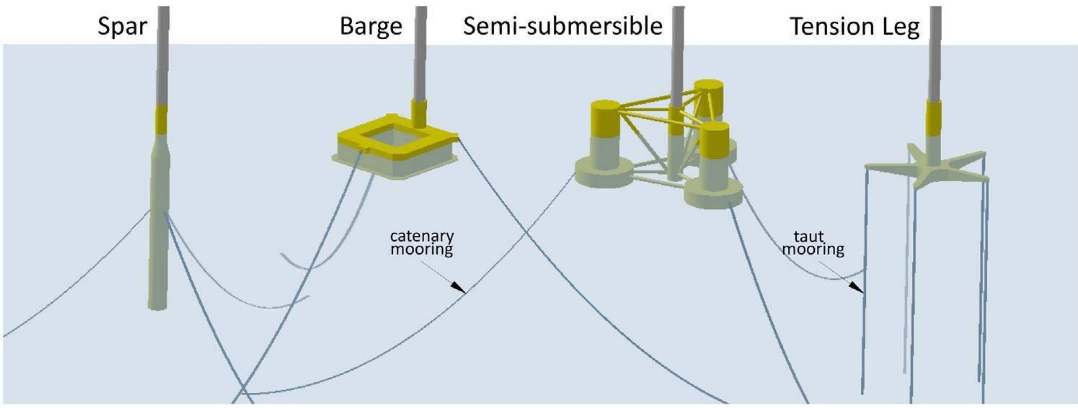

Figure 1: Examples of windmill floaters

There are three ways of ensuring the stability of a windmill base: through ballast (i.e. heavy mass at its lower part), buoyancy (i.e. light volume at its upper peripheral part) or mooring (catenary or taut). In practice, all floaters combine, to a certain degree, all these three methods, as per Figure 2 below, where the position of some actual windmill floaters is depicted within a floater stability triangle.

Significant R&D is being conducted towards efficient and optimal floating wind turbines, mainly aiming to decrease the costs associated with installation, operation, maintenance and decommissioning, where innovative designs, procedures and technologies along with established best practices are required. The work presented here aims at such an innovative design for an enhanced functionality and reduced environmental footprint.

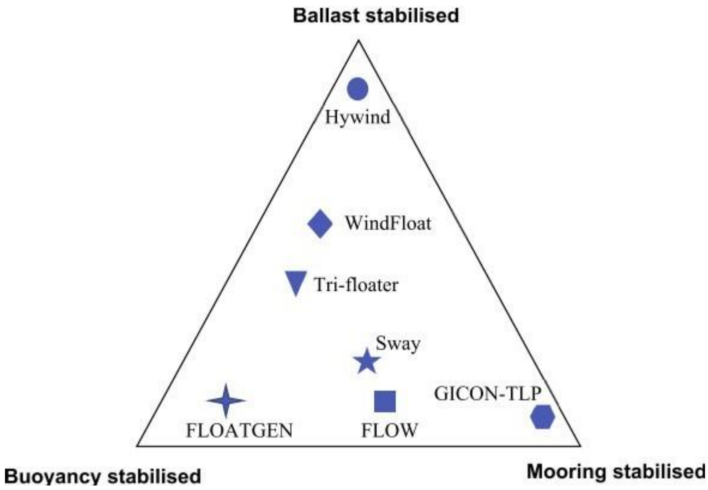

Figure 2: Stability triangle for floating windmill structures, source [1]

4. UNDERWATER H_2 ENERGY BUFFER SYSTEM FOR OFFSHORE WIND-FARM SYSTEMS

The idea outlined here would use hydrogen as an energy buffer for offshore wind-farms, seabed-fixed or floating. It could also apply to coastal or insular windmills. Hydrogen would be produced locally by electrolysis during periods of low electricity demand and stored in innovative underwater pressure tanks to be used for producing electricity during periods of high electricity demand.

Although underwater H_2 storage is a relatively new subject, there are many relevant publications, design proposals and patents, some of them listed as references. Reference [1] proposes storing hydrogen in gravel-filled pipes at the bottom of lakes, hydropower or pumped hydro storage reservoirs (Figure 3). Reference [3] reviews the current (2022) state, the challenges, and the perspectives of Underwater Compressed Gas Energy Storage (UWCGES). Reference [4] reviewed proposed hydrogen and oxygen storage systems including with fuel cell applications and air-independent propulsion systems. Reference [6] proposes an innovative system for hydrogen ocean links, based on thin and cheap high density polyethylene pipes, relying on the hydrostatic pressure, for storing and transporting large amounts of pressurized hydrogen in the deep sea.

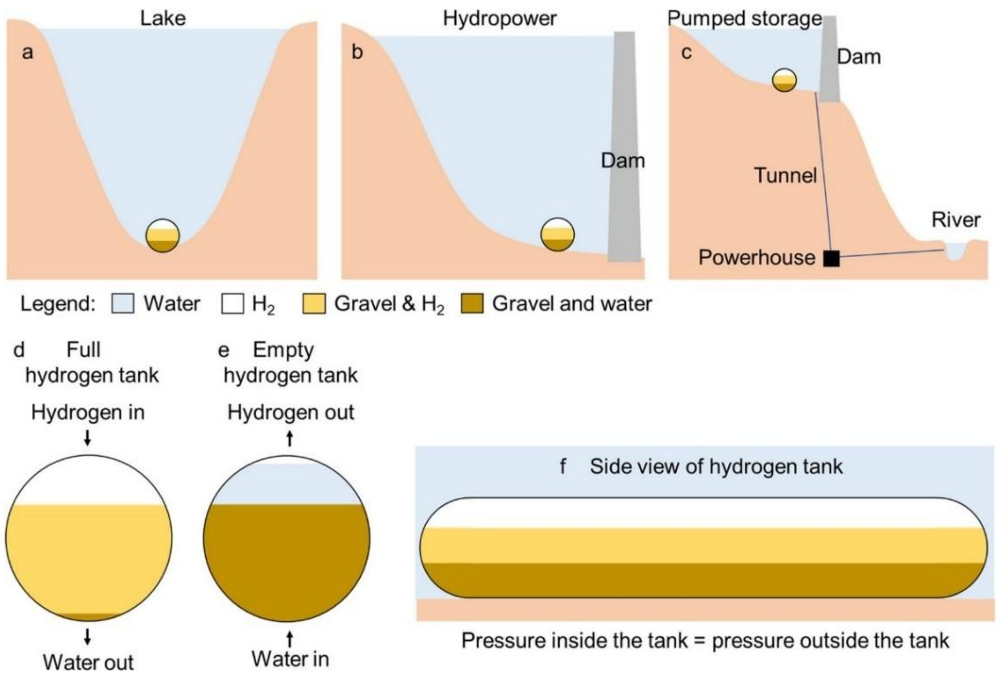

Figure 3: Examples of H_2 storage in underwater pipes partially filled with gravel, reprinted from [2]

The underwater hydrogen storage and processing, as per the above and many other relevant publications, offers substantial benefits compared to the surface storage and processing. Claimed advantages include:

- Much enhanced safety derived from the impossibility of explosion in absence of air even at shallow waters;
- Increased efficiency due to better heat dissipation;
- Depending on the depth, hydrostatic pressure overhead on top of the pressure vessel or pipe design specifications.

However, despite these significant advantages, to date, underwater H_2 has not had any significant applications. The reason lies in the installation and maintenance difficulties inherent to underwater operations as well as in the cost of H_2 solutions, compared to other energy buffer systems, such as Li- ion batteries, [7]. The proposed system aims overcoming such issues by combining the above outlined advantages of underwater H_2 with additional application-specific advantages / improvements as per the following paragraphs.

The proposed underwater hydrogen storage is conceived as the central module of modular, configurable buffer energy system meant to be used at a wide range of applications such as offshore wind farms (fixed foundation or floating), energy buffer / storage for insular and coastal communities, offshore oil & gas etc. It will be based on a long high-pressure pipe, deployed on the seafloor, close to the energy production and consumption sites. Additional modules, like fuel cells, electrolysis modules, O_2 and clean water tanks will be optimally placed at the vicinity of the H_2 storage underwater or on floating / coastal structures, according to the specific application requirements. In any case, all H_2 connections and transmission pipelines shall be immersed for increased safety.

One of the main advantages of the proposed solution, in addition to safety, regards the operational flexibility. The pressurized H_2 tubular pressure vessel will be structurally specified for internal pressures as high as 250-350 bar, thus achieving a good compromise of energy storage density and cost. Although designed specifically for hydrogen, with all necessary coatings and protections, it will allow also for the compressed storage of natural gas (NG) or any H_2/NG mix.

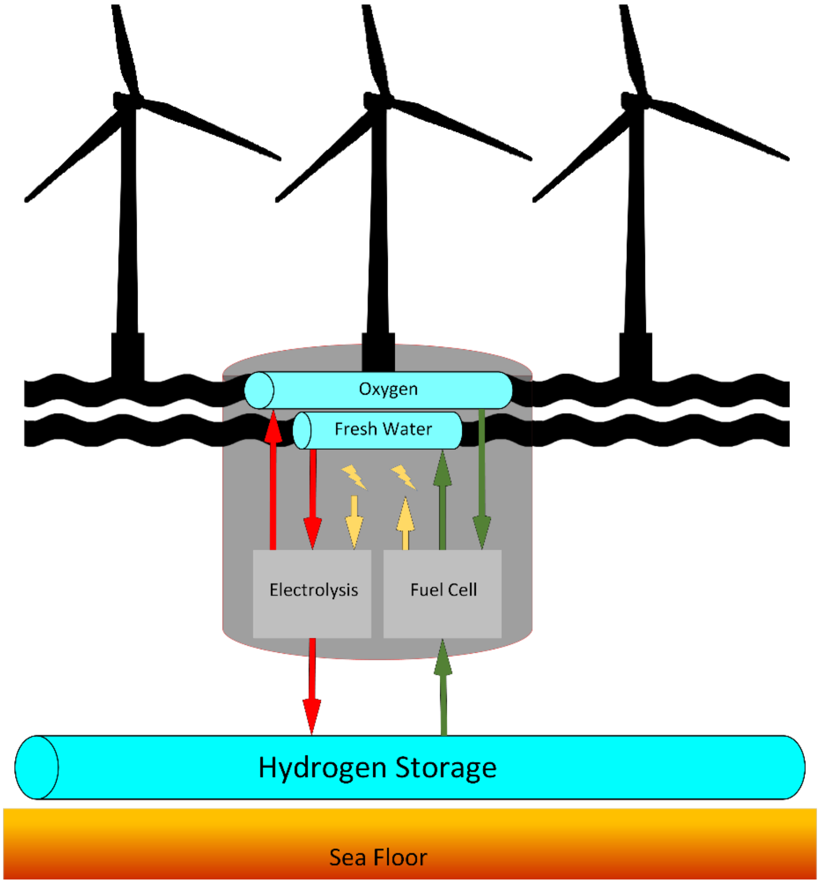

Figure 4: Schematic representation of a hydrogen-based energy buffer system for floating windfarms; H_2 production phase in red; H_2 consumption phase in green; electricity flow in yellow

The proposed solution is better understood through an application scenario, that for the floating windfarms, schematically depicted in Figure 4. Hydrogen is stored in a tubular pressure vessel, deployed on the seafloor under the floating wind farm. It is connected to the electrolysis and the fuel cells modules necessary for the H_2 production and consumption, conveniently placed in the submerged part of each wind turbine floater.

