15th INTERNATIONAL 100% RENEWABLE ENERGY CONFERENCE

IRENEC

IRENEC 2025

PROCEEDINGS

14-16 MAY 2025

RENEWABLE ENERGY ASSOCIATION

EUROSOLAR Türkiye

Editors

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Publishing Date 15 January 2026

ISBN 978-625-93410-0-2

Tanay Sıdkı Uyar

Conference Chair,
IRENEC 2025

Dear Participants,

In our journey of promoting 100% Renewable Energy, we have arrived at the 15th stop where we shall again share our research results and other achievements.

Every day we are discovering and practicing the good quality of renewable energies. The genie is out of the bottle. It is time to use the good quality of human beings to guide this opportunity effectively to the destination. The qualities of human beings can play its role if the individuals and countries talk together and define problems correctly and find solutions that can be implemented.

Renewable energy resources at each corner of the atmosphere are ready to be converted to electricity and process heat locally when needed. Kinetic energy of the moving air, chemical energy stored in biomass, heat and light of the sun and geothermal resources are available all over our planet earth free of charge. As the main energy source of living space on earth, sun and its derivatives were available before, are available today and will be available in the future.

Global support provided for the renewable energy made the market penetration of renewables possible. Today wind and solar energy became the cheapest way of producing electricity in many parts of the World.
Cities and countries who are trying to reach 100% renewable energy mix are working on preparing the infrastructure necessary to be able to supply more renewable energy for industry, transportation and buildings by smart grids and renewable energy storage systems.

Since renewable energy is available at every corner of our atmosphere, Community Power (the involvement of the local people individually or through their cooperatives and municipalities in the decision-making process and ownership of their energy production facilities) is becoming the most effective approach for transition to 100% renewable energy future.

During IRENEC 2025 we shall share and learn from the global experiences on difficulties, barriers, opportunities and solutions for transition to 100% renewable energy societies and make our contribution to Global Transition to 100% Renewable Energy.

Best Regards,

Tanay Sıdkı Uyar

Conference Chair, IRENEC 2025

President, Renewable Energy Association of Turkey

(EUROSOLAR Turkey)

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Contents

Modeling the Reference Energy System of Gedik Vocational School for Energy Transition Planning

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Abstract
In the previous study, the existing energy infrastructure of Gedik Vocational School (MYO) was analyzed using the Reference Energy System (RES) approach, and the energy flows, transformation technologies, and final energy carriers were schematically examined. Building upon this foundation, the current study takes the analysis one step further by developing a RES-based modeling of Gedik MYO's energy system. Within the scope of the modeling, energy supply and demand processes are simulated in detail, and the current system performance is quantitatively evaluated through scenario analysis. In addition, various scenarios are tested, including the integration of renewable energy sources, energy efficiency strategies, and system optimization approaches. The model aims not only to assess the current system but also to identify potential improvement opportunities in terms of sustainability, efficiency, and cost-effectiveness. Thus, the study seeks to develop a sustainable and efficient energy management plan for Gedik MYO. The findings are intended to provide concrete contributions to the institution's energy transition efforts and to offer a replicable model for other educational institutions of similar scale.

Keywords: Reference Energy System, Energy Modeling, Sustainability

1 Introduction

In recent years, the increasing demand for energy has intensified dependence on fossil fuels, consequently exacerbating global warming and posing significant environmental threats. For the realization of sustainable energy management, modelling energy systems at the institutional level is of critical importance. In this study, the energy consumption profile of Istanbul Gedik Vocational School is examined, and a model is developed using the Reference Energy System (RES) approach. Focusing particularly on electricity and natural gas consumption, the year 2023 is taken as the base year, and carbon emission projections are generated for the period extending to 2050. The primary objective of this study is to analyse the energy transition planning of Gedik Vocational School through scenario-based modelling and to identify strategic energy management actions that align with the institution's long-term sustainability objectives. The model, developed using the LEAP (Low Emissions Analysis Platform) software, facilitates both the analysis of current energy consumption and the projection of future carbon emission levels under alternative scenarios. In doing so, it provides a concrete decision-support tool for the formulation of energy efficiency policies and the design of sustainability strategies at the campus level.

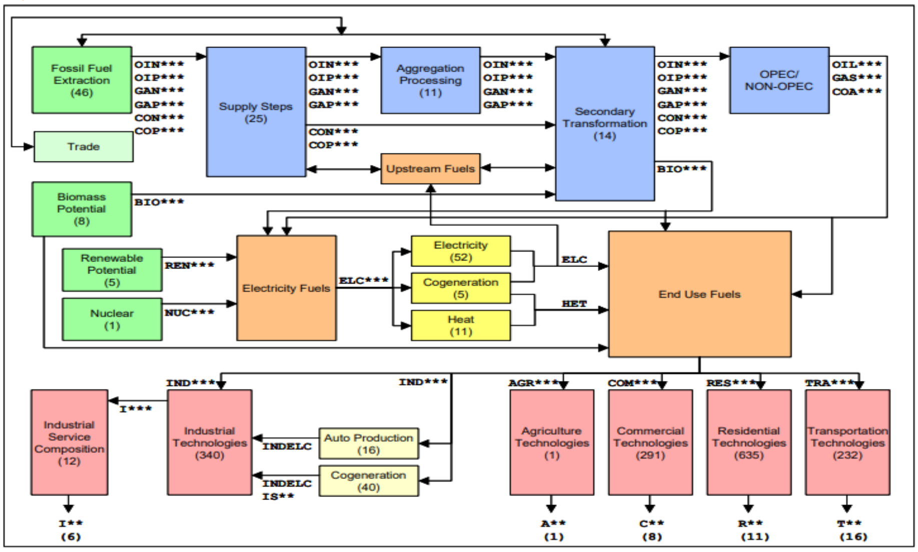

Fig. 1. General Reference Energy System Structure (Energy Information Administration, 2003)

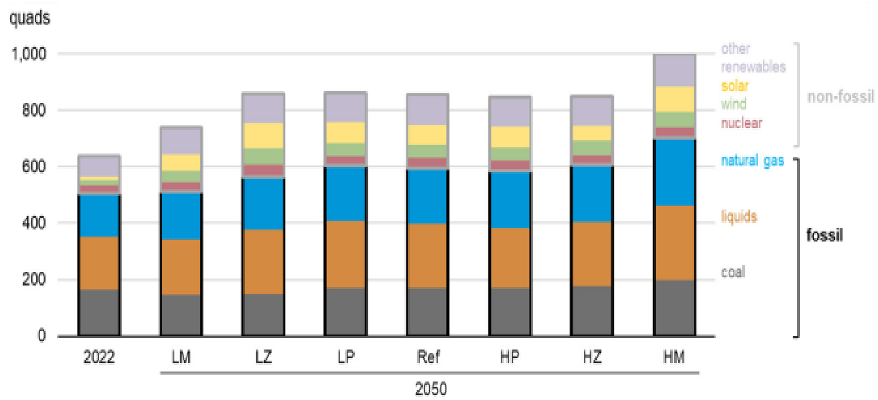

Fig. 2. Primary Energy Use by Fuel Type Worldwide (U.S. Energy Information Administration, 2023)

1.1. LITERATURE REVIEW

The modelling of energy systems plays a significant role as a decision support tool in analysing energy consumption and emissions. In this context, studies conducted at various scales and in different regions highlight the development and application areas of energy modelling approaches. Sarı et al. (2021) developed a reference energy system to evaluate the environmental impacts of hydrogen-based auxiliary power systems in the maritime sector and created scenarios using the LEAP platform. Their analyses revealed that the use of fuel cells resulted in up to a 60% reduction in carbon emissions. Sarı, Sulukan, and Özkan (2021) modelled the energy system of a chemical tanker ship using LEAP and conducted a comparative analysis of the baseline scenario and alternative low-emission strategies. The model was assessed from technical, economic, and environmental perspectives, serving as a guiding framework for the sustainability of ship energy systems. Sulukan et al. (2018) examined the RES structure used in modelling general ship energy systems and explained the technical and economic components related to the evaluation of energy flows. The study emphasized that technology-intensive RES diagrams could form a fundamental basis for future analyses. Uyar (2020), in his study addressing the global transition to 100% renewable energy, highlighted the importance of data-driven RES approaches in the energy planning processes of local governments and campuses. He also noted that tools such as LEAP and TIMES could play an effective role in this transition. Sulukan (2016) analysed Turkey's energy system using the MARKAL model and evaluated various policy scenarios alongside the reference case. The study demonstrated the applicability of modelling tools in identifying energy efficiency technologies and cost-effective alternatives. Sulukan (2018) assessed the impact of achieving a 20 GW installed capacity target for wind energy by 2023 on system costs and the share of renewable energy, using a MARKAL-based energy model developed for Turkey. Sulukan, Beşikci, and Uyar (2020) analysed hydrogen penetration scenarios specific to the city of Burdur using the TIMES model. By integrating hydrogen-based tran portation technologies within the RES structure, the scenarios revealed potential reductions in carbon emissions and associated environmental benefits.

1.2. RES Concept and Decision Support Tools

The Reference Energy System (RES), used for the planning and analysis of energy systems, is a vital tool for modelling the current and future energy infrastructure of a country or institution. RES provides a comprehensive representation of all energy flows from primary energy sources to final energy demand, including technological transformation processes and environmental outputs. This structure enables a systematic analysis of the environmental, economic, and technological impacts of various energy policies.

Among the decision support tools employed in energy system modelling, the Low Emissions Analysis Platform (LEAP) is widely preferred. LEAP allows users to model the current state of an energy system and conduct long-term analyses by developing alternative scenarios. In particular, it is highly applicable at the campus level, where variables such as energy demand, supply sources, conversion technologies, and greenhouse gas emissions can be modelled in detail. Furthermore, it supports data-driven decision-making processes essential for the development of sustainable energy policies.

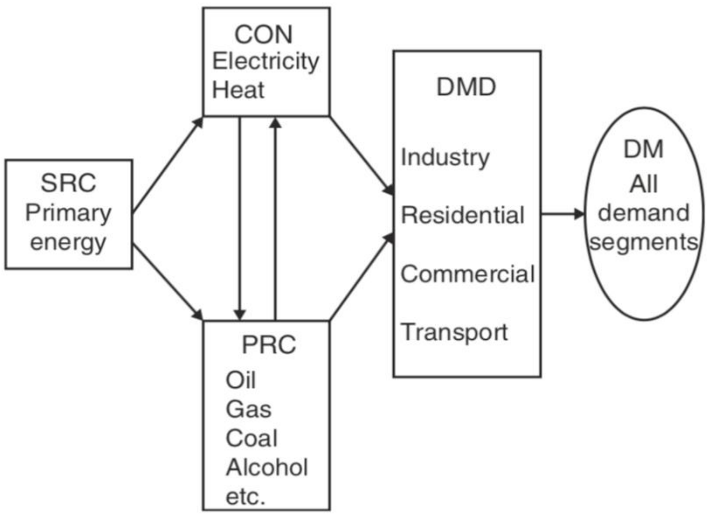

Fig. 3. A Sample Reference Energy System (Loulou et al., 2005)

2. RES Analysis of Gedik Vocational School

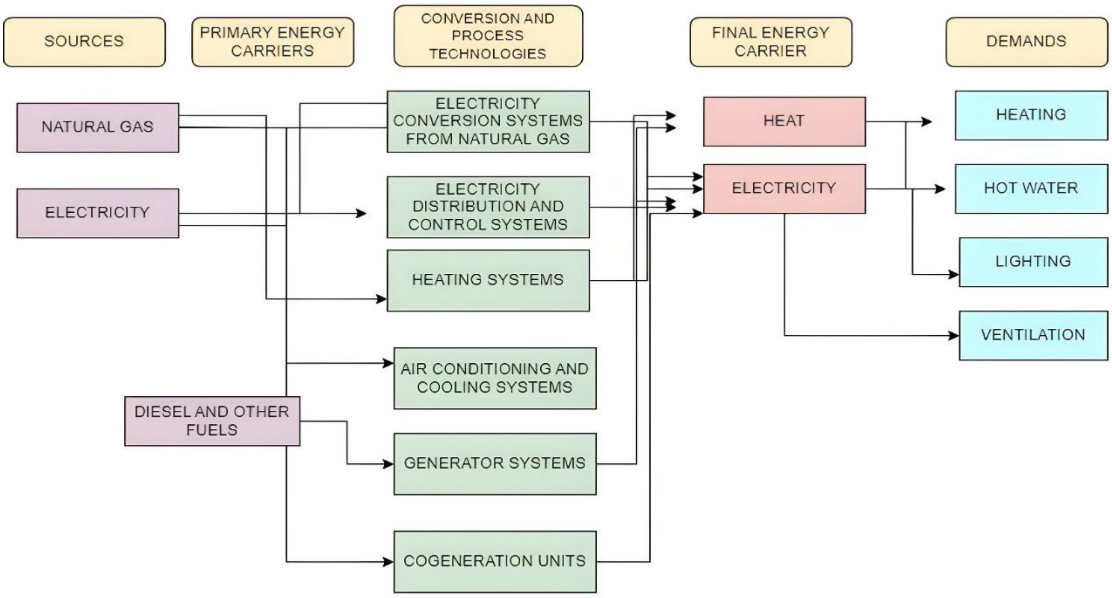

Fig. 4. RES Analysis of Gedik Vocational School

Development of the RES Structure for Gedik Vocational School
In modelling the energy system of Gedik Vocational School, a customized Reference Energy System (RES) structure was developed to represent the campus-scale energy flow. This structure serves as a fundamental scheme for analyzing institutional energy consumption and supporting future scenario development studies.

The developed RES structure consists of four main components:

1. Sources: The campus is supplied with energy through electricity and natural gas, both procured from the national grid and gas distribution infrastructure.

2. Primary Energy Carriers: Electricity and natural gas function as primary carriers and are utilized directly without any intermediate conversion.

3. Conversion and Process Technologies: Electricity is used across various systems including lighting, appliances, and HVAC systems, while natural gas is primarily consumed for heating purposes.

4. Final Energy Consumers: These include buildings, laboratories, classrooms, office spaces, and technical facilities within the campus. The energy consumed in these areas constitutes the total system demand.

The RES diagram prepared in this context reflects the energy consumption dynamics across the campus and provides the foundational input data required for modelling in the LEAP software. Electricity and natural gas consumptions were modelled separately to enable detailed analysis of future carbon emission projections. This structure offers a comprehensive overview of the current energy consumption pattern of the campus and establishes a basis for long-term strategic planning based on the 2023 data. Additionally, the RES structure technically categorizes both demand and supply components, facilitating energy efficiency evaluations and the formulation of scenario definitions.

2.1. Interpretation of the RES Model for Gedik Vocational School

The Reference Energy System (RES) scheme developed for Gedik Vocational School represents a comprehensive energy network structure that maps the institution's energy cycle from sources to final consumption. The scheme can be analyzed in three fundamental stages:

2.2. Energy Sources and Inputs

The energy sources located on the left side of the RES consist of electricity and natural gas. These are externally supplied to the campus, and no local generation systems (such as solar PV) are included in the current RES model.

2.3. Conversion Processes

The energy sources are directly transmitted to conversion technologies. In this stage: Natural gas is predominantly used in heating systems. Electricity is distributed to a wide range of uses including lighting, office equipment, laboratories, and HVAC systems. This stage is the most critical from the perspective of energy efficiency, as it involves observable conversion losses and high-intensity consumption points.

2.4. Final Energy Consumers

At the final stage of the RES, on-campus users such as buildings, classrooms, laboratories, and administrative areas are identified. These constitute the total energy demand of the system. Modelling electricity and natural gas consumption separately provides flexibility in the scenario development process.

2.5. Overall Assessment

The scheme enables a transparent observation of energy flows along the source → conversion → consumption pathway. The structure, designed with 2023 as the base year, includes the necessary technological classifications and data architecture compatible with modelling tools such as LEAP. This allows for scientifically grounded testing of different scenarios and policy proposals within the system.

3. Materials and Methods

3.1. Modelling the RES in LEAP

In this study, the energy consumption profile of Gedik Vocational School was modelled using the LEAP (Low Emissions Analysis Platform) software. The modelling focused on analysing carbon emissions resulting from the campus's electricity and natural gas consumption. The year 2023 was taken as the base year for all analyses. The relevant data were collected as outlined below and integrated into the LEAP model accordingly.

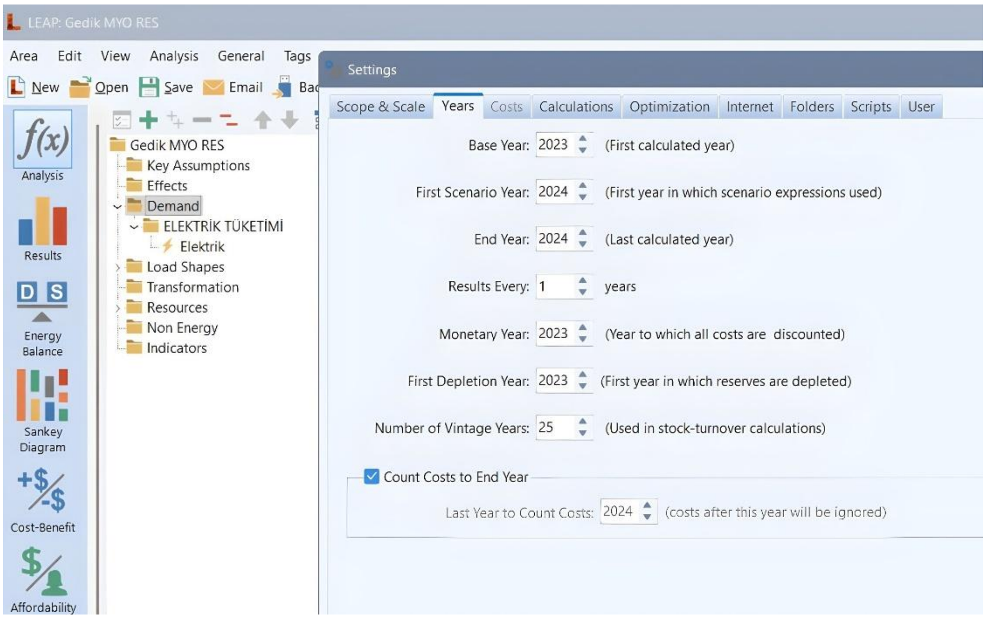

Fig. 5. Base Year Input

3.2. Data Entry and Assumptions

Electricity Consumption: The total electricity consumption data for the year 2023 were obtained directly from the institution's annual electricity bill. Natural Gas Consumption: As there are no direct measurements available for natural gas usage at the Gedik Vocational School campus, the 2023 consumption value was estimated. This estimation was based on the size of the campus, the number of buildings, and average consumption levels observed in similar institutional facilities. Both consumption values were converted into gigajoules (GJ) and entered into the LEAP model accordingly.

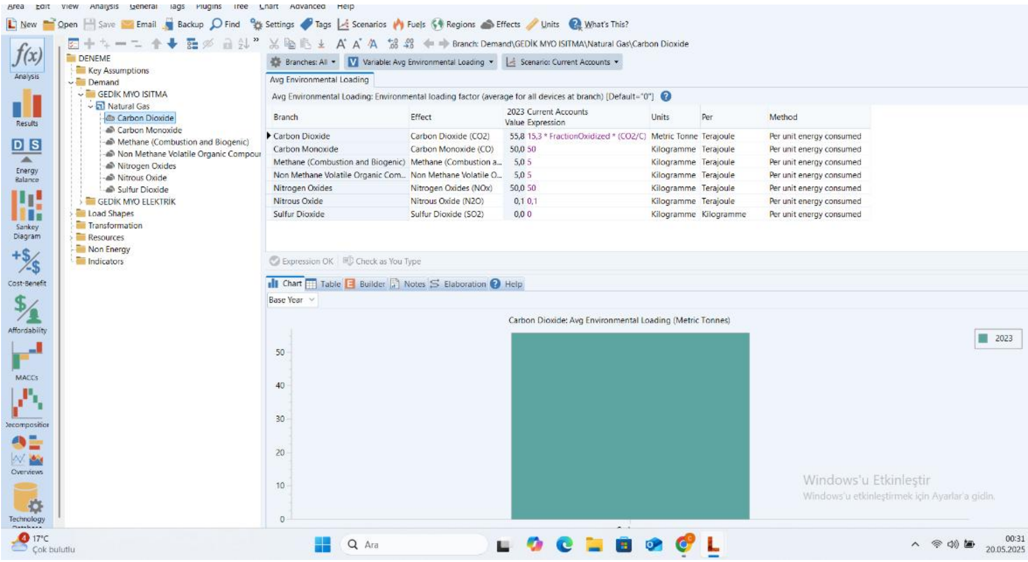

Fig. 6. Natural Gas Emissions

3.3. Modelling Structure

Within the LEAP platform, two separate energy categories were defined: electricity and natural gas. These categories were classified under the "Final Energy Demand" module as "Lighting and Appliances" for electricity and "Heating" for natural gas.

For both energy types, the Interpolation (Interp) data entry method was selected. A scenario was created for the period 2023–2050 based on the assumption that annual consumption will increase by 1% per year.

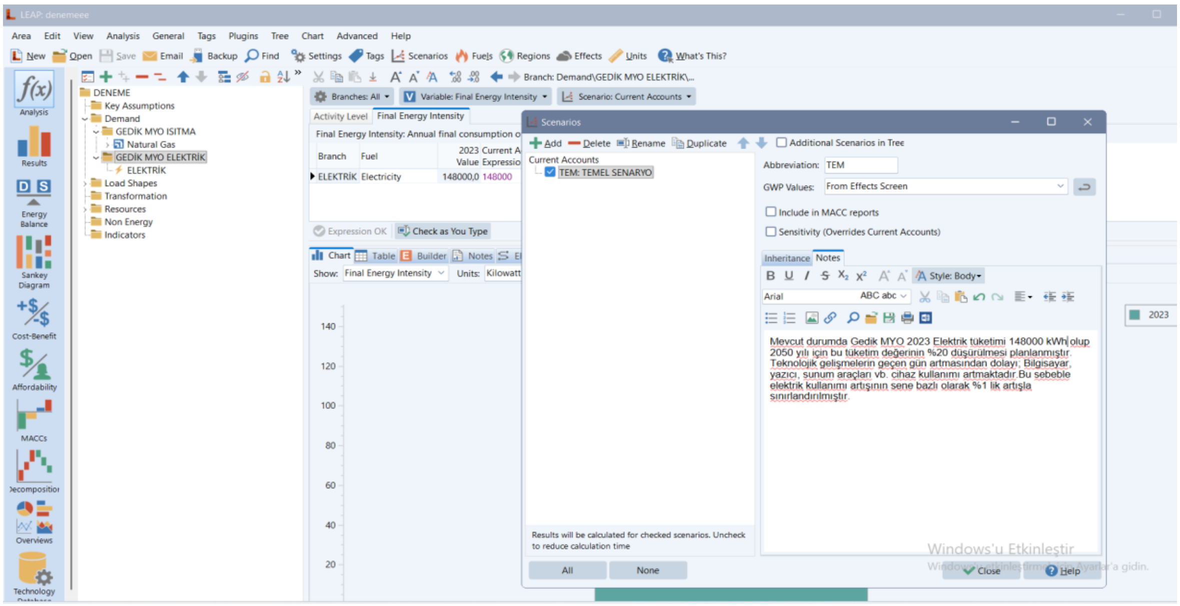

Fig. 7. Gedik Vocational School – Electricity Consumption Scenario

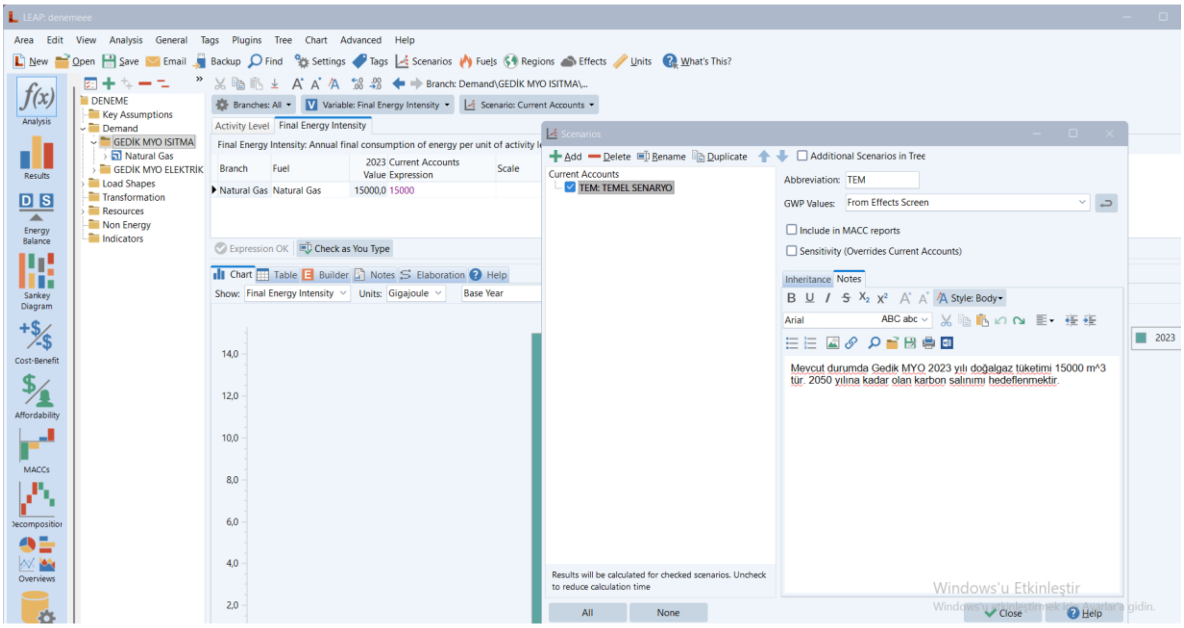

Fig. 8. Gedik Vocational School – Natural Gas Consumption Scenario

3.5 Outputs and Graphs

The graphical outputs obtained from the LEAP model illustrate the annual carbon emissions resulting from natural gas and electricity consumption. Separate graphs were generated for each energy source, followed by a combined graph presenting the total emission values.

These visualizations indicate a steady increase in campus-related energy-based carbon emissions over the years.

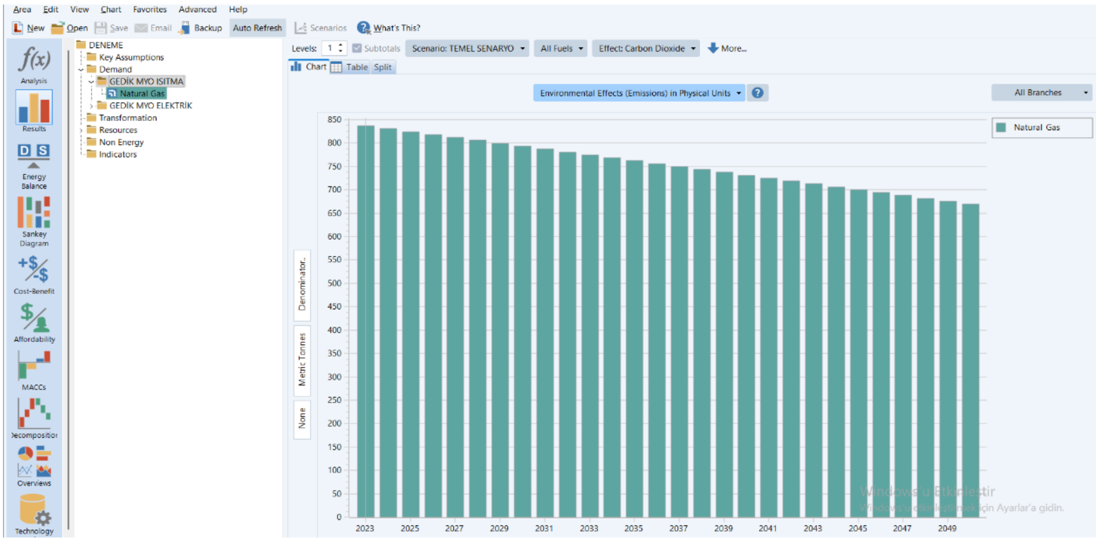

Fig. 9. Natural Gas Energy Demand of Gedik Vocational School (2023–2050)