In periods of low demand, the excess electricity from the wind turbine is used by the electrolysis module to produce H_2 out of clean water, pumped from a water storage tank within the floater ballast space. The oxygen, byproduct of the electrolysis, is stored in a dedicate O_2 pressure tank located in the floater buoyancy spaces.

In periods of high demand, stored H_2 and O_2 are fed into the fuel cell module to produce electricity and clean water. Water is stored into the dedicated ballast storage tanks while electricity is fed to the grid, supplementing the wind turbine electric power.

The claimed advantages of such an arrangement are multiple:

- Hydrogen stays always submerged underwater; there is no contact whatsoever with air or oxygen except on the electrolysis and fuel cell membranes.
- Water and oxygen are in closed circuits, stored in dedicated tanks on the floaters; they are topped up only to compensate eventual losses or inefficiencies but, in any case, the air and water purity requirements are greatly reduced.
- The heavy electrolysis and fuel cell modules, as well as the massive fresh water tanks, are stored in the lower part of the floater, thus contributing to the ballast-generated floater stability. On the contrary, the pressurized oxygen vessels are stored peripherally in the upper floater part, contributing to the buoyancy-generated stability.
- Finally, a single optimized tubular high-pressure hydrogen storage vessel, common across the whole windfarm, is placed on the seabed, as deep as possible, so as to profit from the hydrostatic pressure.

5. SUSTAINABLE ENERGY IN INSULAR ENVIRONMENTS

Islands and insular environments, like the ones in the Aegean Sea, usually relied for their energy to thermal stations. Large islands, like Crete or Rhodes, had big turbine-based plants fed with heavy fuel oil, diesel or propane gas. Smaller islands relied on internal combustion engines, mostly diesel. The energy availability was ensured by:

- Local storage of fuel;
- Periodical fuel shipments by small tankers, usually through dedicated port facilities;
- Redundancy of critical equipment and
- Some limited capacity for interventions.

In some cases, interconnections with electrical underwater cables provided additional security and flexibility. There is a plan to connect most large islands with the mainland, however, the great majority of the Greek islands are not yet connected. As of 2023, there were 28 autonomous insular systems, subdivided in:

- Nineteen “small”, with a peak demand of up to 10 MW,
- Eight “medium-sized”, with peak demand from 10 to100 MW,
- One “large” (Rhodes[1]) with more than 100 MW of peak demand.

The policies of the EU and the Greek government, since more than 3 decades ago, towards a carbon-free society, accompanied by subsidies and other incentives, resulted in a strong penetration of the “green” energy technologies also in the insular regions. The establishment of the “Clean Energy for EU Islands” initiative in 2017, provided additional instruments specifically to insular communities.

Insular environments, especially in the Aegean Sea, have an excellent potential, both for wind and solar applications. However, there are also some important issues, which have to do with power availability, related to the small size and the isolation of the insular grids. Power availability in small, isolated networks can only be ensured through:

[1] Crete has its own thermal power generation plants but is also connected to the mainland grid.

1. Standby conventional (thermal) backup powerplants
2. Energy storage through specific storage means like batteries or hydraulic pumping reservoirs

Evidently, as the thermal power plants are, usually, already in place, they are chosen as means to complement the renewables when demand exceeds the generation capacity from wind or solar. The biggest drawback of this solution lies on the increased carbon emissions associated with the intermittent operation of the thermal units, especially the old ones, that have been designed for continuous operation. In simpler words, thermal powerplants take several hours to reach their optimal operating regime, during which they consume more and emit to the atmosphere much more CO_2 and other pollutants. In theory, in very unfavorable conditions, the combined operational emissions of a windfarm plus its thermal backup plant can emit more CO_2 than if the backup plant operated continuously without the windfarm contribution.

From the other hand, dedicated storage systems add no operational emissions but they contribute significantly to the system's overall environmental footprint (i.e. throughout its lifecycle). This is true specially for the battery-based storage systems, the production and disposal of which is very "dirty". The hydraulic pumped storage method is more efficient and friendly to the environment, [8], but is not always applicable.

Hydrogen-based buffer energy systems, similar to the one proposed for floating windfarms in Section 4 above, can be used in conjunction with seabed-fixed windmills or effectively any coastal or insular renewable energy network. In fact, all the components depicted in Figure 4 inside the floater, could be placed, together with the hydrogen storage pressure vessel, inside a dedicated underwater plant at the seabed near the coast or between islands. Such a scenario is depicted in Figure 5 below.

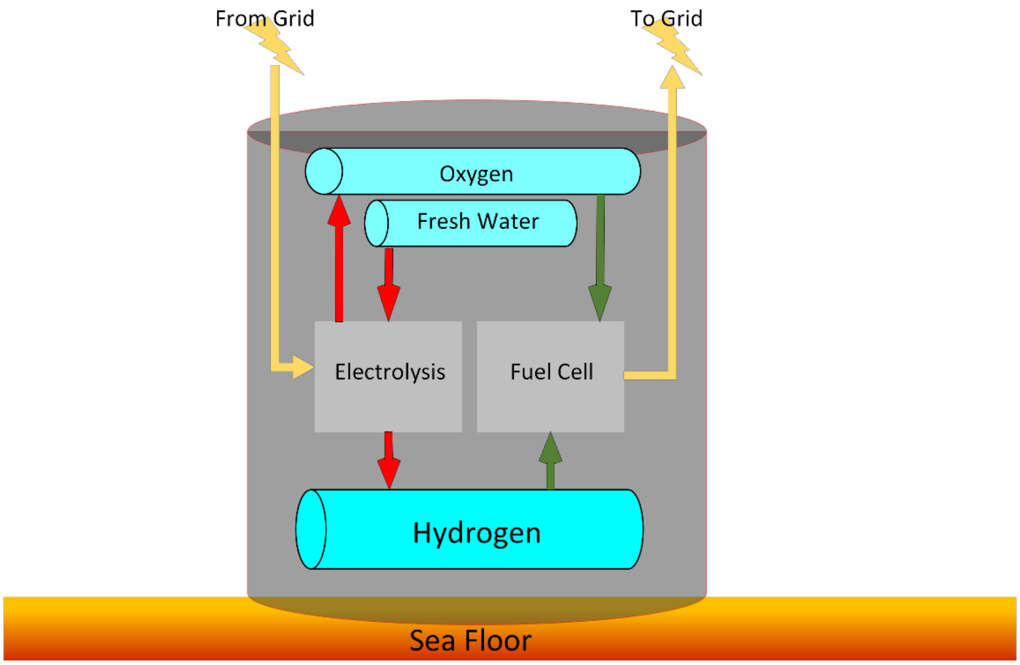

Figure 5: Schematic representation of a hydrogen-based energy buffer system; H_2 production phase in red; H_2 consumption phase in green; electricity flow in yellow

6. CONCLUSIONS – WAY FORWARD

The above-described scenarios offer realistic pathways towards the implementation of efficient and safe hydrogen systems / solutions. It overcomes most H_2 related safety concerns along with important application-specific benefits. The proposed hydrogen-based energy buffer system may, in some situations, prove to be more friendly to the environment than any of the current energy buffer methods. A pilot implementation of such prototype systems may be used to test and further develop, in full security, environment friendly hydrogen-based solutions and/or components, such as underwater storage tanks, electrolysis or fuel cells.

The next step is to proceed with the detailed design and prototype implementation, possibly through a relevant EU funded project.

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THE EMPTY SPACE OF THE CITY: SUSTAINABLE TRANSFORMATION OF URBAN BLOCK INNER COURTYARDS FOR CLIMATE RESILIENT CITIES

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ABSTRACT

The path to climate-resilient cities must address many challenges, such as the urban heat island effect (UHI), the poor air quality and the urban flooding phenomena due to the increased precipitation and impervious surfaces in urban areas. Moreover, the quality of life of the citizens is a parallel target to achieve a healthy and sustainable urban environment.

This research explores the form of the urban block inner courtyard in Greek cities to identify strategies and interventions that could improve its sustainable transformation which could significantly contribute to a more resilient and climate adaptative urban environment.

The idea of transforming these spaces from abandoned “empty” backyards into viable open spaces for the citizens has often been discussed in the past, but in most cases ownership status, the lack of financial instruments and planning tools has been the reason for not achieving a strategical regeneration strategy. Therefore, this research aims at identifying the characteristics and qualities of the urban block inner courtyard and developing instructions and guidelines for the regeneration of these spaces in an overall strategy for the improvement of the quality of life in cities.

First, the urban tissue of Greek cities is analysed. Legislative conditions that have contributed to the formation of the existing patterns of inner courtyards of urban blocks are explained. Building codes, national policies and ownership status of the inner courtyards of the urban blocks of Greek cities are discussed.

Second, the urban form and geometry parameters that contribute to the development of different urban block inner courtyard patterns are explored. Typologies are identified according to the specific form and geometry characteristics.

Third, typologies explored are analysed in terms of their potential to reduce air temperatures during the hot summer period. For the scope of the analysis urban simulation is used to define potential improvements in microclimatic conditions through the change in surface materials and vegetation in four representative case study inner courtyards of the city of Thessaloniki.

All inner courts are characterized according to their existing ambient conditions and to their potential improvement through changes in their materiality and vegetation design and quality. The results of the research are useful for defining priorities of regeneration of these spaces and for giving guidance through a quantitative and qualitative methodology for a sustainable and resilient future of the Greek cities.

Keywords: urban microclimate, urban block, inner courtyard form, city regeneration

1. INTRODUCTION

The idea of inner courtyard in buildings to achieve a climate responsive design is not new. Ancient Greek houses were organised around an inner courtyard, the peristyle, which housed a home garden and provided natural light in the interiors [1]. The idea of the peristyle had also the notion of bringing nature close to the urban living. The roman evolution of the peristyle, the atrium is also an architectural element which prevailed in building design in cities as Pompei and Herculaneum.

The atrium has been described as: “a substantial solution to the amelioration of the microclimate of a building and even of a neighbourhood, via the exploitation of the characteristics of the construction (materials, openings, height, function) in combination with the exterior conditions” [2].

Climatic aspects of courtyards have been examined to optimize the parameters that could improve energy performance of buildings and at the same time enhance microclimatic and daylighting conditions [3]. Plan proportions, buildings hight and geometry, orientation and surface materials are the main parameters investigated. The capacity of inner courtyards to act as microclimate modifiers, which are able to improve, under specific design criteria, the thermal conditions of their immediate surroundings as a major challenge of the urban heat island effect, has been extensively investigated [4–7].

In contemporary cities, the need to maximize the use of space and economical profit turned away the building practice from constructing atria, despite their indisputable advantages for the Mediterranean climate. In Greek cities the urban needs and policies did not favour the adaptation of atria in urban areas, even though most building regulations included their definition mainly in terms of restrictions in size. However, the urban form of Greek cities, characterized by the densely built high-rise compact development, is often defined by the urban block layout plan and geometry, which often includes a central empty space forming in a more abstract perspective an often-irregular form of atrium. Especially in continuous urban blocks, where the buildings are attached to each other, the only space left unbuilt forms an inner courtyard which often remains abandoned and untapped from both the inhabitants and the state.

The inner courtyard of urban blocks has several common characteristics with the idea of the atrium in buildings and could be examined in terms of its potential to contribute on the mitigation of the UHI and the improvement of quality of life in cities. However, the inner courtyard of urban blocks has also significant differences with the idea of the atrium as it has not been initially designed for the same purpose and more importantly it has not been designed as a whole, but it is rather a result of a continuous process of the construction of urban buildings. Therefore, its form is a result of multiple processes and parameters including building codes and regulatory restrictions, plot geometry and size, the economic conditions of each period of construction etc.

The idea of transforming these spaces from empty abandoned backyards into active spaces of social interaction is not new. Pocket parks have been introduced as a means of regeneration of the central courtyards of urban blocks [8], or as a means for wool islands in compact cities [9], while strategies for promoting residential greenery have also been investigated during the pandemic crisis of 2019 to improve citizens health and wellbeing [10].

The Greek city is characterized by the lack of open spaces, as the coverage ratio in urban plots often reaches up to 70% or even higher. Furthermore, the Greek city is largely built until the 80’s resulting in very few plots have been left unbuilt at the urban centres. It is a fact that Greek cities have a low rate of open spaces per inhabitant, but the idea of demolishing buildings to develop parks and public squares is not always a feasible option neither from an economic nor from a state strategic planning perspective.

Besides the low quality of life that is provided due to the lack of open spaces, there is also another implication resulted from the high density of the built environment the increase in urban temperature during hot summer periods caused by the climate change and the heat accumulation in hard impermeable urban surfaces known as the UHI. The objective of this research is to investigate the relationship between the form of the central backyard of urban blocks and the formation of urban temperatures and to investigate ways to improve the thermal conditions of these spaces fostering a climate adaptive urban regeneration future strategy for the Greek cities.

2. METHODOLOGY

First, the urban tissue of Greek cities is analysed. Legislative conditions that have contributed to the formation of the existing patterns of inner courtyards of urban blocks are explained.

Second, the urban form and geometry parameters that contribute to the development of different urban block inner courtyard patterns are explored.

Third, several typologies are analysed in terms of their sustainability potential. For the scope of the analysis urban simulation is used to define potential improvements in microclimatic conditions through the change in surface materials and vegetation.

Finally, the temperature conditions of inner courtyards are discussed and their potential improvement through changes in their materiality, vegetation design and quality are explored. The results of the research are useful for defining priorities of regeneration of the leftover spaces of central courtyards of urban blocks and for giving guidance through a quantitative and qualitative methodology for a sustainable and resilient future of the Greek cities.

2.1. Building codes and regulatory framework

This section intends to summarize the main regulatory restrictions that have defined the form and geometry of the inner courtyard of urban blocks.

As the central areas of the majority of Greek cities have been built before 1985 their form and geometry have been defined by two Building regulations. Law 395/1955 [11] and Legislative Decree 8/1973 [12].

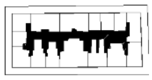
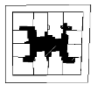
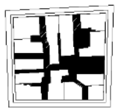
These main building codes have contributed to the formation of the inner courtyard geometry as they included restrictions for the positioning of the buildings in the plot area and in the urban block area, for the minimum distances of the buildings from the plot boundaries, and for minimum size of recessions for daylighting and window location on the building’s facades.

Except from the building codes, national policies and ownership status of the inner courtyards of the urban blocks of Greek cities have largely defined their contemporary shape, use, accessibility levels and conditions of maintenance of the space.

2.2. Description of case studies

For the scope of the research, the microclimatic conditions of four urban block central courtyards are examined. The main characteristics of their geometry and form are presented in Table 1. The considered cases are high density, high rise urban block central courtyards from the central area of Thessaloniki, Greece. Case 1, 2 and 3 have a continuous built form meaning that all buildings are attached to each other forming a closed shape courtyard, while the 4th case study urban block is built in a discontinuous form consisting of semi-detached buildings, resulting also in the better accessibility to the central courtyard form the street.

Table 1: Inner courtyard examined cases’ geometry and form properties.

Cases	1	2	3	4
				
Urban block area (m^2)	6700	4644	2962	5146
Courtyard area (m^2)	1702	1020	676	1612
Built up area (m^2)	4998	3624	2286	3534
Coverage ratio %	74.60	78.04	77.18	68.67
Courtyard perimeter (m)	559	389	249	602
Building height (m)	22	22	22	19

2.3. Simulation parameters and scenarios examined

The potential air temperature in the examined inner courtyard types has been calculated with the use of Envi-met 5.7.1 software. The climatic data of the city of Thessaloniki has been used for the month of July.

Three scenarios have been analysed to define potential differences in ambient conditions for a whole day time range.

1. A conventional case scenario

In this scenario the current conditions of the urban block central courtyard are described. Considering that there is not a uniform condition in all urban block central courtyards in Greek cities several assumptions concerning materials' properties, vegetation existence and equipment have been made to achieve comparable results concerning the temperature conditions prevailing in these spaces. A medium albedo of the buildings' surfaces (0.4) has been assumed for this scenario.

2. A green scenario

For the green scenario the properties of a typical medium size deciduous tree (15 m canopy) were selected from the software's material library. The distance and number of the trees was defined by the model grid size, meaning that a tree was placed at two or three grid points distance (depending on the geometry of the area). For green surfaces, 5 cm height average density grass was assumed and for paved surfaces medium albedo (0.3) concrete tiles have been considered.

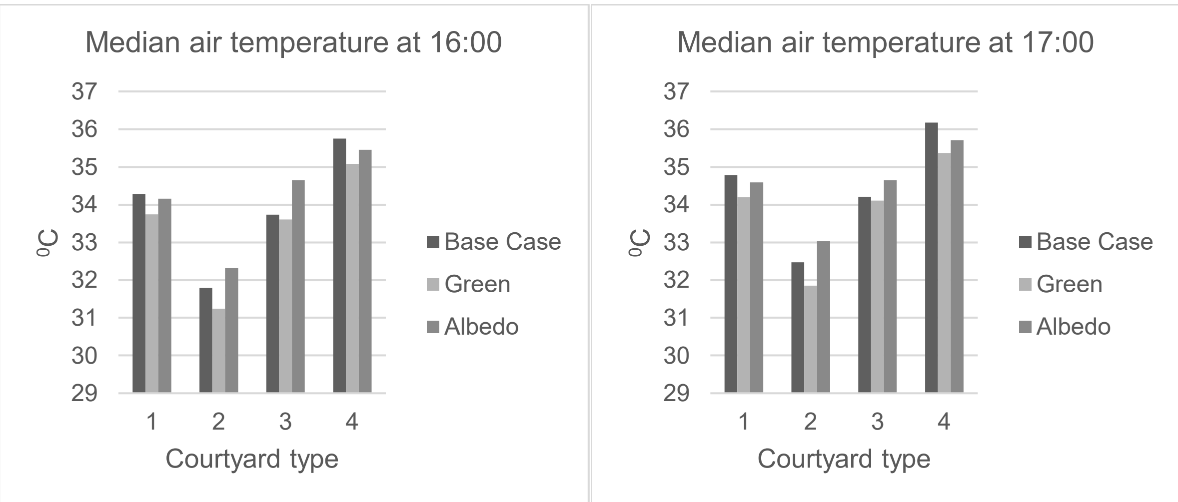
3. A high albedo scenario

The high albedo scenario includes the change in the albedo to 0.7 of both horizontal and vertical surfaces of the buildings surrounding the inner courtyards while maintaining the vegetation like in the Green scenario.

3. RESULTS

The results of the simulations prove that there can be significant differences in the ambient temperature of inner courtyards of the densely built urban blocks examined. The median temperature can vary according to the form of the inner courtyard. The largest difference in median temperatures for the Base Case scenario is 4 ^{0}C between type 2 and type 4 at 16:00 and 3.7 ^{0}C at 17:00. It should be mentioned that type 4 is a discontinuous form urban block courtyard with a 19 m building height while type 2 is a continuous form urban block with a very narrow courtyard and a 22 m height. Therefore, the difference in air temperature implies that the densely built urban blocks with narrow courtyards have less access to solar radiation resulting in lower ambient temperatures.

Moreover, concerning the examined scenarios it should be noted that overall, in the green scenario the air temperatures are reduced. This means that it is important to consider vegetation strategies in the courtyards of urban blocks to improve the local microclimate in these spaces.



a b

Figure 1: Air temperature median values for the 4 cases examined and for the three scenarios (Base Case, Green and High albedo) a) at 16:00, b) at 17:00.

Concerning the high albedo scenario, it is remarked that in type 1 and 4 the high albedo scenario decreases the temperature when compared to the Base Case, while for the type 2 and type 3 it increases the median air temperature.

Besides, the High Albedo scenario has, in all examined types, higher air temperatures than the Green scenario. This can be explained by the continuous reflectance of the surfaces in the enclosed space of the inner courtyards. Other researchers have also remarked that, in a microclimate analysis, a medium albedo around 0.4 for building walls is recommended to avoid high reflections which adversely affect the comfort of users and increase surface temperatures [13].

To better explain this argument, Figure 2 presents the potential air temperature in a central point of courtyard type 1 for a 24h range. The Green scenario presents lower air temperature from the base case scenario while for the high albedo scenario the air temperature is lower than the Base Case, but higher than the Green scenario. The difference is more obvious during the times of the day when the solar radiation is higher and enhances the reflectivity of the surfaces.