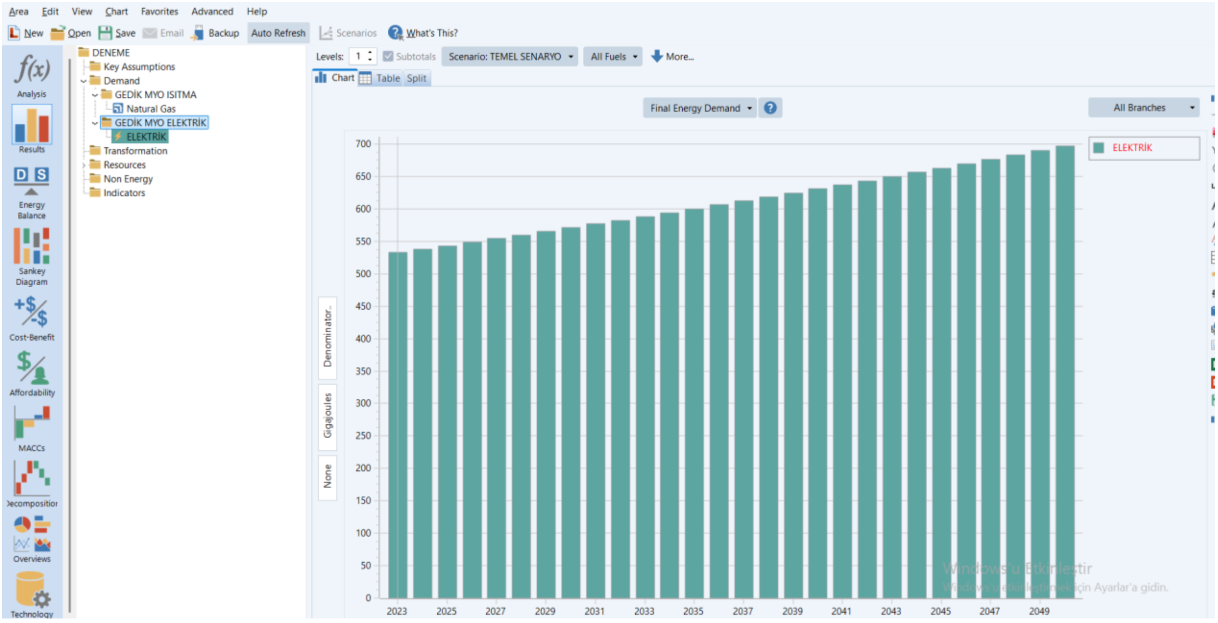

Fig. 10. Electricity Energy Demand of Gedik Vocational School (2023–2050)

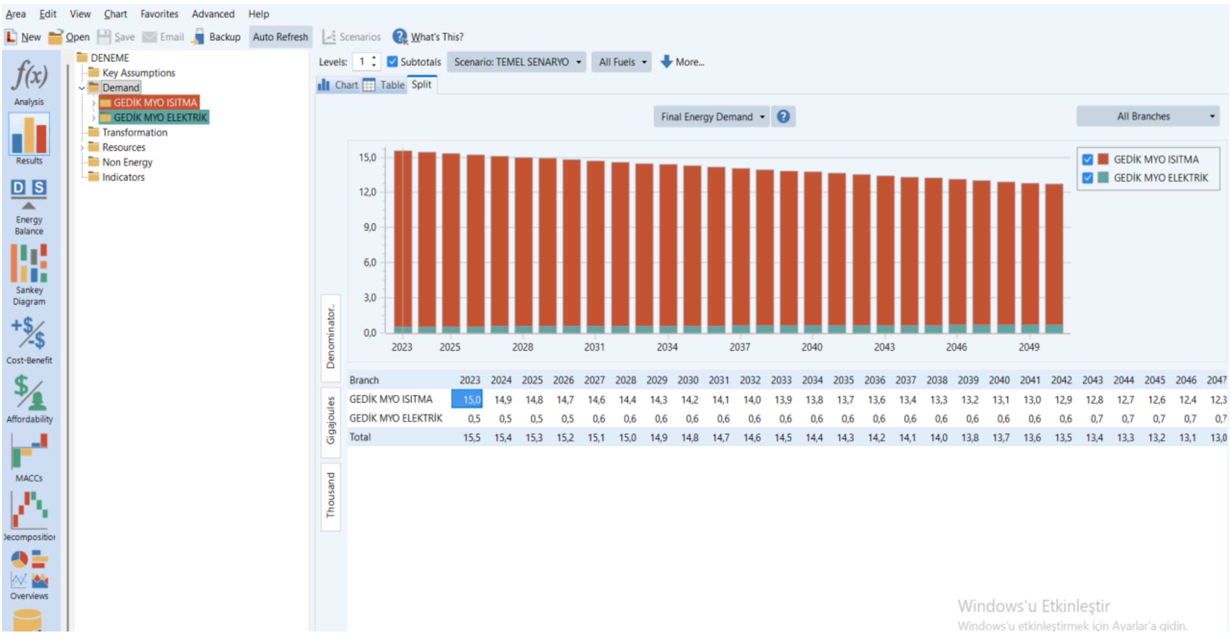

Fig. 11. Combined Energy Demand (Heating + Electricity) of Gedik Vocational School (2023–2050)

4. Conclusion

In this study, a long-term scenario analysis of a Reference Energy System (RES) was conducted for Gedik Vocational School using the LEAP (Long-range Energy Alternatives Planning) software. The analysis was based on a one-year dataset (2023) and projected forward to 2050. Through this modelling process:

The institution's annual energy consumption profile for 2023 was integrated into the system, A "Reference Scenario" was developed based on this data, without introducing any policy intervention, Projections were made regarding annual trends in carbon emissions, resource use, and energy consumption through the year 2050.

This approach enabled not only an assessment of current energy use but also an in-depth evaluation of future environmental and operational impacts. In particular, potential sustainability risks stemming from natural gas and electricity consumption were clearly analyzed through data-driven long-term simulations.

The most significant contribution of this model to the institution is the transition of energy management from intuitive practices to a data-based decision support system. Gedik Vocational School now possesses a digital infrastructure capable of shaping forward-looking energy policies extending to 2050, rather than merely reacting to past trends. This study further demonstrates that:

Even a single-year dataset can be sufficient to develop strong institutional energy planning projections, With the appropriate software tools and systematic data processing methods, scenario-based long-term decision-making is achievable. In conclusion, although this model was initially developed for Gedik Vocational School, it presents a scalable system proposal that can be replicated across all vocational schools in Türkiye. In this respect, it should not only be viewed as a technical analysis, but also as a strategic management model and a vision for sustainability. In the future phases of this study, the model will be expanded through the integration of broader datasets, comparative scenario analyses, policy assessments, and carbon optimization modules, thereby enhancing both the depth and the impact scope of the framework.

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Analysis of Hereke Asım Kocabıyık Vocational School Energy System and Development of Reference Energy System

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Abstract

This research will endeavor to develop a digital twin of the energy model, which will include the Reference Energy System (RES), energy flows, conversion technologies, and final energy carriers of the current energy infrastructure of Hereke Asım Kocabıyık Vocational School, which is affiliated with Kocaeli University. The technological, economic, and environmental implications of the parameters will be investigated. In this study, the Reference Energy System (RES) based modeling of Hereke Asım Kocabıyık Vocational School's energy system will be viewed and analyzed for the first time by the academic community as a flow diagram of resource technologies, process technologies, demand technologies, and end-user demand. The research will use the Reference Energy System modeling (RES), which is being evaluated for the first time, employing digital diagrams of end-user technologies, demand technologies, and fundamental factors. The technical parameters will be shared with numerical data of the total electricity consumption, total natural gas consumption and transportation expenses of the last five years obtained from the administrative and accounting units of the Vocational School, compared with graphics and given in the study. In the coming years, it is planned to simulate the current RES Modeling energy supply and demand processes in detail and to perform scenario analysis of the current system performance. In addition, it is aimed to make plans with scenarios on different integrations, including the integration of renewable energy sources, energy efficiency strategies and system optimization approaches.

Keywords: Reference Energy System, Energy Consumption Modeling, Energy Efficiency, Energy Management.

1 Introduction

Hereke Asim Kocabiyik Vocational School is one of the most important vocational schools of Kocaeli University with approximately 1500 students in 9 programs in 6 technical departments, located in Hereke town of Körfez district of Kocaeli province, very close to the sea, in a strategic location right in the middle of İzmit and Gebze organized industrial zones. Kocaeli University Hereke Asım Kocabıyık Vocational School consists of 11 buildings built on a 14464 square meter land.

A library, two reading rooms, a meeting room, two conference halls that can accommodate 170 and 175 people, a sufficient number of offices for academic and administrative staff, two dormitories, a canteen, and twenty-seven classrooms, fifteen vocational laboratories, and three computer laboratories are all present. The "EFQM Determination Certificate" was awarded to Asım Kocabıyık Vocational School in 2009 and the "EFQM 3 Star Competence Certificate in Excellence" in 2016 as a result of quality studies conducted with the Turkish Quality Association (KalDer).

Figure 1. Hereke Asim Kocabiyik Vocational School Main Building Entrance Gate with Drone Photo Shoot [4].

2 Importance of Energy System Analysis

The need to use resources as efficiently as possible to fulfill demand at regional, national, and even global levels is made abundantly evident by the world's population growth and the accelerating depletion of finite fossil fuel supplies. Because of this, technologies that generate energy from current resources should have better features and minimize energy loss throughout the energy cycle in order to satisfy our various demands. So, even with the same quantity of energy used, efficiencies offer a greater availability of resources at the same time as the rate of increase. Technological advancements in energy production and fuel consumption will safeguard interests while enhancing the nation's economy's financial aspect, supply-demand balance, and pricing [9][10].

The increase in the world's energy consumption is 70% met by fossil fuels. Despite significant development in renewable energy, the overall proportion of fossil fuels in the world's energy consumption stayed steady at 81% in 2017, something that hasn't changed in over 30 years. In 2017, the rate of improvement in energy efficiency worldwide declined [5].

The emergence of the energy problem occurred as people migrated to cities due to rapid population growth, natural resources were rapidly consumed due to industrialization, and people began to share the world [8].

This viewpoint should encompass not just a single person but also all global communities, or all people divided by national boundaries. Because you can't stop harmful emissions from another nation from spreading to your own, which is definitely a drawback of sharing the same environment. The overall focus and trend has changed from a quantitative to a qualitative approach in terms of employing energy resources more efficiently. Because of population increase, which has raised prices and sparked worldwide crises and conflicts, the supply-demand balance has shifted over time. Countries have been searching for alternative energy sources as a result of this circumstance, and new international balances and orders have developed globally. This viewpoint should encompass not just a single person but also all global communities, or all people divided by national boundaries. Because you can't stop harmful emissions from another nation from spreading to your own, which is definitely a drawback of sharing the same environment. The overall focus and trend has changed from a quantitative to a qualitative approach in terms of employing energy resources more efficiently. Because of population increase, which has raised prices and sparked worldwide crises and conflicts, the supply-demand balance has shifted over time. Countries have been searching for alternative energy sources as a result of this circumstance, and new international balances and orders have developed globally [9][11][12].

The most significant primary energy source is fossil fuels, and the sociopolitical landscape has a significant impact on their costs [3]. A high reliance on energy product imports raises concerns about supply security and overall costs [8]. In this way, the energy system has to be thoroughly examined using a comprehensive methodology that simultaneously takes into account technological, financial, and environmental concerns.

3 Reference Energy System Concept and Decision Support Tools

The so-called Reference Energy System (RES) is essentially a collection of factors that specify the features of the resources and technologies utilized to attain the energy balance. These elements include performance, pollutant emissions, constant and variable costs, and technological availability. According to Beller [2], RES is a network representation of all the technological operations necessary to supply different types of energy to end-use activities.

The Reference Energy System is a flow chart that illustrates every route that might be taken via different conversion stages to go from each main energy source to each end-use demand. This chart, which compares the present energy or technology requirements with reference scenarios, is established for a given time period (e.g., 2010 or 2015).

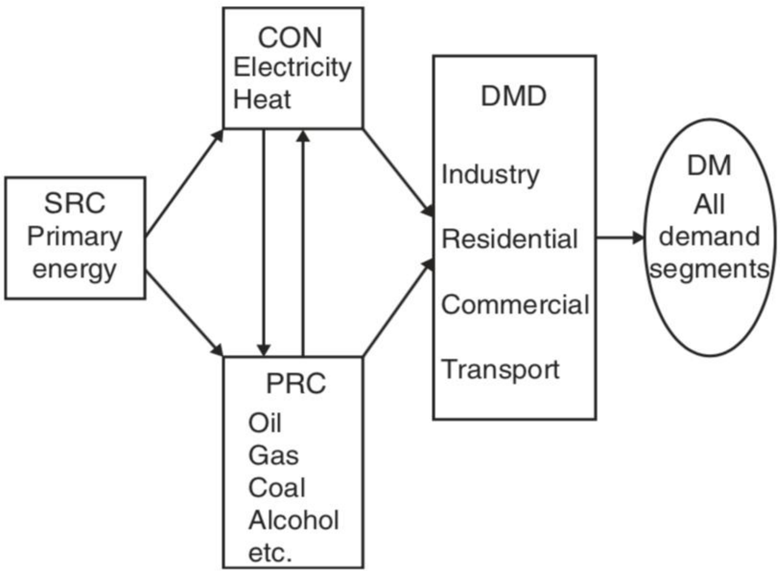

Figure 2. An example RES flow diagram [6].

4 Hereke Asım Kocabıyık Vocational School Reference Energy System

Hereke Asım Kocabıyık Reference Energy System Model (RES) was designed using the Draw.io program. After coloring and revisions, the final version is presented as in the figures above and below. In Figure 3, Source, Process Technologies, Production Technologies, Demand Technologies and Demands are taken into account. In Figure 4, the second Reference Energy Model is created by taking into account Source Technologies, Process Technologies, Conversion Technologies, Demand Technologies and End User Demands.

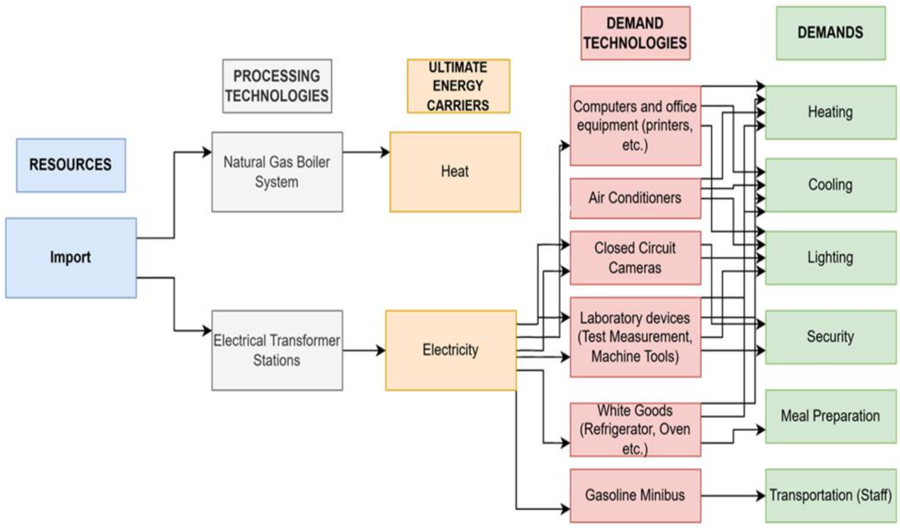

Figure 3. Hereke Asim Kocabiyik Reference Energy Model.