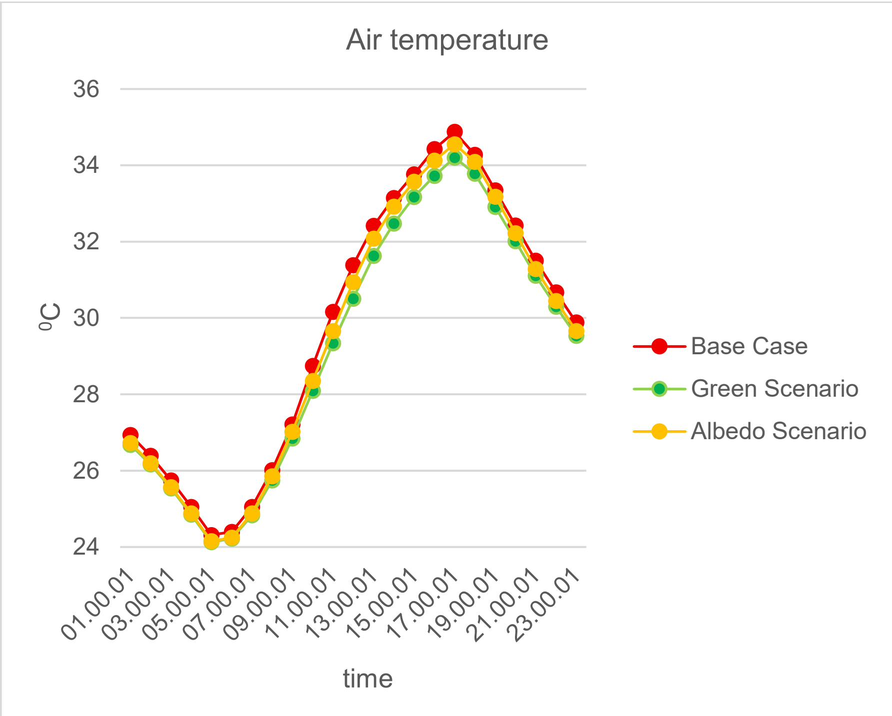


Figure 2: Courtyard type 1 central point 24 hours temperature variation for the three scenarios examined.

4. CONCLUSIONS

This research examined the urban block central courtyard ambient temperature conditions during the summer period in Thessaloniki, Greece to determine the effect of form and geometry on the potential microclimatic conditions of the examined cases. A Base Case scenario, a Green scenario and a High Albedo scenario have been also examined. The results of the research prove that there might be an important variation in air temperatures of the courtyards depending on their form and geometry reaching up to 4 ^{0}C, indicating that more compact urban blocks and narrower courtyards which have limited solar access can have lower air temperatures than discontinuous forms of urban blocks with semi-detached buildings. Furthermore, for the examined scenarios it has been concluded that vegetation strategies might significantly improve the air temperature conditions in the inner courtyards of urban blocks as it was found that, in all examined cases, the planting of the central courtyards reduced their ambient temperature, reaching up to 0.8 ^{0}C lower median values for the examined type 4. The High Albedo scenario has been found to be less effective than the Green scenario as, even though it can improve the air temperatures when compared to the Base case scenario for type 1 and 4, for type 2 and 3 the air temperatures are increased. Therefore, for the use of high albedo surfaces there should be careful investigation of the specific form of the inner courtyard to avoid a negative effect on air temperatures. Finally, further research is necessary on the subject to include more cases and typologies of urban block inner courtyards, to draw safe conclusions on the way air temperature conditions can be improved and to define an overall regeneration strategy for the mitigation of the UHI in Greek cities.

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LAND: A CRITICAL RESOURCE IN ENERGY TRANSITION

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ABSTRACT

Land is a limited natural resource. Energy generation has a land footprint that, in the light of energy transition, has started playing a very important and possibly critical role. A basic index employed in the calculations of the total land required for energy is the land-use intensity of energy, defined as area per unit of energy production, or more specifically, the number of hectares per terawatt-hour of electricity generation in a given year. The actual environmental impacts of this land use depend on a variety of factors, such as the land use for agriculture, stock raising and – the most important – the impact of the land use to the biodiversity of the area.

Recent studies comment that the land footprint of different energy sources, under various decarbonization scenarios, will expand dramatically in the next years, mainly due to the increasing RES developments. The objective and the mission of the present work is to highlight the potential risks and challenges in the land use from many pressing requirements, to stress the role of the energy transition in these needs and also reveal some other conflicting demands that make the problem even more difficult to solve. In the light of the above considerations, the paper will stress the importance of the land use and the need to be included in the decision-making process for energy and other development projects considering also the conflicting uses as well as the externalities that each decision may cause.

Keywords: land footprint, energy projects, land value

1. INTRODUCTION - OBJECTIVES AND SCOPE OF THE WORK

Land use is a very complex issue affecting and being affected by various serious factors including legislation and regulatory framework, environment, biodiversity, food needs and therefore a wide set of activities concerning the whole society.

The present work certainly does not intend to cover such a wide and complicated issue. The objective of the work is to reveal in some way the criticality of the land use in energy projects and the challenges that the use of land faces in various areas with a special focus in the islands, where land is very limited and the pressures for its development – usually in only one dimension – are very strong. These challenges, in addition to over-tourism and the consequent land degradation also include other risks such as the desertification due to lack of precipitation and the fires that outbreak every summer destroying very big areas of productive land.

Energy production has many impacts on public health and the environment beyond just carbon footprint, including water use, materials consumption, local particulates' emissions and land use. The land occupation of various energy systems can displace natural ecosystems, lead to land degradation, and put strong pressures in food production.

Environmental and social impacts of energy projects have been stressed and analysed extensively, especially their carbon footprint. However, land use intensity of energy has rarely been an issue of special focus. The siting of energy projects in most cases requires big areas and cause conversion of the land use.

It is exactly this conversion that causes so many conflicts and, in some cases, delays in projects and serious social problems. In fact the conversions of the land use are met very often during the last years in Greece and cause social reactions and conflicts. Agricultural productive land is converted to buildings area, forests and protected areas are converted to areas with energy developments, seashore is getting full with touristic amenities and many other examples. The issue is serious and critical; it may get irreversible in some years if not serious measures are taken.

Land-intensive energy sources face growing opposition during the siting process, potentially slowing down the rate of the clean energy transition. The land footprint of energy may become an even larger driver of environmental impacts in the coming decades, since countries shift their mix of energy sources to meet decarbonization targets, potentially towards more land-intensive energy sources.

2. ENVIRONMENTAL IMPACTS AND EXTERNAL COSTS AND OF LAND USE

External costs of land use are negative effects of land development that are not reflected in the market price but are borne by society as a whole. These costs include environmental damage like habitat loss, pollution, and the fragmentation of communities, as well as social costs like increased congestion, community disruption and the loss of natural amenities. Land use planning and regulations aim to correct these market failures by ensuring that those who incur the costs of land conversion pay for them, a concept known as the "polluter-pays principle".

In all energy projects, whatever source of energy is involved, there are environmental impacts, some of them more and some less significant.

Currently the impacts of a project to the environment is also approached with the assignment of a cost that reflects the impacts of the project to the nature and the society. There are called externalities or external costs and intend to approach the damage to the environment quantitatively, so that the polluter, the organization that causes this damage somehow, will pay for the restoration of the environment – if possible.

Accordingly, the most important environmental impacts of land use are described in the form of the corresponding external costs.

Types of External Costs in Land Use

Environmental Externalities:

- ✓ Habitat Loss and Fragmentation: Conversion of land for development destroys natural habitats, leading to biodiversity loss.
- ✓ Pollution: Land use contributes to air and water pollution and increases the volume of solid waste.

- ✓ Climate Change: Altered land surfaces can impact local and global climate patterns.
- ✓ Noise and Odors: Development can create negative sensory impacts on surrounding communities.

Social Externalities:

- ✓ Community Disruption: Development can disrupt established communities and social networks.
- ✓ Increased Congestion: Land development, particularly in urban areas, can lead to higher traffic volumes and congestion.
- ✓ Aesthetic Impacts: Infrastructure and development can degrade the aesthetic quality of landscapes and communities.

Economic Externalities:

- ✓ Infrastructure Costs: Development often necessitates new and expensive public infrastructure like roads, utilities, and public transit, the costs of which may not be fully borne by the developer.
- ✓ Loss of Natural Amenities: The depletion of natural spaces and their associated benefits (e.g., recreational opportunities) represent a loss of value to society.

Addressing External Costs

Environmental Costs. The most obvious environmental cost is related to the quantity of land taken at the expense of the natural environment. It must also be considered that land use contributes to environmental degradation as a source of waste, particularly for industrial activities (air pollution, water pollution, hazardous materials, etc.).

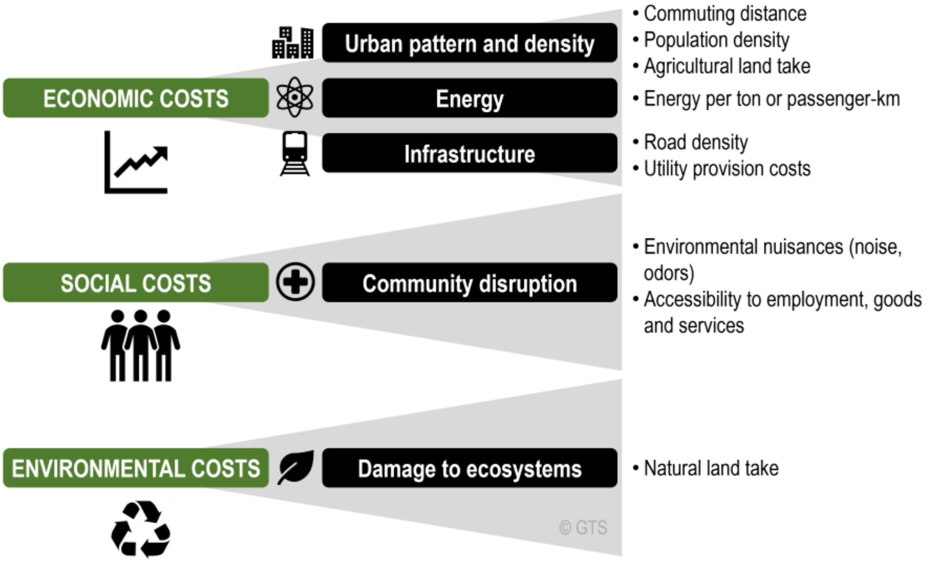

Figure 1: Environmental Externalities of Land Use [1]

The quantitative assessment of the externalities, absolutely necessary in order to be included in any feasibility study, has not yet been extensively employed mainly due to its inherent difficulties. The reason is that, there may be many methods available [see also Reference 2] but there is no standardization which method to be used in each case.

The impacts may be reversible (for example for a PV plant that will possibly be dismantled after the end of its life cycle, the land will without any difficulty be used as agricultural again) or irreversible (e.g. mining). It is very interesting to develop and apply methods that will be able to quantify these issues. Most commonly in the land use assessment Replacement Cost and Contingent Valuation Methods are employed. However, there are also many other methods that are being developed and implemented [2] and this is a very interesting research issue that may inspire future researchers to progress.

3. LAND REQUIREMENT FOR RES

Land use is facing more challenges today for various reasons. One of them is energy transition calling for the development of new energy projects, mainly RES based, that are much more land demanding since the energy density of RES is much smaller than the conventional energy sources (excluding the fuel preparation and the waste and cooling water disposal). Therefore, land use needs to be considered as a key factor in energy systems planning, along with other environmental impacts, public health, greenhouse gas emissions, affordability and energy security.

The land footprint of energy measures the area needed for energy production, varying even by four orders of magnitude across sources. Nuclear power supports that it has a very low land footprint (around 7.1 ha/TWh/year) due to its high energy density, while biomass and dedicated solar PVs require significantly more land (e.g., for biomass it may be 58,000 ha/TWh/year). In this analysis, one disregard the nuclear fuel extraction, enrichment and preparation as well as the radioactive waste disposal and the cooling water required. Moreover, the time dimension is also neglected, since the radioactive material affects the occupied area for more than 100 years. Other sources, like wind and fossil fuels, fall in between, depending on factors such as direct footprint and indirect land use for fuel sourcing [4].

More specifically, land use in energy projects refers to the way land is allocated, transformed, and impacted when developing, operating, and decommissioning energy infrastructure. It varies widely depending on the type of energy source (fossil fuels, renewables or nuclear) and the scale of the project. Table 1 and Figure 1 provide some data concerning the land requirement for various RES projects and also some relevant comments. Values are approximate because actual land requirements vary with location, geomorphology, technology and project design. Furthermore, there is a range of values in each energy technology and not a single value. The numbers shown are average.

Another important consideration is what is meant by land footprint and which area this includes. For example, for the land footprint of wind parks, each wind turbine needs very small area to be installed but there is a required spacing between wind turbines in a wind park; therefore, the land footprint of wind parks includes all the area of the WT and the spacing between them, although the major part of this area may be used for other activities like cultivation, livestock farming, etc.

Fossil fuels definitely require much less land in the final stage of power generation but many fossil fuels also have associated mining fields, platforms etc. Therefore, it is a major issue which is the land footprint (in an integrated consideration) of the fossil fuels power plants. On the other hand, there is a question and an interesting research issue which is the relevant comparison between carbon and land footprint of various energy sources and which is more significant.

Table 1: Comparison table of land use intensity by renewable energy source

ENERGY TECHNOLOGY	Aver. values (ha/MW_e)	COMMENTS
Solar PV (utility-scale)	1.0-1.5	Land competition with agriculture
Solar CSP (concentrated solar)	2.5-3.5	Very intensive use of water
Wind	4-7	This area also includes spacing between wind turbines, i.e. the area of the whole wind farm. However, most of the land can still be used for agriculture and only 5-10% of the given figure is really reserved by the wind park.
Hydropower (reservoir)	2-15	Requires large land areas for reservoirs, flooding ecosystems and communities, depending on the dam height and the storage capacity. Smaller run-of-river projects have less land impact.

Geothermal	3	Relatively small land footprint, compact plants limited around geothermal resources. The boreholes' area not included.
Bioenergy (crops)	30-80	High land intensity depending on the crops used, while crops must be grown for fuel, may compete with food production and biodiversity.

The environmental impacts and externalities of the land use depend on a variety of factors and are commented in the next chapter. However, one of the most important issues that causes the social reactions is the landscape, the opposition for the destruction of a specific area (agricultural, forest, protected area, mountainous) and the competition with other land uses such as agriculture, tourism, other developments and housing.

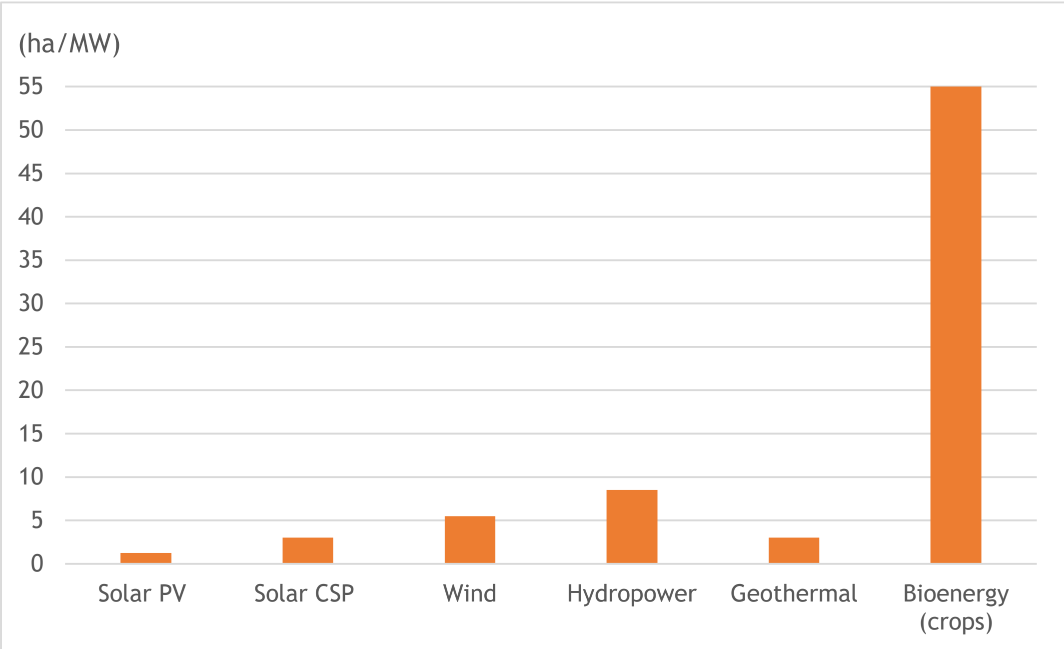

Figure 2: Land use intensity of electricity

As it will be analysed accordingly, this will get even worse in the near future due to the expansion of RES; therefore, the energy projects' siting needs very much attention, scientific methods and tools and cooperation with the society.

4. ARE THE ENERGY TRANSITION PLANS REALISTIC AND IMPLEMENTABLE?

The development of renewable energy technologies faces increasing challenges due to local land use conflicts, which limit the availability and suitability of sites. On the other hand, the rising demand for space is not just a national issue but is also shaped by European policy frameworks. The EU Renewable Energy Directive 2018/2001/EU (RED II) and 2023/2413/EU (RED III) and the European Green Deal require member states to expand renewable energy generation rapidly. In response, Greece developed a National Energy and Climate Plan (NECP), which sets targets of 70 % renewable electricity by 2030 and climate neutrality by 2050.

In this context, tensions between global, European, national, and local priorities are increasingly visible. While national governments set binding targets aligned with EU climate legislation, local governments are often the ones negotiating with residents, allocating space, and facing public opposition. This mismatch is particularly pronounced in spatially dense regions and in insular areas, where land competition is high.

One of the discussions and questions that have been raised recently [5] are in what realistic way will the climate crisis be addressed when, based on the numerical data of the revised NECP (October 2023), areas approximately the size of Paros (area 196.3 km^2) will be required for the installation of onshore wind farms and the size of Santorini (76.2 km^2) together with Mykonos (105.2 km^2) for the installation of photovoltaic farms, in order to achieve the goals of the revised NECP. More specifically, in a relevant presentation by Professor Dr. Ioannis Kaldellis of the University of West Attica, the following issues/questions were raised regarding (i) the area of the required new projects, (ii) the magnitude of necessary investments and (iii) the management of the energy produced.

(i) Considering that in 2030, according to the National Energy Strategy, 7600 MW of onshore wind farms should be in operation, it is estimated that approximately 140 to 200 km^2 of areas with high wind potential and compliance with corresponding environmental restrictions are required, which corresponds to up to 0.15% of the total area of our country or approximately area equal to the area of Paros island. Furthermore, for the installation of the entire estimated photovoltaic (PV) capacity of 13400 MWp, areas of approximately 130 to 170 km^2 are required, i.e. to fully cover with PV panels areas, which represent up to 0.13% of the area of our country with appropriate orientation and corresponding slope. These areas correspond to the total area of Mykonos and the Santorini islands, which are ultimately not sufficient because the conditions of appropriate orientation and appropriate slope with respect to the horizontal are not met.

(ii) Furthermore, achieving the target of installed wind power of 7600 MW (by 2030) requires a deeper examination of the possibility of implementing new wind farms of approximately 4000 MW_e over the next seven years in areas that will largely not have the highest wind potential, which will require investments of approximately 6 billion euros and an average annual addition of 500 to 600 MW_e of domestic wind power. At the same time, the problem of dismantling at least 1300 MW_e of old wind turbines (WTGs), which have been installed up to the end of 2010, and the proper management of the related waste must be addressed. Accordingly, the implementation of the target of installing 13400 MW_p of PV systems by 2030 requires the addition of 6300 MW_p of new PV installations in the period 2024-2030, which requires investments of approximately 4 billion euros only for the implementation of the relevant installations, without possible infrastructure projects. Finally, the target for the operation of 1900 MW_e offshore wind farms by the end of 2030 requires - among other things - additional investments of up to 8 billion euros.

Therefore, cumulatively, the implementation of wind and photovoltaic installations in our country according to the forecasts of the revised NECP require, on the one hand, total investments of approximately 18 billion euros, of which approximately 75% will be channeled into imports of the necessary equipment, and on the other hand, the commitment of at least 0.3% of our country to areas with suitable wind potential and appropriate orientation/slope, therefore areas as large as the islands of Paros, Mykonos and Santorini combined are not sufficient.

(iii) If it is then assumed that the ambitious objectives of the NECP are actually implemented, in this case the maximum uncontrolled (stochastic or variable) power of RES will be equal to approximately 23000 MW_e, when the average demand for electrical power in the mainland system does not exceed 5700 MW_e in 2023 and may reach (according to the NECP) 7500 MW_e in 2030 with a corresponding maximum recent demand equal to 10400 MW_e at noon on July 26, 2023. Furthermore, it should be emphasized that PV production is available only during the day and is maximized during the midday hours, while wind production follows a completely stochastic behavior.