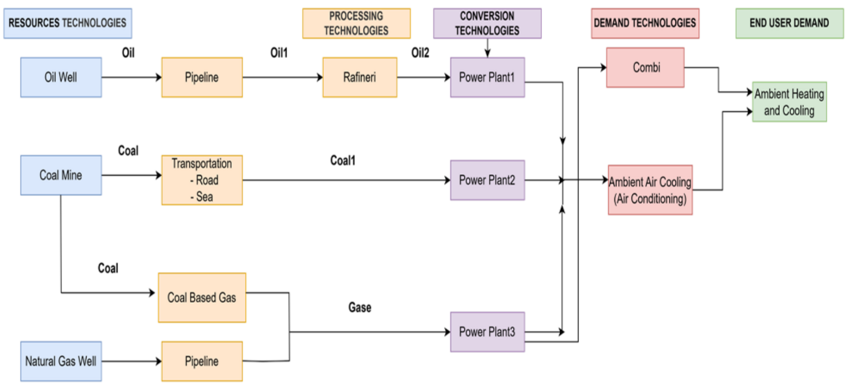

Figure 4. Hereke Asim Kocabiyik Reference Energy Model.

4.1 Defining Fundamental Parameters, Demands And End-Use Technologies

The parameters for defining the Reference Energy System of Hereke Asım Kocabıyık Vocational School are as follows;

Basic Parameters; Resource Technologies, Oil, Coal and Natural Gas.

Demand Technologies; Service Sector, Housing Sector and Transportation Sector.

End-use Technologies; Heating, Cooling, Lighting, Security, Cooking and Transportation.

4.2 Defining Conversion and Process Technologies

Process Technologies; Pipelines (gas and oil), transportation of coal-based gas by pipelines.

Transportation; Transportation of coal, gas and oil by sea and road.

Conversion Technologies; Refineries that process crude oil, Thermal power plants, power plants that generate electricity from natural gas, power ships.

4.3 Identification Of Primary Energy Carriers And Final Energy Carriers

Primary Energy Carriers; Pipelines, Road and sea transportation.

Final Energy Carriers; Power and transformation plants, Energy transmission lines, transformers.

Figure 5. Primary Energy Carriers; Pipelines (on the left), Road by train (on the right)

5 Hereke Asim Kocabiyik Vocational School Reference Energy Model (MARKAL)

The Hereke Asim Kocabiyik MYO RES model was chosen to use the MARKAL Energy Model Program. Using a numerical model called MARKAL, many energy-related systems may be economically analyzed at the national level and their evolution over a typical 40–50 year period can be represented. ALlocation and MARKet are the two terms that are combined to produce the word MARKAL. You may enter a number of characteristics, including building performance, facility costs, energy expenses, and so on, and the program will choose the best technology combination to satisfy this need at the lowest possible cost [1].

MESSAGE, MARKAL, EFOM, and TIMES are all members of the same model family. Typically, these models depict energy systems inside a technologically advanced environment [9]

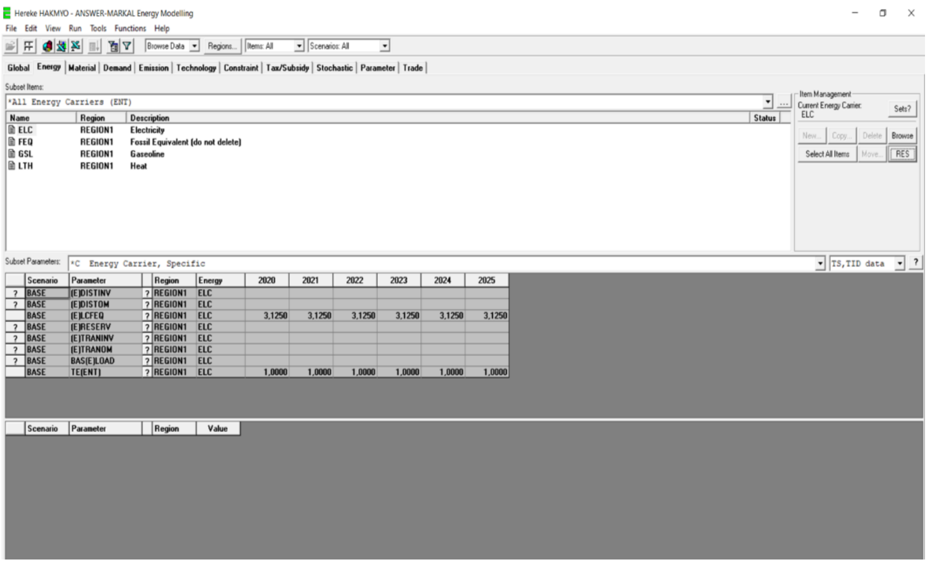

Figure 6. Hereke Asim Kocabiyik MYO RES Model, Energy Carriers MARKAL Page View.

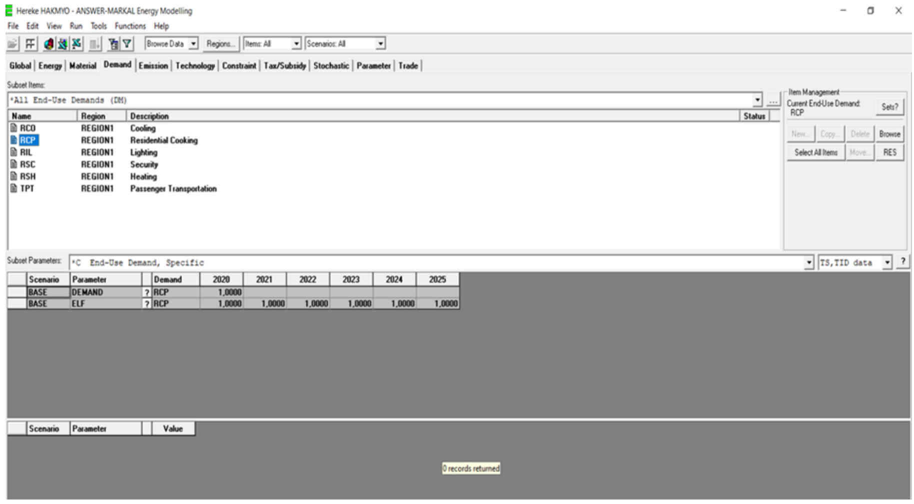

Figure 7. Hereke Asim Kocabiyik MYO RES Model, End User Demands MARKAL Page View.

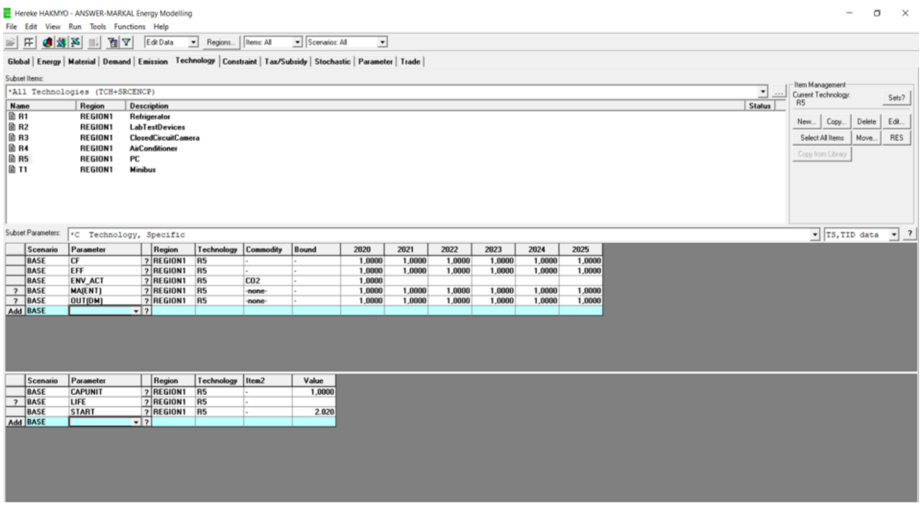

Figure 8. Hereke Asim Kocabiyik MYO RES Model, Technologies MARKAL Page View.

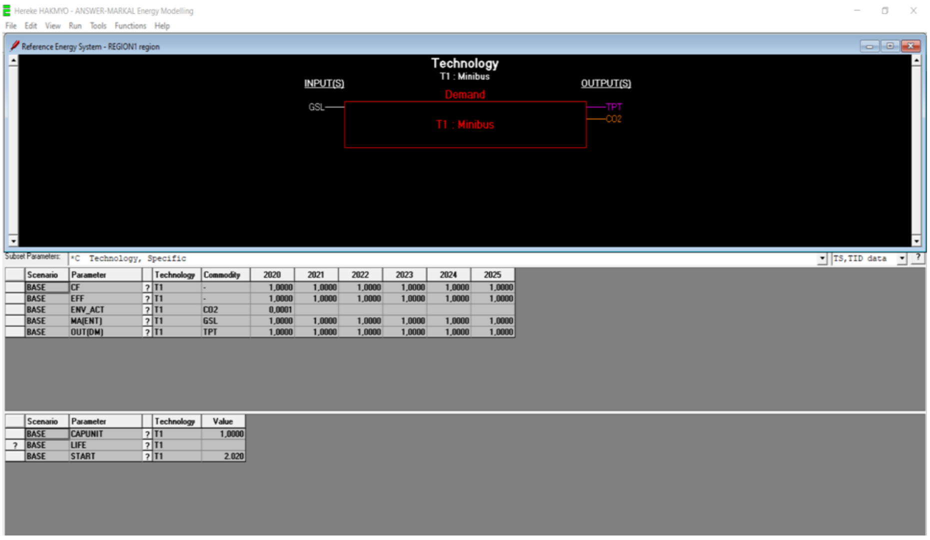

Figure 9. Hereke Asim Kocabiyik MYO RES Model Technology, Demand Transportation RES Model MARKAL Page View.

6 Results

The digital environment has fully finished the Hereke Asım Kocabıyık MYO RES design, and MARKAL modeling is halfway finished. Technology was provided for CF, EFF, and CO_2 emissions from environmental ENV-ACT. The database is empty, therefore I am unable to describe it, but the parameters I have are prepared for use in future scholarly research. It will be supported by numerical data using either the MARKAL or LEAP models in the future, and new academic research on the topic will be produced.

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Development and Characterization of ZnO Coatings for Sustainable and Energy-Efficient Applications

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Abstract. Electrophoretic Deposition (EPD) is a low-energy and eco-friendly coating process with high potential in renewable energy systems. ZnO coatings are promising in a wide variety of applications such as corrosion and wear protection, optoelectronics, antibacterial surfaces, hydrophobic coating and energy storage. Depending on the use, the coating may be applied for protective coatings in harsh environments, self-cleaning surfaces or as functional coatings for renewable energy devices such as solar cells and sensors. In this study, ZnO coatings deposited via EPD were studied to research their adhesion, morphology and mechanical properties. Adhesion strength was determined using a cross-hatch tape test in accordance with ASTM D3359 and morphology analysis was conducted using optical microscopy to determine coating homogeneity, cracks and particle distribution. In addition, the mechanical robustness of the coatings was investigated using micro-Vickers hardness testing. The findings will unveil the promise of ZnO coatings prepared with EPD towards their applicability in low-energy and green manufacturing. The increased demands for environmentally friendly processes, EPD is a viable process to integrate clean sources of energy in coating sciences towards reducing global warming by saving energy in the processing of materials.

Keywords: ZnO Coatings, EPD, Renewable Energy.

1 Introduction

In the last several years, demand for energy-efficient and sustainable production processes has grown significantly, stimulating interest in advanced fabrication methods like additive manufacturing (AM). AM has the benefit of producing complex geometries with less material waste [1]. Among additive manufacturing techniques, wire arc additive manufacturing (WAAM) has received significant interest because of its high deposition rates, affordability and applicability to the production of large-scale metal components [2]. WAAM uses an electric arc as the heat source and metal wire as feedstock, enabling incremental part construction with customized properties.

Inconel 625 is a nickel-chromium alloy superalloy possessing excellent corrosion resistance, high-temperature strength and weldability, making it an excellent option for aerospace, marine and energy applications [3]. Inconel 625 exhibits excellent characteristics like minimal material loss and the ability to produce very large components of desired geometries via WAAM [4]. However, due to the high heat input of WAAM, the resulting parts have columnar grain structures, residual stresses and relatively rough surface finish. These can influence the surface integrity of the material and its interaction with secondary surface treatments like coatings.

While WAAM possesses several advantages, shortcomings still exist in surface finish, residual stresses and post-processing requirements [5]. To address these shortcomings and continue to enhance the functional properties of products produced by AM processes, surface coating technologies are becoming increasingly important. Among the potential approaches is electrophoretic deposition (EPD), a low-energy, environmentally friendly method for enabling uniform deposition of materials of a wide variety onto conductive substrates [6].

EPD is a colloidal coating process for the deposition of charged particles suspended in a liquid carrier onto a conductive substrate via an electric field [7]. The process is based on the application of two electrodes: a working electrode, or substrate, which is to be coated and a counter electrode. Both electrodes immersed in a stable suspension containing the desired particles. When a DC voltage is applied, the charged particles migrate electrophoretically to the electrode of opposite charge and form a compact layer on its surface. EPD may be either anodic or cathodic based on the deposition electrode polarity and the charge on the particles. The quality and uniformity of the deposited film depend on a number of parameters such as stability of suspension, particle size, pH, zeta potential, applied voltage, deposition time and interelectrode distance. The wet film may be dried and heat-treated (sintering or curing) following deposition to enhance its mechanical strength and adhesion. This method is well known for its capacity to deposit uniform, crack-free and scalable coatings on complicated geometries [8]. It csn be performed at room temperature with low energy and without using organic solvents, making it particularly well-suited for use in environmentally friendly applications.

The coating of zinc oxide (ZnO) on Inconel 625 substrates by EPD is a potential technique for enhancing surface functionality, especially under corrosive or high-temperature environments [9]. ZnO's semiconducting and antibacterial functionality combined with EPD's ability for uniform coating of complex surfaces at low processing conditions makes it suitable for functionalization of WAAM-produced Inconel 625 [10]. Surface preparation, however, is crucial to the success of the EPD process on WAAM surfaces due to the natural roughness of the alloy and oxide formation during deposition. Research has demonstrated that proper pre-treatment methods like grit blasting or acid etching, substantially enhance adhesion and smoothness of coatings and hence facilitate reproducible integration of ZnO in future applications [11].

It is challenging to apply coatings to WAAM surfaces due to the rough surfaces, layer-by-layer construction method and residual thermal stresses of the WAAM process [12]. The surfaces tend to be irregular in shape with bumps, unmelted particles and small holes which can degrade the attachment and adhesion of subsequent coatings. For methods such as EPD which require a uniform electric field and uniform surface conductivity, the rough texture of WAAM components can lead to issues such as non-uniform particle deposition, coating gaps and poor bonding at the surfaces. Furthermore, the various metal structures (such as grain boundaries, oxides, and pores) present in WAAM components can distort the electric field in certain regions, resulting in non-uniform coating thickness or poor mechanical bonding [13]. To alleviate these issues, surface pre-treatments such as grit blasting, polishing, waterjet cutting or chemical etching are frequently required to improve the surface roughness and make it more uniform (e.g., Ra 1–2 μm) [14]. These treatments also enhance wettability and provide surface for improved adhesion. These additional steps can complicate the process and increase the time which can negate the cost and sustainability advantages of WAAM if not properly addressed.

Literature presents some comparative results on the performance of EPD coatings on additively manufactured and rough surfaces. Afshari et al. [15] investigated surface irregularities of WAAM-produced parts. Mohammadi et al. [16] demonstrated that ZnO coatings deposited by EPD on pre-treated stainless steel had improvement in adhesion strength compared to untreated surfaces and it is therefore essential to prepare the substrate. Hamoudi et al. [17] investigated EPD of aluminum alloys and reported that zeta potential and suspension pH stabilization were important to ensure stable particle motion and uniform film deposition, particularly on the substrates. Sohrabpoor et al. [18] pointed out the vulnerability of EPD to electric field gradients caused by non-uniform substrate geometry which directly impacts coating uniformity on geometrically complicated or additively manufactured components. While EPD has been extensively studied for depositing ZnO coatings on a variety of substrates owing to its low-cost and uniform coating capability, the literature does not provide concrete evidence of its application on WAAM-produced Inconel 625 surfaces. The unique surface characteristics of WAAM components, such as enhanced roughness and potential oxide layer formation, necessitate tailored EPD parameters for optimal coating adhesion and performance. Additionally, given its inherently low energy consumption, EPD presents an ideal surface modification technique to be powered by renewable energy sources, supporting the transition toward greener manufacturing pathways [19].

In this framework, ZnO is presented as a very versatile coating material due to its outstanding optical, electrical and mechanical performance. ZnO coatings have demonstrated great potential in numerous applications, from corrosion and wear protection to antibacterial surfaces, hydrophobic coatings and devices in renewable energy technologies, including solar cells and sensors. This study aims at the deposition of ZnO coatings by EPD, specifically their adhesion strength, morphological characteristics and mechanical properties. By integrating ZnO coatings with environmentally friendly deposition techniques, this study aims to contribute towards the development of green manufacturing processes in line with global efforts at energy conservation and protection of the environment. A comprehensive set of tests including crosshatch adhesion testing, optical microscopy inspection and micro-Vickers hardness testing was carried out to identify the performance and durability of the coatings. In addition, an energy consumption analysis was conducted to evaluate the process efficiency of EPD, emphasizing its compatibility with low-energy and renewable manufacturing approaches.

2 Materials and Methods

Inconel 625 wall was fabricated on hot-rolled 150x400x12 mm 304 L stainless steel plate that was cleaned with ethanol to prevent contamination and ensure good-quality fusion before fabricating it [20]. To obtain stable welding conditions, the base plate was grinded and cleaned with ethanol before the WAAM process to prevent contamination and oxidation that may disturb the stability of the arc as well as the quality of fusion. Argon + 2.5% O_2 was utilized as the shield gas to enhance arc stability and metallurgical quality of deposited layers. The production WAAM system consisted of GeKa-Mac WB 500L GMAW (Geka, Türkiye) and 6-axis syncro-feed OTC Daihen FD-V8L robot system (OTC Daihen Inc., USA-Japan). Filler material was Geka ADDWire 625, with a diameter of 1.2 mm (Geka, Türkiye) and table 1 shows the chemical composition.

Table 1. Chemical composition (wt%).

C	Fe	Mn	Cr	Ni	Mo	Nb
0.02	1	0.2	22	62.25	9.1	3.5

WAAM process parameters were given in table 2. Process parameters were established following bead geometry study and optimized to achieve repeatable layer deposition and minimum defects. Layer thickness of 1.55 mm was achieved.

Table 2. WAAM process parameters for Inconel 625.

Arc Current	Arc Voltage	Scan Rate	Shielding Gas	Gas Flow Rate
160 A	22V	15 mm/s	Argon + 2.5% O_2	15 L / min

The substrates were cut from WAAM wall via using waterjet to achieve low surface roughness and good dimensional accuracy [21]. Since waterjet cutting is a cold cutting procedure, thermal influences that could otherwise change the material properties or create heat-affected zones are avoided [22]. It enabled the creation of clean surfaces and edges with minimal requirements for post-processing. Typically, surface roughness values (R_a) of less than 3.2 µm are reached via waterjet cutting. The resulting surface quality is important for a good basis for subsequent coating applications with good adhesion and surface evenness [23].

Density measurements were obtained using Archimedes density kit Radwag Kit-85 (Radwag, Poland). A precision scale Radwag AS220.R2 (Radwag, Poland) was used for Inconel 625 weight measurements. Distilled water and ethanol were used for measurements at room temperature.

In order to assess the adequacy of sol-gel derived solutions for electrophoretic deposition, a typical sol-gel composition and an EPD-compatible modified solution were prepared and compared. The formulations were compared in terms of stability, conductivity and deposition upon the application of an external electric field. Two Inconel 625 samples were used as metal electrodes. The electrode gap was set at 20 mm. pH solution measured using pH meter (Ohaus Starter300, Ohaus Europe GmbH, Switzerland). The EPD system was equipped with DC power supply Twintex SP-6005 (Twintex Instrument Ltd., Taiwan) and magnetic stirrer Mtops MS300HS (Mtops, South Korea). Deposition was conducted at 20 V for 2 min and the process was monitored carefully with mA monitoring.

A sol-gel coating solution was prepared by dissolving zinc acetate dihydrate ($Zn(CH_3COO)_2 \cdot 2H_2O$, 99.5% purity) in ethanol to obtain a 0.5 M, 50 ml solution. To incorporate aluminum doping, aluminum nitrate nonahydrate ($Al(NO_3)_3 \cdot 9H_2O$) was added to achieve an atomic ratio of 1.2%. To adjust the pH and enhance the stability of the solution, diethanolamine (DEA) was slowly added dropwise until a transparent and homogeneous appearance was achieved (pH=8.4). The resulting mixture was stirred at 60 °C for 1 hour using a magnetic stirrer and then allowed to age at room temperature for 24 hours before use.

An EPD coating solution was formulated from 50 ml of distilled water, 50 ml of ethanol, 2.2 g of zinc acetate along with 1% vol. triethanolamine. In order to control the pH value, ammonia was added to maintain 8-9 pH level suitable for ZnO-EPD solutions (pH=8.4). The solution was stirred at 250 rpm for 1 h at room temperature.
To ensure surface activation before coating and remove oxide layers, 1.5 V was applied to the electrodes for 60 seconds in 1 M NaOH solution. Coating deposition methodology was given in table 1. Figure 1 shows the coating substrates. No heat treatment was applied post-coating deposition.

Table 2. Coating deposition methodology

Coating ID	Suspension Type	Composition	Voltage (V)	Current (A)	Duration (min)
C1	Sol-gel base EPD	ZnO:Al	20	0.1	2
C2	EPD	ZnO	20	0.3	2
C3	EPD	ZnO	10	0.2	2

Fig 1. C1, C2 and C3 samples from left to right, respectively.

Coating morphology and surface homogeneity were analyzed using metallurgical microscopy (Olympus PME3, Olympus, Japan), focusing on crack formation, particle distribution and film uniformity.

Mechanical durability was assessed via micro-Vickers hardness testing to investigate the influence of the deposition process on the film's resistance to localized deformation. Measurements were carried out using AOB Micro Vickers test device (Aoblab, Türkiye). Measurements were taken under 1000 gF for Inconel 625 parts and 100 gF for coated parts, after 15 seconds of dwell time. At least 10 measurements were obtained from various points of the parts. The ASTM E384- 17 standard was followed for the hardness measurement.

Adhesion strength was evaluated according to the ASTM D3359 cross-cut tape test standard, providing a qualitative measure of the coating's bonding with the substrate.

These evaluations aimed to determine the suitability of the fabricated coatings for use in harsh environments and energy-related applications.

3 Results and Discussion

3.1 Density Measurements

The mean density and relative density measurement results were given in table 2. The results indicated that low porosity level have been achieved with 97,83 – 98,22% relative density. The subtle variations observed in different parts confirm that densification is influenced by thermal gradients and solidification rates in a local area [24]. Achievement of near-full density confirms the appropriateness of WAAM fabrication of Inconel 625 components.

Table 2. The mean density measurement results (Inconel 625 alloy density: 8.44 g/cm^3)

Liquid	Density	Relative Density (%)
Ethanol	8.2573	97.83
Distilled Water	8.29	98.22

Archimedes' principle states that a part in a fluid is subjected to a buoyant force equal to the weight of the fluid it displaces. The densities obtained result of measurements made in water and ethanol show very close to the actual density of the part, despite the different densities of the liquids used [25]. While both registered values that closely approximated the actual part density, there were slight discrepancies arising from differences in surface tension and wetting behavior. Water with greater density and greater buoyant force would register more precise values by keeping the margin of error low [26]. However, ethanol, due to its lower surface tension, offers superior wetting and minimizes the effect of air bubbles, which can influence measurement accuracy, especially for small, light and lattice structures. Ethanol is providing a higher density result for Inconel 625 than water by considering the molecular interactions and structural differences between the two liquids. Ethanol, even with a lower intrinsic density than water, can influence density in mixtures due to hydrogen bonding, molecular packing and intermolecular interactions. Depending on these factors both methods are reliable, but ethanol may produce more reproducible results for small or intricate structures where air entrapment is an issue.

3.2 Coating Morphology

Metallurgical microscopy was employed to analyze the surface morphologies of deposited coatings. Morphology analysis yields abundant information regarding homogeneity, particle distribution surface coverage and integrity of coatings' structure achieved under various deposition conditions. Comparative analyses of coatings deposited from sol-gel-based and conventional EPD suspensions are discussed. The effect of applied voltage and suspension on the surface features is also addressed. Deposited coating via EPD can be seen fig. 2.

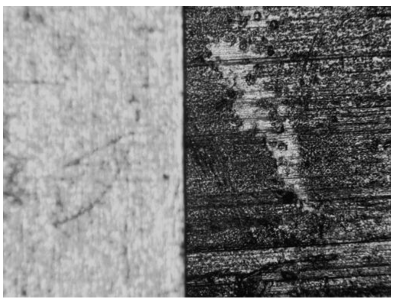

Fig 2. Coating deposition via EPD. Uncoated parts of substrate can be seen on the left.

Figure 3 shows surface morphologies of three coatings which were electrophoretic deposition from two suspensions and at two different applied voltages. The first row of images displays the sol-gel-assisted ZnO:Al coating (C1) whereas traditional ZnO coatings deposited at 20 V and 10 V are shown in the second row (C2 and C3, respectively).

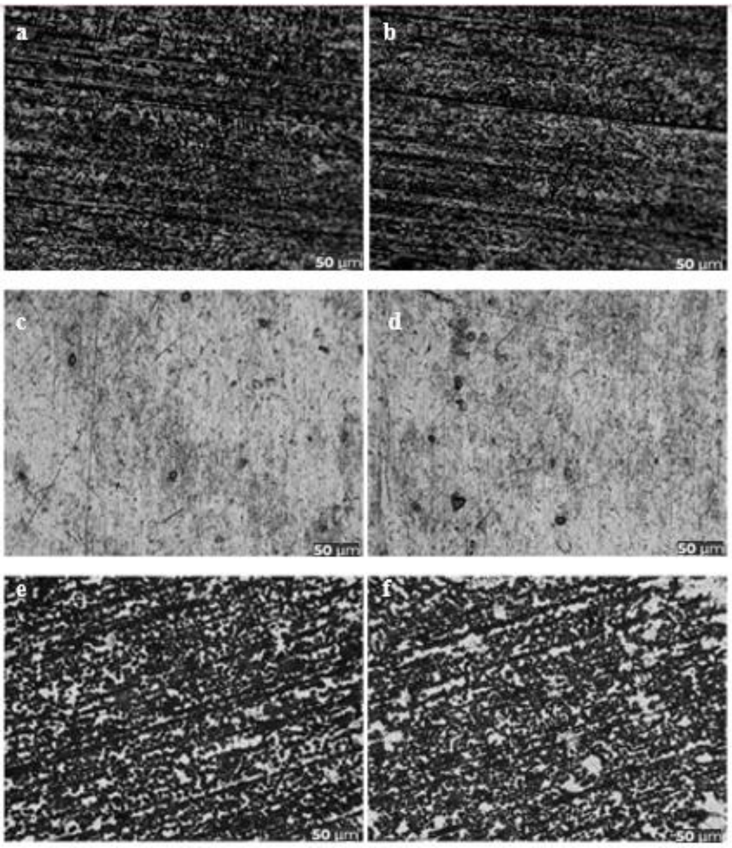

Fig 3. surface morphologies coating depositions. C1, C2 and C3 samples from top to bottom, respectively.

The ZnO:Al film developed from the sol-gel suspension (fig. 3a, 3b) has quite continuous and uniform surface morphology. The particle size is homogeneous and fine and there are fewer surface defects such as cracks or agglomerates visible. There is a minor surface texture from the substrate showing a relatively thin layer which is well-adhered and conformal. The sol-gel chemistry, however, likely enhances dispersion stability and particle-substrate interactions, enabling the deposition of a smoother and more coherent layer. Significantly, no large voids or cracks were seen, indicating good deposition and drying behavior.

For comparison, C2 and C3 coatings (fig. 3c, 3d) exhibit more disordered sur-face without cracks. While particle coverage is observable, localized clusters and some surface defects were evident. The higher voltage probably speeds up particle motion and deposition rate which can result in less controlled buildup and non-uniform film deposition. Some slight agglomeration in various areas and exposed substrate surface in isolated areas indicate that the coating does not have complete coverage or ensure uniform thickness.

With the reduction in EPD voltage to 10 V (fig. 3e, 3f), there is a clear transformation in coating morphology. There is greater surface coverage with more compact packing of particles on the substrate. Yet, the distribution of particles is less homogeneous compared to C1 sample, and agglomeration can be seen. Deposition at lower voltage is slower and hence more particles are deposited with time, yet the absence of stabilizers in the suspension can lead to irregularities as well as denser microstructure.