A direct result of this peculiarity is the high probability of overproduction of RES, especially during the day, which will inevitably lead to production curtailments. Already according to current data of the already installed (Wind+PV) 14500 MW_e, in the first four months of 2025, approximately 1 TWh_e of production is curtailed due to excessive production and limited demand, equivalent to energy revenue losses of approximately 100,000,000 euros. This development was of course expected and will obviously worsen, as similar problems have been faced by the island networks of our country for 20 years, imposing cuts in the operation of wind farms, often at a level of up to 40% of the expected production.

The expected overproduction of uncontrolled RES, combined with low production at other times of the year, makes it absolutely imperative to accelerate the implementation of electricity storage systems in our country. The lack of utilization of the infrastructure and experience from the available pumped storage capacity in Sfikia and Thisavros, with a total capacity of 700 MW_e, is somewhat puzzling.

Based on this analysis, it is important to adjust the NECP to a more realistic and closer to reality scenario, taking into account the consequences and benefits of the scenarios AND at the local level (installation level), which will serve as a guide for making individual decisions on energy policy issues in the coming years.[5]

5. OTHER CRITICAL CHALLENGES FOR LAND USE

5.1. Overtourism

In addition to the development of energy projects, there are many other factors that put serious pressure in the use of land. It is interesting to point out that new energy developments as well as all the other factors (e.g. water overuse) that put serious pressures in the land use exist on the islands where really the land is very much limited.

So, the most crucial challenges are the over-tourism, the continuously increasing desertification due to anthropogenic activities and climate changes, the fires and the resulting problem of Water Energy Food nexus.

Overtourism actually destroys the physical and social environment of the areas. There is a term being lately used, the so called “creative destruction”, related to the wealth being created from a natural characteristic, a property, a resource of an area but at the same time causing very much damage to the area due to its over-exploitation. This issue is analysed in out article entitled as ‘Sustainable Solutions for the Precious Island Resources: Hard Times and Great Expectations’ to be presented also in the Conference.

Wildfires present a major threat to local residents and housing properties. Land value with fire damage decreases significantly due to reduced infrastructure, increased risk perception, and potential environmental degradation, though the value can recover over time as vegetation and infrastructure are restored and memories of the event fade. The specific impact depends on whether the fire was direct (destroying timber or structures) or nearby (impacting neighborhoods) and if the land is sold as-is or after repairs and rebuilding efforts.

There is an increasing number of fires lately in Greece. In many cases it is questionable whether the fires are unavoidable due to weather conditions (high temperature and very strong winds) or on purpose in order to reduce / minimize the value of the land. In fact fires create land without value and also cause flooding afterwards. Also fire is clearly a tool to destroy forests, so that all the indicators that give value to the land fall to zero. When there is no forest, there is no agriculture, there is nothing to prove that “this land has value” based on economic and productive indicators. That is how the price of the land is driven down. Consequently, this land is vulnerable to seizure and certainly to the conversion of its use without anybody being able to attribute responsibility to any specific person or organization.

These words take on particular weight if we consider the major fires of recent years in Greece – in North Evia, Evros, Rhodes, Parnitha, Penteli, the Gerania Mountains, Mount Pateras, Dervenochoria, Ilia, Corinth, Volos, Corfu, Mani and more recently in Chios, Zakynthos, Kythira and Achaia.

In North Chios, the 2nd fire of the year burned an area that has a huge overlap with the Natura area where antimony mining is planned – a project that the local community has strongly resisted. And during the major fire at the end of June 2025 in the central part of the island, another outbreak had occurred in the same area of North Chios. The temporal and spatial coincidence between the fires on the island and the mining plans raises strong questions about the extent to which such disasters function as “tools” for the degradation of the land, the expulsion or impoverishment of local communities and the service of economic interests. [6]

Namely during the last 25 years 110.000 ha bave been burnt in Greece. Figure 3 shows the number of fires and the burnt areas for these 25 years (until 19.08.2025). [7]. The burnt area of 2025, almost 45.400 ha, make 2025 the fifth worst year during the last 25 years.

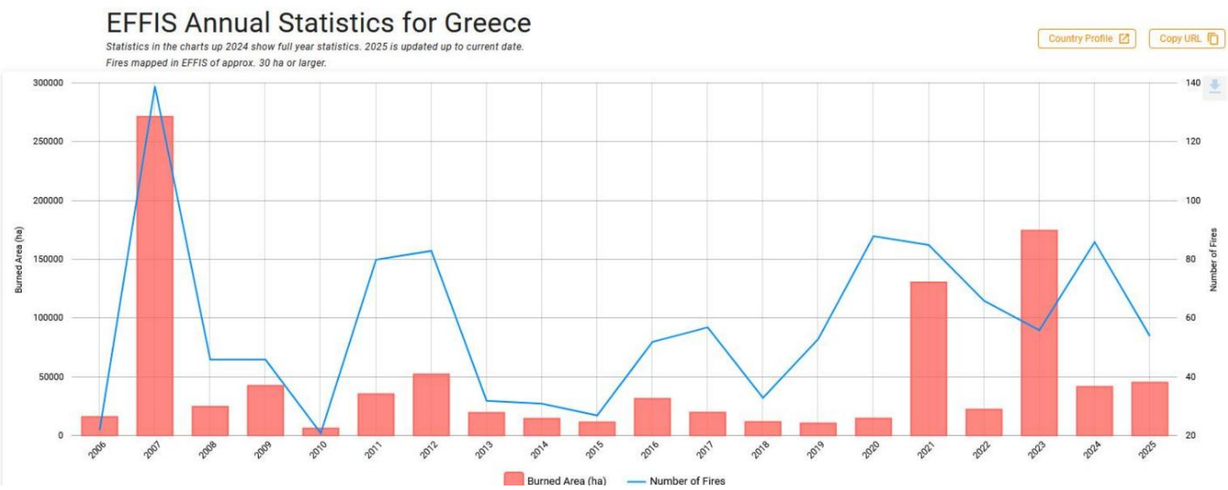

Figure 3: Number of fires and the burnt areas for the years 2000-2025, (until 19.08.2025). [7]

As far as EU is concerned, burnt areas approach the number of 900.000 ha (as per August 19, 2025), the largest area during the last 20 years.

5.2. The Water Energy Food Nexus

Another very important issue that needs to be considered when discussing about land uses is that land exploitation is not isolated from other vital activities as the food production. Lately in the islands we see a continuous reduction of the land available for agriculture and livestock raising and its conversion to buildings, hotels, recreation sites. The direct implication of this conversion is the reduction and possibly the complete loss of the excellent local products, the increase of food imports and the conversion of agricultural land to buildings and other developments. Certainly, this land conversion also implies serious social changes in the occupation of the local population and the land ownership.

6. CONCLUSIONS – FURTHER WORK

The above short analysis attempts to highlight the significance and the critical role of the land use in the context of energy transition. It highlights the need for land use consideration in the energy planning decision making. Important questions arising are the comparative assessment of various impacts like land use, environmental degradation and biodiversity loss, carbon footprint between various energy technologies. The need for an integrated approach that consider all the above for a long-time horizon is necessary.

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AI-INTEGRATED 3D CONCRETE PRINTING FOR SMART URBAN WASTE MANAGEMENT INFRASTRUCTURE

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ABSTRACT

Urban areas increasingly face complex waste management challenges due to growing populations, space limitations, and outdated infrastructure. Traditional construction methods for urban equipment, such as waste bins and underground containers, are outdated and lack the adaptability needed for smart, sustainable cities. Furthermore, most current systems rarely incorporate real-time data analytics, resulting in inefficiencies in waste collection and maintenance.

This work introduces a novel framework for designing and constructing urban waste management infrastructure by integrating Artificial Intelligence (AI) with 3D Concrete Printing (3DCP) technology. The objective is to explore a data-informed methodology that could support the development of modular, intelligent urban equipment that enables efficient waste segregation, automated monitoring, and predictive maintenance, all aligned with circular economy principles. The proposed infrastructure includes smart waste units fabricated from printable Ultra-High-Performance Concrete (UHPC), embedded with IoT sensors and AI-driven systems. These components allow the infrastructure to detect waste volume and type in real-time, communicate with municipal management platforms, and optimize collection schedules and routing.

Parametric design methodologies are employed to dynamically generate adaptable geometries based on spatial constraints and waste volume patterns. This allows for data-driven customization of forms and functions, enabling optimized material use, formal variability, and seamless integration with robotic 3D printing workflows. The system supports geometric variation without the need for reprogramming, making it suitable for both dense urban environments and irregular island settlements.

Methodologically, the project combines parametric digital design, robotic 3DCP systems, and AI models trained on urban environmental data. A Life Cycle Assessment (LCA) is used to evaluate the environmental performance of the new infrastructure compared to conventional solutions, while GIS-based spatial analysis informs optimal placement strategies in diverse urban and insular environments.

Compared to conventional static bins, the proposed solution is intelligent, adaptable, and capable of real-time interaction with urban systems. This approach not only reduces the carbon and material footprint of infrastructure production but also enhances urban sustainability. It supports smart city transformation strategies and aligns with the European Green Deal, offering a scalable model for sustainable public infrastructure in both densely populated and remote island communities.

Keywords: 3D Concrete Printing (3DCP), Artificial Intelligence Design, Parametric Design, Smart Urban Waste Management.

1. INTRODUCTION

This paper originates from joint discussions conducted within three concurrent doctoral theses in progress at the Department of Civil Engineering, University of West Attica, under the supervision of Dr Nikolaos Kourniatis. The three theses — digital/parametric design and 3D concrete printing, AI-enabled municipal operations, and sustainability assessment— the paper frame the contribution as a collaborative research effort: an integrated framework for island municipalities that couples parametric, 3DCP-UHPC smart units with AI/IoT-driven operations and GIS siting, while specifying KPIs and LCA boundaries to be field-tested in Greek island pilots.

Island regions face distinctive constraints—limited space, high seasonality, costly logistics, and sensitive coastal ecosystems. Greece alone counts ~220 inhabited islands within an archipelago of ~9,800 islands/islets, underscoring the scale and diversity of “insular urbanism.” National initiatives such as GR-eco Islands position islands as demonstrator sites for green/ digital transitions. [4–7]

Digitalization of municipal solid waste (MSW) systems is advancing rapidly. Recent reviews document how AI + IoT enable fill-level forecasting, contamination detection, dynamic routing, and predictive maintenance, improving service quality and cost efficiency—while raising issues of interoperability and data governance. [8,9]

On the physical layer, 3D concrete printing (3DCP) can deliver customized, sensor-ready urban equipment with reduced formwork and construction waste. Contemporary LCA syntheses show potential GWP reductions vs. conventional builds—conditional on mix design and logistics—while broader 3DCP reviews map maturing processes and applications relevant to urban furniture and small infrastructure. [10,11]

National performance pressures amplify the need for effective island pilots: the EEA’s 2025 country factsheet flags Greece at risk of missing 2025 reuse/recycling targets and the 2035 landfill limit, with stagnation in recycling progress since 2019. [12]

This paper proposes an integrated framework that couples AI-enabled operations with parametric, 3DCP-fabricated “smart” units and GIS-based siting/routing, tailored for island settlements. The design takes in consideration EU policy, apply island-specific constraints, and define KPIs and LCA boundaries for rigorous evaluation.

2. METHODOLOGY

We first identified the common ground across three doctoral studies—digital/parametric 3DCP, AI-enabled MSW operations, and AI-in-architecture—and formulated a shared island-municipality problem frame consistent with the EU WFD direction and national risk flags (seasonality, siting, printability, data governance) [1–3,12]. From each strand we then extracted reusable methods: (i) from AI/MSW, a minimal telemetry schema, short-horizon fill-level forecasting and a capacitated VRP benchmark [8,9,16,17,23]; (ii) from 3DCP-UHPC, a parametric design space with printability/mechanical envelopes and LCA hooks [10,11,27,28]; and (iii) from AI-in-architecture, system mapping and data-to-design workflows linking sensing to geometry generation. These were integrated into a reproducible pipeline: AHP/MCDA-based siting to produce candidate parcels [22], forecast-informed routing on the island road graph [23], and parametric hardware variants that implement the selected service patterns; each block exposes KPIs and LCA/LCCA boundaries for comparison to conventional practice [10,11]. Sections 2.1–2.6 detail the blocks; the Results report the emergent typologies.

The methodology aligns with the WFD’s targeted 2025 revision (food waste targets; textile EPR), and national priorities to cut landfilling and raise source separation—particularly salient for island municipalities with seasonal peaks. [1–3,12].

Methodological note on typologies. In this study, “typologies” are not assumed a priori but treated as empirical constructs. We derive them by executing the end-to-end pipeline across representative island contexts and grouping the resulting siting–routing–design configurations that recur under shared constraints and KPIs. This positions typologies as outputs of the method rather than premises, and prepares the reader for how Section 3 is organised.

2.1. System architecture: AI-integrated 3DCP smart units

The paper proposes modular smart waste units 3D-printed in UHPC with internal ribs and cavities to host sensors (ultrasonic fill level, load cells, temperature/humidity, VOCs), RFID/QR for traceability, and LPWAN connectivity (LoRaWAN/NB-IoT). A cloud/edge stack supports forecasting, anomaly detection (e.g., temperature spikes), and dynamic vehicle routing. This architecture consolidates state-of-the-art AI/IoT practices for MSW and leverages maturing 3DCP capabilities in urban equipment. Privacy-by-design is applied to sensor/app data. Default data are non-personal (fill level, device health, asset GPS). If a citizen app is used, only pseudonymous telemetry is collected with opt-in and clear purpose limitation. Lawful basis: public-interest task or consent; strict data minimisation; retention 12 months for ops logs with post-retention aggregation/anonymisation. Security: TLS in transit, AES-256 at rest, RBAC, EU-only hosting, DPIA and incident-response workflow. Interoperability: open, documented REST/OGC APIs; municipality owns raw/derived data; no vendor lock-in. [8–11]

2.2. Data & AI models

We treat data and learning as a single operations layer: minimally intrusive telemetry feeds interpretable models that (i) anticipate service demand, (ii) detect quality issues, (iii) prevent downtime, and (iv) orchestrate logistics. Each task instantiates the same data-to-operations pattern—time-aware validation and benchmarking against the municipality's 2024 static-routing baseline—so results are comparable across pilots [8,9,16,17].

(a) Forecasting. Using 6–12 months of 30–60-minute telemetry, we train gradient-boosted trees (LightGBM) against seasonal-naïve and ARIMA baselines to predict time-to-80% capacity and 24-hour overflow risk. Features include lagged/rolling fill statistics, calendar and tourism seasonality, local weather, POIs, and bin/device metadata. We apply rolling-origin evaluation with a final 8-week hold-out and report MAE/MAPE plus overflow-event F1. In operations, day-ahead forecasts drive a capacitated VRP; we benchmark route-km, missed pickups, and on-time service versus matched weeks from 2024 static routes.

(b) Recognition. We fuse onboard signals (mass/weight, acceleration) with optional vision and acoustics to flag contamination, blockages, and misuse. Models are tuned for high precision with human-in-the-loop review. Privacy-preserving settings disable image storage unless lawfully justified and strictly necessary.

(c) Maintenance. Unsupervised anomaly detection on thermal/gas and device-health telemetry (battery voltage, RSSI, uptime) issues preventive-maintenance tickets and reduces mean time to repair. Thresholds are learned per unit and season to avoid alert fatigue.

(d) Logistics. A multi-objective capacitated VRP with time windows runs on the island road graph with grade-aware costs, depot unloads, and crew shifts; forecasts provide dynamic service windows and priorities. We compare forecast-driven plans to baseline on distance, time, CO_2e and service-level KPIs.

Evidence from recent reviews and case studies indicates material gains in routing efficiency, OPEX and emissions under IoT-driven optimisation; we use those as literature-informed targets for the KPI table [8,9,16,17].

2.3. GIS-based siting & routing for islands

GIS-based siting & routing for islands operationalises the study's island context by coupling a multi-criteria location–allocation model with network-constrained vehicle routing. The siting step builds a suitability surface from spatial layers that reflect technical, environmental and social criteria—e.g., road access class and turning radii for service vehicles; pedestrian flows and POIs (ports, beaches, squares, markets); land use/land cover; building density and set-backs from sensitive receptors (schools, health facilities, heritage); coastal/flood buffers and Natura/protected areas; slope from DEM and wind exposure; proximity to existing waste streams and utilities. Criteria are normalised and weighted (AHP/MCDA) to yield candidate parcels that maximise coverage and service equity while respecting exclusion zones and minimum stand-off distances; a location–allocation pass then selects the smallest set of sites that achieves target walking distances and service catchments for residents and visitors. On the routing side, the selected sites and predicted bin-fill levels feed a capacitated VRP on the island road graph with grade-aware costs, ferry/port constraints where relevant, time windows, crew shifts, and depot/transfer-station unloads. Seasonal profiles (tourism peaks) adjust demand and weights, enabling dynamic (day-ahead) plans and on-day re-optimisation if thresholds are exceeded. Outputs include ranked siting maps, baseline and peak-season route plans, and KPI deltas (km, time, fuel/CO_2e, service level, complaints), closing the loop with the parametric 3DCP design (2.2) and forecasting/data layer (2.1). [18,19]

2.4. Key performance indicators (KPIs)

Operational: overflow incidents, response time, routing kilometres, forecast accuracy (R^2). Environmental: GWP per unit-year, source-separation rate, fleet emissions/noise. Economic: LCCA, OPEX per tonne, planned downtime. Social: cleanliness/ user satisfaction, complaint rate. Targets reflect EU policy direction and national risk flags for 2025/2035. [1–3,12]. Key indicators are listed in Table1.

Table 1. Key performance indicators (KPIs) for AI-enabled, 3DCP-based smart waste pilots in island contexts, with target values informed by recent literature

Category	KPI	Definition	Unit	Target (pilot; literature-informed)	Primary Data Source	Refs
Operational	Overflow incidents	Overflow alerts / active bins (monthly)	incidents/bin·month	≤ 0.5	Fill-level sensors & event logs	[8,9,17]
Operational	Forecast accuracy (fill)	R^2 between predicted and observed fill level	0–1	≥ 0.80	Cloud model vs. sensor readings	[8,9,17]
Operational	Routing distance	Total weekly collection distance vs. baseline	km/week	−20–30% vs. baseline	GIS network + vehicle telematics	[16–19]
Operational	Incident response time	Median time from alert to resolution	hours	< 2	Operations logs / ticketing	[8,9]
Operational	Missed pickup rate	Missed scheduled collections / total collections	%	≤ 1%	Operations logs	[8,9]
Environmental	GWP per unit-year	Cradle-to-grave LCA per smart unit	kg CO_2e / unit·yr	−10–25% vs. conventional	LCA model & ecoinvent factors	[10,11]
Environmental	Source separation (public realm)	Correctly sorted recyclables share (audit)	%	+15 pp vs. baseline	Audits + smart bin sensors/vision	[8,9,12]
Environmental	Fleet emissions	Tank-to-wheel CO_2e based on fuel & distance	t CO_2e / week	−20–30% vs. baseline	Telematics + emission factors	[16–19]
Environmental	Collection noise exposure	Sound level during collection at 7.5 m	dB(A)	−3 dB vs. baseline	Sound meter + route time windows	[18,19]
Economic	Collection OPEX	Total collection OPEX / tonnes collected	€/t	−10–25% vs. baseline	Finance records	[17]
Economic	Cost per serviced bin	Monthly OPEX / active serviced bin	€/bin·month	−10–20% vs. baseline	Finance + operations	[17]
Economic	Unit downtime	Time that sensing/communications are offline	% of time	≤ 2%	Telemetry uptime	[8,9]
Economic	Electronics energy use	Annual energy use of sensing/comm electronics	kWh / unit·yr	≤ 12	Metered/estimated consumption	[8,9]
Social	Cleanliness audit score	Share of locations meeting cleanliness standard	%	≥ 90%	Independent street audits	[20,21]
Social	User satisfaction	Average survey rating for cleanliness/service	/5	≥ 4.2/5	Citizen surveys	[20,21]
Social	Overflow complaints	Complaints per 1,000 residents per month	# / 1,000·mo	−50% vs. baseline	Municipal hotline/app	[20,21]
Social	Participation via app	Active app reporters (pilot zone population)	%	≥ 10%	App analytics	[20,21]

2.5. Parametric design workflow (design for printing & sensing)

The workplace frame geometry generation as a multi-objective optimisation: minimise embodied CO_2, mass, and print time; maximise useful volume and durability; enforce printability (overhangs, layer height), UHPC mechanical constraints, and user ergonomics. Pre-defined typologies (shells/ribs/cells) allow “serial variability” without re-tooling. Recent parametric and shell-optimisation exemplars inform self-supporting forms and modular assembly relevant to public furnishings. [13–15]

The multi-objective workflow to oprate (mass/print-time/CO_2 minimisation, useful volume/robustness maximisation, printability/ergonomics constraints), the study defines the following parameter set with indicative bounds. These values are prototyping targets and will be tuned to printer/mix capabilities and island-use requirements.