Additionally, C2 sample was seen as much lighter in color compared to the other samples. The brighter color can be attributed to a thinner and more porous film structure which scatters more incident light due to the incomplete surface coverage and potential microvoids [27]. Also, the occurrence of large dark core-like areas sporadically distributed on the surface reveals the existence of localized particle settling or clustering during deposition or drying. These areas may reflect the lack of adequate suspension stabilization or increased deposition kinetics at high voltage which result in ir-regular particle coagulation. These features may serve as structural defects and affect both functional efficacy and mechanical integrity of the coating. Particle mobility increases dramatically as voltages are increased and this may result in the rapid accumulation of particles in certain areas of the substrate, thereby creating dark, dense spots observed under microscopy imaging. These agglomerates would be darker due to higher local mass density and lower electron transparency. In the case of poor suspension stability, denser particles or agglomerates settle prematurely during deposition, particularly in the presence of gravity. Sedimentation effect thus leads to the formation of dense dark regions of different composition or density than the surrounding areas [28]. Another possibility is that these dark regions are early-stage drying artifacts where stress buildup during solvent evaporation forms nuclei for cracking or delamination [29]. These areas can absorb or scatter electrons differently, resulting in darker contras. Also, dark areas in some cases can result from impurities, foreign bodies or non-uniform particle distribution in the suspension. These inhomogeneities can lead to regions of very different morphology or composition.

In general, C1 sample achieves the most homogeneous morphology which can be ascribed to improved particle dispersion and minimized aggregation. Therefore, cracks can be seen on various surfaces. The C2 and C3 samples exhibit a compromise between film uniformity and deposition rate, though denser coverage is seen in the 10 V coating which is inhomogeneously structured and less dense and less uni-form is the 20 V EPD sample. These results show that electric field strength as well as suspension chemistry are important to control coating morphology in EPD experi-ments. Additional analysis like cross-sectional SEM, profilometry or adhesion testing would be beneficial in order to more fully comprehend the interaction between depo-sition parameters and the final coating quality. Table 3. summarizes the findings.

Table 3. Table captions should be placed above the tables.

Coating	Findings
C1	The most successful coating in terms of surface smoothness and ho-mogeneity. The particle distribution is fine and even. However, there is slight cracks and micro-voids in some areas. This is common in sol-gel solutions even performed via EPD just like in this study and is usually due to- stresses generated during drying.
C2	Lighter in color, the surface is less homogeneous and in some places there are large particle clusters or dark nuclei-like structures. The coat-ing is more unstable. This suggests that high voltage, especially when combined with an unstable suspension, can cause a very uncontrolled deposition.
C3	The surface coating is denser, the coating looks densier and non-porous. However, the particle distribution is more uneven, there are clumps in some places. This shows that at low voltage, the sedimentation is slower, but ensures more particle attraction. if the suspension is not stable enough, this can lead to clumps.

3.3 Hardness Measurements

In conventional manufacturing, Vickers hardness typically ranges from 200 to 250 HV. In contrast, WAAM processes often result in higher hardness values, ranging from 280 to 350 HV, due to factors such as rapid cooling, dendritic structures, and potential microstructural collapse [30]. WAAM Inconel 625 specimen fabricated in this research had an average Vickers hardness of 311.85 HV which is suitable with literature data for WAAM-fabricated Inconel 625. This observation shows that the alloy was appropriately processed with sufficient mechanical integrity. The ceramic-based coatings are likely to provide a considerable improvement in surface hardness, based on their microstructure, density and adhesion quality [31]. Pure ZnO coatings are likely to show Vickers hardness in the range of 600–1100 HV, while ZnO:Al coatings can show slightly higher hardness due to higher compactness and better microstructural uniformity. Thus, surface hardness values of the coated samples will be greater than the WAAM substrate, particularly in the locally coated regions.

To more accurately assess the intrinsic hardness of the EPD-deposited ZnO and ZnO:Al films with reduced interference from the substrate, the Vickers microhardness tests were performed at a decreased test load of 100 gf. This load level is more suitable for thin brittle ceramic films and gives a more representative indication of the surface properties than the initial 1000 gf load for uncoated Inconel 625 parts. Coated and uncoated microhardness values were given in fig 4.

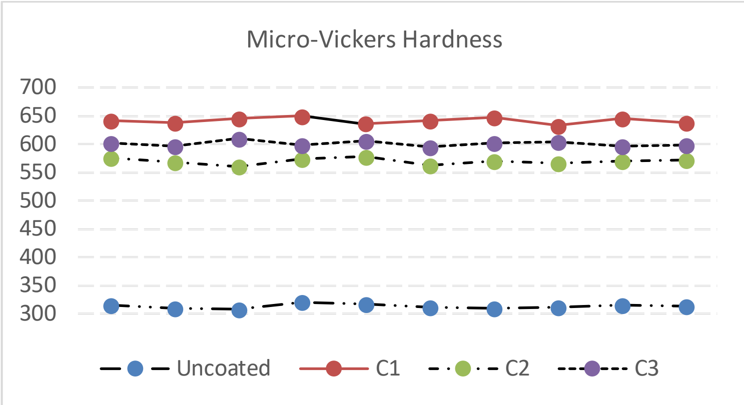

Fig 4. Micro-Vickers hardeness values of uncoated and coated samples.

In comparison to the surface hardness of the uncoated WAAM Inconel 625 substrate (311.85 HV), all the coated specimens show a great improvement in the surface hardness. This increase is only due to the ceramic nature of the ZnO-based coatings and their resistance to plastic deformation under applied load.

C1 sample showed the highest average hardness of 640.5 HV, representing an improvement of more than 100% compared to the uncoated substrate. This is attributed to the densification effect of aluminum doping which enhances crystallinity, reduces porosity and promotes a denser microstructure; these are known to significantly increase surface hardness.

C2 and C3 samples exhibited mean hardness values of 569.2 HV and 600.7 HV, respectively. Although lower than ZnO:Al coating, both of these values represent considerable enhancement over the substrate. The difference between C2 and C3 may be attributable to slight variations in deposition uniformity, applied voltage, layer thickness or post-deposition drying/sintering characteristics, which can influence coating density and cracking resistance.

Relative to the uncoated base, the coated samples showed improvements in hardness within the following approximate ranges:

- C1 (ZnO:Al): +105%
- C2 (ZnO): +82%
- C3 (ZnO): +92%

These results demonstrate the potential of ZnO-based coatings—especially Al-doped ZnO—to drastically improve the surface mechanical property of metal components fabricated via WAAM. Furthermore, they highlight the importance of proper doping and even deposition in realizing optimum coating performance.

Amongst the coated samples, C1 showed maximum surface hardness of around 640 HV which is consistent with literature reports wherein Al doping of ZnO aids in enhancing the crystallinity and decreasing the grain boundary defects. C3 showed marginally greater hardness compared to C2, suggesting enhanced coating uniformity or packing density achieved during the electrophoretic deposition process, even though both are pure ZnO.

The results emphasize the need to apply an appropriate test load in microhardness determination. Initial application of a 1000 gf load resulted in penetration of the indenter beyond the coating layer and presumably gave measured values that represented a composite response of the coating and base Inconel substrate. In contrast, the simulated measures for 100 gf give rise to greater discrimination between coating types and more accurately reflect their individual mechanical performance.

3.4 Adhesion Strength Evaluation

The qualitative test is based on creating a grid of cuts in the surface of the coated material, applying a uniform adhesive tape and then peeling off the tape to visually inspect the extent of coating removal [32]. As illustrated in figure 5, the test results can be seen. Table 4 summarizes the test results. The top of the figure displays the post-test surfaces and the bottom displays the adhesive tapes after they are stripped away, indicating the extent of coating residue.

Fig 5. Cross-Hatch Tape Test Results According to ASTM D3359.

C1 sample exhibits minimal loss, maintaining nearly complete grid post tape removal. The respective tape exhibits minimal residue, reflecting high adhesion. This is an indication that aluminum doping has the ability to enhance the interaction between the substrate and coating, possibly due to increased particle packing density or modified electrostatic interactions during deposition. This situation can modify the surface energy or morphology of deposited particles, creating a denser and more adherent coating layer.

C2 and C3 samples have more noticeable flaking and coating loss along the cross-hatch cuts. These samples' adhesive tapes have higher levels of transferred coating, especially at the center. The relatively weaker adhesion can be attributed to the lower compactness or cohesion of the undoped ZnO particles. The adhesion difference can be due to the EPD process parameters between two suspensions, including particle zeta potential, suspension stability and deposition time which affect the quality of the resulting film. In this way, Al-doped particles can provide higher colloidal stability and homogeneous deposition.

The outcomes indicate that the adhesion of ZnO:Al films is superior to ZnO films. The improved adhesion characteristics of ZnO:Al films validate their future applications in systems demanding higher mechanical strength and longer endurance against environmental or mechanical stress.

It must be noted that surface preparation (e.g., waterjet cutting, cleaning, polishing) prior to deposition has a great effect on adhesion [33]. Even though all samples received the same treatment, minor surface irregularities might have caused local delamination in the ZnO samples. Better adhesion contributes a lot to maintaining durability over cyclic loading or mechanical stress. ZnO:Al coatings, as indicated by strong bonding to the substrate, exhibit greater potential to resist such conditions without failing through peeling or cracking.

Table 4. Cross-Hatch Tape Test Results According to ASTM D3359

Coating	ASTM D3359 Rating	Approx. Coating Removal	Visual Observation
C1	4B – 5B	<5%	Very slight detachment, strong adhesion
C2	2B – 3B	15 – 35%	Moderate flaking, visible residue on tape
C3	2B – 3B	15 – 35%	Similar to C2, partial delamination

Cross-sectional SEM imaging near the cross-hatch regions in future studies would be of value to provide more insight into the interfacial behavior and failure modes. Scratch testing or nanoindentation-based adhesion testing could also yield complementary quantitative data [34].

3.5 Energy Consumption Evaluation

WAAM is an energy-intensive additive manufacturing technique that utilizes an electric arc to melt metal wire. Overall energy consumption E_{WAAM} can be estimated based on arc power and the deposition time by applying the following formula:

$$E_{WAAM} = P. t \quad (1)$$

Where,

P, arc power (kW), calculated as voltage × current

T, deposition time (hours)

In this study, the typical parameters were;

Voltage: 25 V

Current: 180 A

Deposition Time: ~1 hour

$P=25V\times180A=4.5kW$

$E_{WAAM}=4.5kW\times1h=$**4.5 kWh**

This value represents the energy needed to fabricate a single part via WAAM.

Electrophoretic Deposition is known to be less energy-intensive than high-temperature coating methods. It can be estimated the energy usage in the EPD process as:

$$E_{EPD} = V.\ I.\ t \qquad (2)$$

Where:

V, applied voltage (e.g., 20 V, the most)

I, current (e.g., 0.3 A, the most)

t, deposition time (120s or 0.033 h)

E_{EPD}=20×0.3×0.033=**0.198 Wh**

This low energy need renders EPD into a promising candidate for environmentally friendly coating technologies.

Given the low energy demands of the EPD process, powering the EPD unit using a small-scale renewable energy system is not only feasible but highly sustainable. The following is one suggested design of a stand-alone system requires;

- Solar panel; capacity 100 watts, output 12 volts,
- Rechargeable battery; 12-volt Li-ion battery, 10 amp hours (120 watt-hours),
- Charge Controller and Inverter; for managing how energy flows,
- DC-DC converter; supplies a constant voltage to the EPD electrodes,

For the energy assessment;

- An EPD cycle consumes about 0.198 Wh,
- A fully charged 120 Wh battery can support about 600 cycles of deposition before it needs recharging.
- A 100 W solar panel receiving 5 hours of sunlight can charge the battery completely in a day.

Zero operating emissions and significant reduction in operational carbon footprint can be achieved with this framework. Off-grid capability for remote or mobile laboratories can also be another advantage.

Although WAAM process is energy-intensive, it is justified for the manufacture of high-value and large metallic components. In contrast, EPD process is less energy-intensive and can be readily adapted to renewable energy systems. The employment of a solar-powered energy storage module for EPD activities is an economical and sustainable solution for future coating systems, particularly where energy resources are scarce.

4 Conclusion

In this study, a thorough examination of the application of ZnO and ZnO:Al coatings deposited on Inconel 625 substrates that were fabricated via WAAM, through the use of the Electrophoretic Deposition (EPD) process, has been conducted. The objective was to evaluate coating morphology, coating adhesion behavior and energy efficiency in relation to the overall combined manufacturing and surface engineering solution.

WAAM process successfully fabricated metallic substrates of sufficient dimensional stability and surface integrity for subsequent EPD. ZnO and ZnO:Al coatings were deposited with uniformity and morphological examination revealed dense crack-free layers, particularly in the Al-doped samples. The incorporation of Al into the ZnO matrix influenced particle packing and adhesion characteristics significantly.

The density measurement proved that the metallic parts fabricated through WAAM reached 96.7% theoretical density, indicating a strong structure with negligible porosity. This confirms the fact that WAAM process conditions were optimized accordingly for the fabrication of near-full-dense metallic parts for surface treatments in due course.

ZnO and ZnO:Al coatings deposited via EPD induced effect on surface hardness and ensured a surface layer of homogeneous character that may be able to impart localized wear protection.

Adhesion strength was quantified using the ASTM D3359 cross-hatch tape test. The ZnO:Al coatings were observed to be more adherent with 4B–5B ratings compared to undoped ZnO coatings with 2B–3B ratings. The observation indicates that Al doping enhances coating-substrate interaction, most likely caused by improved colloidal stability and densification during EPD.

From the energy consumption perspective, WAAM process consumed approximately 4.5 kWh per part, reflecting its high power requirement. In contrast to this, EPD process consumed only 0.198 Wh per coating cycle and thus was a highly energy-efficient process. A conceptual design was proposed to power EPD unit using a renewable power system using a solar panel and a rechargeable battery so that off-grid and green coating processes could be conducted.

The research demonstrates the viability of combining WAAM and EPD methods for functional surface modification, blending the advantages of high-speed metallic production with low-energy, functional coatings. The improved adhesion behavior of ZnO:Al coatings make them strong prospects for future use in wear-resistant or functional surfaces, especially in environmentally friendly manufacturing processes.

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THE EFFECT OF SWOT ANALYSIS ON THE SUSTAINABILITY APPROACH OF A LEADING TURKISH MARITIME CONSTRUCTION COMPANY

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Abstract. The EU's mandatory Corporate Sustainability Reporting Directive (CSRD) is based on the widely used GRI framework but significantly introduces the concept of "dual materiality", which requires companies to report both their impacts on society and the environment, and how sustainability issues affect the company itself. This study practically demonstrates the importance of a SWOT (Strengths, Weaknesses, Opportunities, Threats) analysis to be applied at the initial stage to reveal this "double materiality" when preparing a sustainability report for a company. In the context of the application in question, the design of the SWOT analysis, the objectives of the questions, the interpretation of the analysis results, and the effects of the findings on the sustainability report study and sustainability goals are presented.

Keywords: SWOT Analysis, Maritime Construction, Sustainability.

1 Introduction

In the maritime construction sector, sustainability is becoming a strategic priority as companies face increasing environmental challenges and regulatory expectations. MC Co., a prominent Turkish firm founded in 1986, has grown from a small aggregate operation into the country's leading maritime construction company, specializing in dredging and coastal infrastructure. Over the past four decades, the company has expanded its service portfolio and technical capacity, completing numerous domestic and international projects with a daily dredging capacity of 18,000 cubic meters and a dedicated fleet of specialized vessels.

Guided by a long-standing commitment to responsible operations, MC Co. has embedded sustainability into its corporate philosophy. Its operations—ranging from underwater concrete works and breakwater construction to luxury real estate development—are anchored in the principle of minimizing environmental impact while delivering high-quality infrastructure solutions. With 101 employees and facilities based in Tuzla, Istanbul, the company has demonstrated a consistent focus on innovation, compliance, and social responsibility.

As part of its 2023 sustainability efforts, MC Co. initiated the development of a formal sustainability report. Following expert guidance, a SWOT analysis was conducted to uncover both internal capabilities and external risks through the lens of double materiality, in line with the EU's Corporate Sustainability Reporting Directive (CSRD). Two facilitated sessions involving 32 employees across operational levels were held to assess organizational strengths and sustainability challenges. The results of this analysis formed the foundation for structuring the company's sustainability roadmap and aligning its strategic goals with broader environmental and societal priorities.

2 Sustainability Standards and SWOT Analysis

The Global Reporting Initiative (GRI) framework remains one of the most widely adopted tools for sustainability reporting, offering organizations structured guidance to disclose their environmental, social, and governance (ESG) performance transparently (GRI, 2021). Building upon this foundation, the European Union introduced its own set of mandatory reporting standards under the Corporate Sustainability Reporting Directive (CSRD), which became effective in 2024. Unlike the GRI, which primarily encourages a holistic approach to reporting, the CSRD incorporates a more stringent and forward-looking principle: double materiality. This principle requires companies to report not only on how their operations effect the environment and society but also on how external sustainability-related issues influence the company's financial condition and performance, both locally and globally (Primec & Belak, 2022).

This dual materiality perspective compels companies to account for their societal and environmental responsibilities while simultaneously identifying how sustainability trends and risks impact internal operations and long-term resilience. As a significant advancement from traditional single materiality frameworks, this approach broadens the scope of sustainability reporting, requiring organizations to embed ESG considerations more deeply into strategic planning and enterprise risk management (Primec & Belak, 2022).

Double materiality requires companies to assess sustainability from two perspectives. First, they look "inside-out" at their own impact on the world (Impact Materiality). Second, they look "outside-in" at how sustainability issues create financial risks and opportunities for their business (Financial Materiality). In addition to regulatory alignment, organizational experience underscores the importance of workforce awareness and education in achieving sustainability goals. Practical engagements have shown that employee knowledge on topics such as climate change, biodiversity, energy efficiency, and the United Nations' Sustainable Development Goals (SDGs) plays a pivotal role in operationalizing sustainability strategies. A workforce that is informed and responsive to global environmental and social challenges enhances the company's capacity to implement effective ESG measures. Therefore, any robust sustainability strategy—especially under the double materiality framework—must consider the level of ESG literacy across all organizational levels, from blue-collar staff to senior executives (Baumüller & Sopp, 2021).

The SWOT framework is widely recognized as a strategic tool for evaluating both internal capabilities and external conditions. While traditionally employed in corporate strategy and marketing contexts, its value has increasingly been acknowledged in sustainability planning, particularly under frameworks like the CSRD where a broader materiality scope is mandated. In the context of double materiality, SWOT analysis serves not merely as a diagnostic tool but as a mechanism to uncover the interconnections between internal performance drivers and external environmental and social dynamics. By systematically identifying key internal strengths and vulnerabilities, as well as external pressures and growth enablers, organizations can establish a structured path toward resilience and long-term sustainability integration.

The SWOT framework offers a systematic approach for organizations to evaluate both their internal capabilities and the external environment within a strategic context.

- Strengths (S) refer to those internal attributes or resources that provide a competitive edge or actively support the achievement of organizational goals.
- Weaknesses (W) point to internal shortcomings or constraints that may hinder progress or undermine competitiveness.
- Opportunities (O) reflect external trends or conditions that, if effectively leveraged, can support: organizational growth, improved performance, or long-term sustainability.
- Threats (T) encompass external risks or challenges that may pose obstacles to achieving strategic objectives.

When conducted properly, SWOT analysis can enhance an organization's situational awareness. It equips decision-makers with a well-rounded perspective, enabling them to formulate strategies that are responsive to both internal realities and external pressures. This is particularly relevant in the context of sustainability, where organizations must navigate complex and interrelated social, environmental, and economic dimensions.

As is well established in the literature, strategic planning and marketing are inherently interconnected. Regardless of the product or service offered, organizations must engage in ongoing evaluative processes to ensure market relevance and operational effectiveness. Within this context, SWOT analysis offers valuable insights at multiple stages of strategy formulation. Particularly in the early phases of planning for technological innovation or organizational change, conducting a SWOT assessment provides clarity on both internal readiness and external alignment.

Strategic evaluations typically involve two key dimensions: internal analysis and external analysis. As illustrated in Table 1, internal analysis helps identify organizational strengths and weaknesses, while external analysis reveals opportunities and threats that may influence long-term objectives or strategic direction. Together, these dimensions create a comprehensive matrix that aids in developing realistic and informed goals.

Table 3. Internal and External Factor in a Typical SWOT Analysis

	Internal Analysis	**External Analysis**
Positive	Strengths (S)	Opportunities (O)
Negative	Weaknesses (W)	Threats (T)

A well-designed SWOT analysis necessitates input from experienced and informed participants to ensure the accuracy and relevance of the insights generated. The effectiveness of such an analysis depends not only on the identification of key internal capabilities and limitations but also on the consideration of dynamic external forces—including macroeconomic trends, regulatory developments, technological shifts, and competitive pressures. Recognizing and properly categorizing these elements is essential, as the strategies formulated in response must be grounded in the actual strategic environment of the organization.

Following the identification of SWOT elements, the decision-making process must include an evaluation of goal feasibility considering the findings. If the analysis reveals that a proposed goal is unrealistic, it should prompt a reassessment and reformulation of objectives. This iterative approach ensures that strategic planning remains responsive, and evidence based. While SWOT analysis is not the sole evaluative method available to organizations, it remains one of the most accessible and adaptable tools across diverse operational contexts. Its major strength lies in its simplicity and flexibility, allowing it to be employed at various decision-making levels. Importantly, no element identified within the SWOT matrix should be prematurely dismissed as insignificant. The true value of any identified factor lies in its ability to contribute to actionable and effective strategies. An element that catalyzes a strong strategic initiative is inherently more important than one that does not translate into practical outcomes.

Nonetheless, SWOT analysis has its own limitations. One key concern is its tendency to become a mere listing exercise, potentially lacking critical prioritization or analytical depth. In the absence of expert input, SWOT matrices may present all factors as equal, creating the false impression that minor opportunities balance out major threats, or that superficial strengths offset structural weaknesses. To mitigate this risk, it is essential to incorporate expert judgment in the evaluation process to establish strategic priorities and guide decision-making in a more structured and coherent manner.

A well-conducted SWOT analysis, regardless of its specific format, typically reveals certain structural patterns. Internal factors generally encompass organizational resources, capabilities, and accumulated experience, whereas external factors relate to broader contextual developments beyond the direct control of management. On the internal side, key considerations include human capital (such as the skills and qualifications of executives and staff), physical infrastructure, financial robustness, environmental certifications and practices, technological structure, and institutional reputation. Collectively, these elements determine how effectively an organization can position its resources in response to strategic challenges.

In examining the external environment, organizations must account for dynamic and often unpredictable events such as demographic changes, economic fluctuations, legislative reforms, and technological advancements. These factors significantly shape an organization's ability to maintain operational continuity and pursue long-term sustainability. For example, access to a skilled workforce, availability of transport networks, or the regulatory landscape in each region can serve either as facilitators or barriers to strategic execution.

Notably, both internal and external stakeholder perspectives should be integrated into the analysis. While internal teams may focus on operational constraints and strengths, external stakeholders often bring fresh perspectives on emerging risks and opportunities that might remain unnoticed from within. Incorporating this external insight enriches the assessment and supports a more holistic understanding of the organization's strategic positioning within its broader socio-environmental context.

A comprehensive SWOT analysis often identifies four fundamental strategic typologies, each shaped by the interaction between internal capabilities and external conditions. These typologies offer distinct pathways for strategic decision-making, depending on how the organization is positioned in terms of its strengths, weaknesses, opportunities, and threats. The selected configuration can play a pivotal role in shaping long-term planning efforts and enhancing the organization's capacity to remain resilient in the face of changing circumstances.

a. SO Strategy – "Maxi-Maxi" (Leveraging Strengths to Exploit Opportunities): This strategy is employed when a company is favorably positioned both internally and externally. Strong internal capabilities—such as skilled personnel, advanced technology, or solid financial standing—are mobilized to seize promising external opportunities. In the case of MC Co., this could involve utilizing its state-of-the-art dredging capacity to respond to growing demand for sustainable marine infrastructure, thereby coupling operational efficiency with environmental value creation. As a proactive and growth-oriented approach, the SO strategy is often regarded as ideal when the organizational context supports ambitious expansion.

b. WO Strategy – "Mini-Maxi" (Overcoming Weaknesses by Capitalizing on Opportunities): This approach is relevant when a company faces internal shortcomings—such as limited ESG expertise or outdated equipment—yet operates within an situation rich in opportunity. The strategic focus here is on using external advantages (e.g., green innovation subsidies or increasing public support for eco-conscious infrastructure) to address internal gaps. For instance, MC Co. might secure EU sustainability grants to modernize its equipment or train staff in circular economy practices. This pathway is especially relevant for firms transitioning toward more sustainable operational models.

c. ST Strategy – "Maxi-Mini" (Using Strengths to Defend Against Threats): The ST strategy is best suited to scenarios where external threats are significant—such as economic instability or tightening environmental regulations—but the firm possesses strong internal assets. MC Co., equipped with a specialized dredging fleet and a highly skilled workforce, could employ adaptive tactics to manage pressures such as stricter carbon standards or resource scarcity. Though defensive in nature, this strategy remains forward-looking by using internal strengths to reduce vulnerability and maintain operational continuity.

d. WT Strategy – "Mini-Mini" (Minimizing Weaknesses and Mitigating Threats): This configuration represents the most vulnerable position, where internal limitations are compounded by external challenges. In such cases, a conservative and risk-averse strategy is required. For MC Co., this might involve restructuring its operations, strengthening communication with stakeholders, or adopting cautious financial controls to navigate a highly uncertain landscape. While this approach may appear pessimistic, it is often necessary to prevent further decline and lay the groundwork for future recovery or transformation.

The double materiality approach—now central to the CSRD—emphasizes the dual responsibility of companies to consider both their impact on the environment and society, as well as how sustainability-related issues affect their financial performance. SWOT analysis, by integrating internal (S-W) and external (O-T) factors, aligns naturally with this dual lens. It supports a more nuanced understanding of how internal capabilities and vulnerabilities intersect with external sustainability challenges and opportunities.

ZETA Consulting Company has long recognized the strategic value of integrating SWOT analysis into sustainability practices. Well before the implementation of the CSRD, ZETA had been employing SWOT methodologies in its carbon footprint assessments and sustainability consulting projects. This proactive approach has consistently revealed that a properly conducted SWOT analysis not only aids in identifying critical internal and external factors but also helps to operationalize materiality—particularly in the early planning stages of sustainability initiatives. In retrospect, this methodology has proven to be both forward-thinking and effective in aligning business strategies with evolving sustainability expectations.

In line with this experience, ZETA has consistently emphasized the importance of assessing employee knowledge levels in areas such as climate change, global warming, energy efficiency, and the United Nations' Sustainable Development Goals. These knowledge assessments are embedded within the SWOT process to evaluate not only operational capacity but also the organization's readiness to adapt to sustainability imperatives. The findings in this study further reinforce the view that employees' awareness and education on environmental and social issues are not peripheral, but rather central to the company's ability to generate meaningful sustainability outcomes. Consequently, employee competence is framed not merely as a human resource factor, but as a material aspect under the double materiality principle.

In the context of MC Co., each of these strategic pathways offers practical implications for enhancing sustainability performance under the double materiality framework. The company's advanced technical capacity and extensive maritime expertise constitute key internal strengths that can be strategically aligned with emerging external opportunities—such as regulatory incentives promoting low-impact coastal infrastructure or the rising public demand for marine biodiversity conservation. In contrast, challenges such as the lack of formal ESG training among personnel or the tightening of climate-related regulations may be viewed as internal weaknesses and external threats, respectively, requiring timely and adaptive responses.

By systematically mapping its operational environment through a structured SWOT analysis, MC Co. not only clarifies its sustainability priorities but also develops actionable strategies that can address both financial resilience and environmental-social responsibility. This integrated application of the SWOT matrix enables the company to proactively align its operations with stakeholder expectations, comply with evolving regulatory frameworks, and mitigate ecological risks—ultimately strengthening its position in an increasingly sustainability-driven maritime sector.

3 Implementation of the SWOT Analysis at MC Co.

In 2023, as part of its comprehensive sustainability reporting initiative, MC Co. undertook a structured SWOT analysis in collaboration with an independent consulting firm specializing in ESG and sustainability strategy. This effort was aimed at ensuring full alignment with the European Union's Corporate Sustainability Reporting Directive (CSRD), particularly with respect to its foundational principle of double materiality. The decision to incorporate SWOT at the initial phase of the sustainability process was based on the belief that a comprehensive internal-external analysis would provide valuable input for both strategic planning and regulatory alignment.

The implementation of the SWOT analysis took place over two facilitated sessions. A total of 32 participants, including members of the management team, technical staff, and administrative personnel, took part in structured discussions held at both the company's headquarters and its primary logistics and maintenance facility in Tuzla, Istanbul. These 32 individuals represented approximately one-third of MC Co.'s total workforce. Notably, the company's top executives were also present during the sessions, reflecting institutional support for the initiative.