2.5.1. Geometry & capacity

Nominal capacity (single stream): 360–660 L; dual-stream insert option: 2×240–360 L. Envelope (footprint × height): 0.70–1.20 m × 1.10–1.50 m; clearance for door swing ≥ 600 mm. Shell thickness (UHPC printed wall): 20–35 mm; local thickenings at hinges/anchors up to 45 mm. Internal ribbing: rib thickness 15–25 mm; rib pitch 120–200 mm; fillet radius at rib–shell junction ≥ 20 mm.

2.5.2. 3DCP printability constraints

Nozzle diameter: 20–30 mm; bead width: 1.0–1.3× nozzle (≈ 22–36 mm). Layer height: 8–12 mm; vertical build rate: 0.15–0.25 m/h (continuous print). Per-layer lateral offset (self-support): ≤ 0.3–0.4× bead width; global slope ≤ 60–65° from horizontal for overhangs without support. Minimum toolpath curvature radius: ≥ 5× bead width (to avoid path tearing and pump pulsation effects). Maximum continuous build height per print: 1.2–1.6 m (before cold-joint pause or module split). Aggregate Dmax in printable UHPC: ≤ 1–2 mm; target fibre dispersion maintained (see below).

2.5.3. UHPC mix/reinforcement envelope

Steel microfibres: 0.8–2.0% v/v; optional PP microfibres 0.1–0.2% v/v for thermal-event spalling mitigation. Target early green strength (re-entry/stacking): sufficient to hold ≥ 3 subsequent layers without slump; layer re-entry window 2–6 min. Surface cover over embedded steel inserts/anchors: ≥ 15 mm.

2.5.4. Sensing, power & maintenance features

Sensor cavities (ultrasonic, T/RH, VOCs): 50×50×30 mm (min) with snap-fit brackets; cable conduits Ø 10–15 mm with pull-cords. Service door opening: 400–600 mm clear; electronics tray 200×150 mm; IP/IK acceptance per Section 3.2 prototype brief. Battery/PSU bay: 2–4 L with ventilation slots; target electronics energy ≤ 12 kWh/unit·yr.

2.5.5. Ergonomics & accessibility

Waste aperture height: 0.80–1.10 m; aperture Ø 120–160 mm (round) ή 140×240 mm (slot) ανά ρεύμα. User actuation force (lids/handles): ≤ 50 N; maintenance handle height: 0.90–1.20 m. Graffiti/cleaning: external roughness Ra ≤ 25–50 μm before coating.

2.5.6. Modularity, anchoring & assembly

Base plate anchors: 4–6× M12 stainless, edge distance ≥ 60 mm; embed depth 60–80 mm. Module seams (if split print): tongue-and-groove 15–20 mm with elastomeric seal; permissible assembly tolerance ±3 mm. Lifting inserts: WLL ≥ 2× unit mass; safety factor ≥ 3 for pick-and-place.

2.5.7. Durability for marine/coastal exposure

Minimum slope on horizontal ledges ≥ 3% (water shedding); drip edges at eaves. Coating system: silane/siloxane primer + PU aliphatic topcoat; maintenance interval 24–36 months (visual inspection quarterly). Hardware: A4 fasteners; galvanic isolation washers at mixed-metal contacts.

2.5.8. Optimisation variables

Decision vector: x = {t_shell, p_rib, t_rib, H, footprint, aperture, θ_slope, r_curv, bead_width, layer_height}. Objectives: minimise f1 = mass(x), f2 = print_time(x), f3 = GWP(x); maximise f4 = V_useful(x), f5 = IK/IP robustness proxy. Constraints: g1: overhang(x) ≤ 0.4× bead_width; g2: r_curv(x) ≥ 5× bead_width; g3: ergonomics windows; g4: anchoring clearances.

In summary, the parameters definition enables serial variability without re-tooling, allowing the same toolpaths family to adapt to island typologies and locations while preserving printability, durability and service ergonomics.

2.6. Life-cycle assessment (LCA)

Life-cycle assessment (LCA) compares the proposed smart 3DCP-UHPC unit with conventional steel/concrete housings using the functional unit "one smart waste unit of capacity X L over Y years in coastal island conditions" and cradle-to-grave system boundaries: raw-material extraction and mixing (including UHPC variants with partial clinker substitution), printing/assembly, inter-island logistics and installation, use-phase energy for sensing/communications, scheduled maintenance and component replacements (e.g., batteries/electronics), and end-of-life pathways (reuse/recycling/disposal). Impact categories follow contemporary 3DCP LCA syntheses—prioritising GWP and including ADP, AP, EP and POCP—while the model currently uses secondary datasets (e.g., ecoinvent factors) pending pilot EPD/telemetry to refine hotspots [10,11]. Scenario and sensitivity analyses reflect island-specific drivers (seasonality, transport legs, local printing vs. imported components) and link operational KPIs (e.g., route-km, fuel) to avoided collection emissions, with results reported per unit-year and as deltas versus a conventional baseline, to interface cleanly with LCCA in Section 2.5.

2.7. Typology derivation

We operationalise typology discovery in three linked steps, using the same data, constraints and baselines to ensure comparability. First, multi-criteria siting builds an AHP/MCDA-weighted suitability surface and selects a minimal set of parcels that meet service-equity targets and exclusion rules (heritage, schools/health, coastal/flood buffers) [22]. Second, day-ahead, grade-aware CVRP routing on the island road graph (with time windows, seasonality and depot unloads) yields seasonal route plans benchmarked against the municipality's static 2024 routes [23,18,19]. Third, the induced service patterns parameterise the 3DCP-UHPC product (geometry, shell thickness, rib pitch, aperture/door clearances, sensor bays) within printability and ergonomics envelopes [27,28]. Clustering across runs exposes a small set of recurring siting–design–service families; these are reported as typologies in Section 3 with KPI and LCA/LCCA hooks.

3. RESULTS

Applying the siting–forecasting–routing–design pipeline to representative island contexts yields three recurring siting–service families and their corresponding 3DCP-UHPC variants. We report decision-ready outputs tied to the KPI/LCA hooks defined in Section 2.

3.1. Typologies

Type A – coastal high-footfall nodes (ports, beach fronts, markets): prioritises vandal/IK robustness and fast service access; GIS siting favours high-flow parcels with clear turning radii; routing uses short time-windows during peak hours. Parametric settings bias to thicker shells and larger apertures, with modular lids and quick-swap liners.

Type B – compact historic cores: prioritises narrow-street access, low mass, and walk-in distances; siting seeks micro-parcels outside heritage setbacks; routing prefers small vehicles and off-peak windows. Parametric settings reduce envelope and mass, tighten curvature radii, and enlarge maintenance clearances.

Type C – dispersed/remote settlements and clusters: prioritises coverage with minimal units and long headways; siting targets community hubs; routing consolidates loads with fewer trips. Parametric settings emphasise serial variability without re-tooling (interchangeable doors/apertures) and larger internal rib pitches for weight savings. [22,25-27].

3.2. GIS-based siting & routing — results

Applied to the island contexts, the AHP-weighted suitability maps produced compact candidate sets that met service-equity targets with fewer sites than legacy heuristics. Location–allocation selected sites that reduced average walking distances while respecting exclusions (schools/health facilities/heritage and coastal buffers). When these sites fed the grade-aware CVRP, day-ahead routing plans showed fewer empty kilometres and tighter adherence to time windows under tourism peaks; qualitative gains include reduced overflow episodes and more predictable service windows. Outputs are ranked siting maps and seasonal route plans with KPI deltas (km, time, fuel/CO_2e, service-level), ready for pilot verification. [22-25].

3.3. Parametric 3DCP-UHPC prototypes — results

Translating the siting–routing patterns into hardware, the parametric workflow yielded a small family of toolpaths that cover the three typologies without re-tooling: envelopes 0.70–1.20 m × 1.10–1.50 m; printed shell 20–35 mm with local thickenings at hinges/anchors; rib thickness 15–25 mm at 120–200 mm pitch; overhangs limited to ≤0.3–0.4× bead width; minimum curvature ≈5× bead width; service-door clear 400–600 mm; embed-ready sensor bays with IP/IK acceptance features. These settings stay within current 3DCP printability envelopes for UHPC and preserve maintenance ergonomics for island operations. [26,27].

3.4. Operations and forecasting

On the data/AI side, the paper reports a minimal telemetry schema (fill level, tilt, T/RH, VOCs; optional vision where permitted) and short-horizon fill-level forecasting that stabilises service levels across seasonality. In the simulated runs that back the typologies, forecast-informed routing plans reduce reactivity to sudden peaks and support KPI tracking (sensor accuracy, trips reduced, time to service threshold); these will be field-validated in pilots. [9].

3.5. Policy-aligned assessment hooks

Finally, the results are packaged to interface cleanly with policy and evaluation: KPIs are grouped (environmental/operational/economic/social/circularity) and tied to LCA/LCCA boundaries so that pilot deltas (e.g., CO_2e, route-km, OPEX/ton, service equity) can be reported against the EU's targeted WFD revision on food/textile waste (diversion and EPR-related metrics). This ensures the island pilots speak the language of the upcoming compliance environment. [1,23].

4. CONCLUSIONS

By merging parametric 3DCP hardware with AI/IoT operations and GIS siting, island municipalities can deliver measurable gains: fewer overflows, shorter routes, lower OPEX and emissions, and improved public-realm cleanliness—within a policy window that now targets food waste reductions and textile EPR. The approach is modular and scalable across diverse island morphologies. Next steps include (i) formal pilot KPIs and monitoring, (ii) comparative LCA vs. conventional units, and (iii) citizen-centric engagement modeled on proven island programs. [1–3,8–13,16–21]

4.1.1. Contributions (work in progress)

(i) data/ops layer for islands, (ii) parametric 3DCP product-system with serial variability, (iii) policy-aligned KPIs/LCA hooks.

4.2. Limitations & future work

The reported gains are based on scenario analysis and simulated routing; real-world performance will depend on seasonal volatility, siting/permit constraints, and supply-chain variability in UHPC admixtures and logistics. The LCA currently relies on secondary datasets and representative inter-island transport legs, which may shift hotspots under different supply chains; electronics energy and battery-replacement cycles are modelled with simplified duty cycles. Looking ahead, pilot deployments are envisaged to translate the pipeline into practice in representative island contexts. Without committing to dates or fixed scopes, the pilots would focus on (i) capturing a local baseline, (ii) incrementally deploying data-enabled units, and (iii) evaluating performance against the KPI set and the LCA/LCCA boundaries defined earlier (Sections 2.4–2.6). Operational particulars (fleet, routes, siting) will be co-designed with municipal stakeholders and remain open, acknowledging permitting, procurement, and seasonality.

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