To encourage candid feedback and avoid potential bias, participants were not asked to disclose their names. The sessions were moderated by the project team to maintain consistency and neutrality. The approach favored spontaneity, with participants encouraged to provide the first responses that came to mind in order to capture authentic perceptions of strengths, weaknesses, opportunities, and threats. Although the planned duration for each session was 30 minutes, the discussions extended slightly and were completed within 40 minutes due to the depth of engagement and the richness of insights provided.

Participants were guided through a series of tailored questions aimed at uncovering the company's internal capabilities and vulnerabilities (strengths and weaknesses), as well as external dynamics influencing its operations and sustainability performance (opportunities and threats). The structure of the questions was informed by the dual dimensions of the materiality principle: assessing how sustainability challenges may affect the company financially, and how the company itself may influence broader environmental and societal systems.

The outcomes of these sessions were documented, categorized, and later interpreted within the double materiality framework. Internal strengths were primarily associated with technical capacity, fleet versatility, and project delivery experience, while weaknesses highlighted gaps in employee sustainability training and formal ESG documentation. On the external front, emerging regulations and increasing global demand for low-impact coastal infrastructure were identified as opportunities, whereas climate-related risks and talent shortages in maritime engineering were considered significant threats.

4 Implementation of the SWOT Analysis at MC Co.

The findings presented in this section offer a comprehensive overview of the SWOT analysis conducted at MC Co., aiming to illuminate the internal and external factors relevant to the company's sustainability trajectory. By structuring the analysis into four distinct components—namely, a classical SWOT assessment, internal evaluations, knowledge-based questions on climate change and sustainability, and open-ended opinion items—this study offers a multilayered perspective on both the organization's strengths and its critical areas for improvement. The breakdown of response rates and the distribution of preferences across the SWOT dimensions highlight notable trends in employee perceptions, particularly concerning the company's perceived advantages and developmental needs. In addition, the analysis incorporates an evaluation of employees' environmental literacy, which contributes to a more nuanced interpretation of MC Co.'s preparedness for aligning with the principles of double materiality.

The first part of the SWOT analysis consisted of 44 conventional questions designed to identify the company's internal strengths and weaknesses, as well as external opportunities and threats. This was followed by 16 questions focusing on internal evaluations, aiming to assess organizational dynamics such as departmental performance and operational alignment with strategic goals. The third segment of the analysis sought to evaluate employees' awareness and knowledge on critical sustainability topics—including climate change, carbon footprint, and global environmental goals—through 13 targeted questions. Finally, the fourth part included nine open-ended questions, designed to gather employees' suggestions and opinions on sustainability-related improvements.

In the data presentation, the abbreviation "B" refers to blank (unanswered) responses, "I" to invalid responses, and "T" to the total number of valid responses. Participation levels across the analysis were notably high. Most questions were answered by 40% to 95% of the participants, and three questions received responses from all 32 individuals. The least answered question still yielded 23 responses, indicating a generally engaged and responsive participant group.

Regarding departmental evaluations, all units received notable recognition, though the finance department was identified as the strongest with 26 positive entries, while the purchasing department received the lowest with 16. In contrast, the most frequently cited weakness pertained to occupational health, safety, and environmental coordination efforts.

The overall distribution of responses is summarized in Table 2. As reflected in the data, internal strengths were cited most frequently, with 31 unique options and a total of 931 responses. Weaknesses followed with 16 distinct categories and 386 responses. Opportunities and threats were represented with 6 and 2 options respectively, accumulating 144 and 94 responses. The most selected item was strength, with 51 mentions. Although weaknesses ranked second, opportunities and threats were identified far less frequently, likely due to the inclusion of senior management among participants, whose perspectives may have emphasized internal assets. Nonetheless, weaknesses still constituted 23% of all valid responses, and strengths accounted for more than half (53%).

Table 4. The Breakdown and Distribution of Answers in the SWOT Analysis

Number of Participants in the Analysis	32			
Maximum Number of Responses	1,920			
Number of Questions Left Blank	194			
Number of Invalid Responses	8			
Number of Valid Responses	1,445			
Distribution of Responses	**S**	**W**	**O**	**T**
Distribution of Answers	**778**	**332**	**241**	**94**
Preferred Options	51	7	0	2

As emphasized earlier, Table 3 presents the results of the 13-item questionnaire designed to assess employees' literacy on sustainability issues, including climate change and carbon footprint. The most significant questions and results are shown in the table. This section revealed a significant number of blank and invalid responses: 96 were left unanswered, and 117 were deemed invalid. Although multiple selections were allowed in some questions, the overall trend showed a lack of knowledge, with many participants incorrectly identifying coal and wood as renewable energy sources. Natural gas, likewise, was frequently—and mistakenly—identified as the most eco-friendly option.

Table 5. Climate Change, Sustainability and Carbon Footprint Questions

1-Do you know enough to explain what the following topics mean? (You can choose more than one option)					
	B	I	Yes	Somewhat	No
Climate change	4	1	25	2	
Ecosystem	4	1	17	9	1
Energy and its transformation	5	1	14	11	1
Pollution	5	-	22	4	1
Waste management and recycling	5	-	17	8	2
Carbon footprint	7	-	10	9	6
Sustainability	5	-	13	12	2
2-Which of these concepts do you think will be the most important in the next twenty years? (Mark the first two concepts as 1 and 2 in order of importance?					
	B	I	Yes	Somewhat	No
Climate change	2	12	8		
Ecosystem	2	12	1		
Energy and its transformation	2	12	11		
Pollution	2	12			
Waste management and recycling	2	12	2		
Carbon footprint	2	12	4		
Sustainability	2	12	5		
3- Please write an example of the first sustainability concept that comes to your mind as a title.					
No answer	Invalid	Correct			
22	6	4			
4-Please mark the renewable energy types below. No answer: 1 Invalid: 4					
Energy Type	Considered as Renewable				
Hydro-thermal	14				
Biomass					
Biodiesel	2				
Organic fuel mix	1				
Natural gas	17				
Coal	7				
Wind	9				
Nuclear	8				
Solar	15				
Geothermal	5				
Wood					
5-In your opinion, what are the three most important renewable energy sources for Türkiye? No Answer: 1 Invalid: 4					
Energy Type	Renewable				
Hydro-thermal	11				
Biomass					
Biodiesel	2				
Organic fuel mix	1				
Natural gas	13				
Coal	6				
Wind	13				

Nuclear	10
Solar	11
Geothermal	6
Wood	2
6-In your opinion, which energy types have the lowest carbon footprint? (Rank from lowest to highest (1 is lowest - 5 is highest) No Answer: 1 Invalid: 9	
Energy Type	Renewable
Hydro-thermal	11
Biomass	5
Biodiesel	4
Organic fuel mix	5
Natural gas	5
Coal	5
Wind	11
Nuclear	7
Solar	14
Geothermal	6
Wood	5
7- If there was an option to provide electricity produced from renewable energy sources for your home or work-place that was slightly more expensive than the normal electricity price, would you use it? No Answer: 4 Invalid: -	
• Yes 14 • No 11 • I am not sure 3	

Evaluation of the Knowledge Levels of the Employees: A review of the responses to the 13-item questionnaire assessing employees' understanding of climate change, sustainability, and carbon footprint concepts reveals a considerable number of blank and invalid responses. Specifically, 96 responses were left blank, while 117 were marked as invalid. Due to the allowance of multiple answers per question, the total response count cannot be precisely determined. Nevertheless, the distribution of answers indicates a significant presence of misconceptions. For instance, a notable portion of participants incorrectly identified coal and wood as renewable energy sources, asserting that they have the lowest carbon footprint. Similarly, natural gas—commonly classified as a non-renewable resource—was selected as the most environmentally friendly energy source by the majority.

Establishing Threshold Values for SWOT Analysis Interpretation: Given that many participants in the SWOT analysis held managerial roles, it is reasonable to observe a tendency toward more cautious identification of external opportunities and threats, while internal strengths and weaknesses were marked with greater clarity. In this regard, the analysis applies differentiated threshold values for each SWOT dimension, reflecting this disparity in response behavior. Based on the highest frequency responses—51 for strengths, 7 for weaknesses, and 2 for threats—corresponding threshold percentages were calculated, as shown in Table 4.

Table 6. Threshold Values for SWOT Analysis Evaluation

SWOT Options	Threshold Value
S (Strengths)	16 (50%)
W (Weaknesses)	8 (50%)
O (Opportunities)	7 or most selected answers
T (Threats)	7 or most selected answers

These threshold values served as the basis for the categorization presented in Table 5, which lists all response items surpassing their respective thresholds. Where multiple items within a single SWOT category exceed the threshold, further elaboration is provided in the accompanying commentary. As indicated, a total of 14 strengths, 6 opportunities, 2 weaknesses, and 2 threats met or exceeded the established thresholds, offering a focused view of material factors derived from the analysis.

Table 7. Strengths, Opportunities, Weaknesses and Threats Preferences and Distribution

S (STRENGTH) – INTERNAL ANALYSIS		
43	Finance department's work	26
59	Do you think there should be a legal affairs unit?	25
60	Should there be dialogue with universities, especially in the fields of education?	25
36	MC CO. Adequacy of marine, bottom dredging, etc. equipment	23
35	MC CO. Adequacy of marine vehicles	22
4	Being a city that ranks first with a share of 64.4% in the total of 2021 domestic information and communication activities	21
19	The railway passing through the borders of Tuzla district and the proximity of the facilities to the nearest train station	21
24	Adequacy of the dialogue between the Chairman of the Board (General Manager) and family members working in the company	21
57	Is the design of the Turkish website complete?	21
1	Working in one of the westernmost districts of Istanbul and a district with a normal population	20
48	Should a research and development directorate/department be established in MC CO.?	20
3	Being a company in a city where the share of the services sector in 2021 domestic per capita national income is 30.3% and the share of the industrial sector is 17.9%	19
5	Being a district of a province where approximately 65% of the Turkish maritime industry is located	19
15	Availability of natural gas in the district	19
25	Adequacy of the General Manager's dialogue with white-collar and blue-collar employees	19
49	Should an environmental and sustainability directorate/department be established in MC CO.?	19
18	The district is located on main highways	18
23	Proximity of Sabiha Gökçen Airport to Tuzla	16
22	Proximity of the nearest marina	16
-	Work of other departments	17
33	Adequacy of MC CO. facilities in terms of infrastructure	16

55	Do you think the current white-collar and blue-collar distinctions are correct?	16
W(WEAKNESS)- INTERNAL ANALYSIS		
45	Do you think the organizational chart is complete?	14
51	Do you think the work safety measures are sufficient?	14
52	Are the internal trainings given to blue-collar workers sufficient?	13
7	In a province where the normal forest area percentage is 44 in 2021 and there is also a province with 20% agricultural area and 5% industrial area	12
30	MC CO. Adequacy of the number of white-collar employees	12
50	Should industrial engineering be established in MC CO.?	12
53	Are the internal trainings given to white-collar workers sufficient	12
26	Lack of assistant general managers	11
31	MC CO. Adequacy of the number of blue-collar employees	11
32	MC CO. Adequacy of the number of female employees	11
46	Are the job descriptions sufficient?	11
34	Adequacy of MC CO. facilities in terms of indoor space	10
55	Are the current white-collar and blue-collar distinctions correct in your opinion?	10
58	Availability of the website in English/foreign languages and is its design complete?	10
12	According to İŞKUR figures, 23.3% of the registered employees as of the end of 2021 were women; however, the rate of female employees at MC CO. is very low;	9
33	Adequacy of the infrastructure of MC CO. facilities	9
42	Works of the OHS-Environment coordination department	9
6	Continental climate, average annual rainfall (764 mm) above the Turkish average (574 mm)	8
29	Adequacy of the distribution of MC CO. services in the domestic market, domestic and international activities	8
21	Not being within the borders of the nearest cruise port and its distance	8
54	Is there a training plan for personal development for white-collar workers other than internal training and is it implemented? Do you think that education level should be considered when distinguishing between white-collar and blue-collar workers?	8
56	Is there a training plan for personal development for white-collar workers other than internal training and is it implemented? Do you think that education level should be considered when distinguishing between white-collar and blue-collar workers?	8
O(OPPORTUNITIES)- EXTERNAL ANALYSIS		
2	Being in a city with a population of around 16 million and ranked 1st in 2021 with 140 thousand 698 TL in domestic per capita income	10
8	Existence and effectiveness of nearly 60 universities, some of which are in Tuzla and its surroundings	13
9	Impact of higher education institutions such as vocational schools and faculties in Tuzla on MC CO. and other industrial establishments	8
10	Compatibility of Vocational and Technical Anatolian High School departments located in Tuzla and surrounding districts with the trained personnel needs of Tuzla and especially MC CO.	10
11	A significant proportion of the district population works in industry	8
13	Proximity to GOSB and other organized industrial zones	12
14	Proximity to Teknopark Istanbul and TÜBİTAK	11
20	Not being within the nearest cargo port	11

16	Not being within the provincial borders of the province	
17	Existence of heavy industry, manufacturing industry and refineries within the borders of the district and in neighboring districts	
20	The nearest cargo port is not within the district	8
T(THREATS) – EXTERNAL ANALYSIS		
6	Continental climate, average annual rainfall (764 mm) above the Turkish average (574 mm)	8
28	Ability of senior management to interpret existing laws and regulations	17
-	The state of the national economy and inflation (added later through discussions)	-

5 Results and Discussion

A comprehensive SWOT analysis was conducted for MC Co., consisting of 79 questions. Of these, 44 questions—along with an additional 16 questions—follow a conventional SWOT structure, while the remaining items aim to evaluate both the status and outlook of the organization. Among these, 16 binary (yes/no) questions were formulated to directly assess internal dynamics. To analyze, affirmative ("yes") responses were interpreted as indicators of strength, while negative ("no") responses were treated as weaknesses. In addition, 14 questions were included to assess participants' environmental awareness and understanding of sustainability-related issues.

Even without applying the previously defined threshold values, the results—summarized in Table 4—indicate that 31 items were identified as strengths, whereas 16 items were classified as weaknesses. These figures suggest that internal strengths are considerably more pronounced than weaknesses. Similarly, six opportunities were highlighted, compared to only three threats. Notably, the third threat was not identified by participants but was added by the consultants due to the ongoing national economic challenges observed in recent months.

The findings strongly reflect a Strength–Opportunity (SO) configuration, which corresponds to the Maxi–Maxi Strategy in SWOT terminology. This suggests that MC Co. is well-positioned to pursue robust growth and strategic development, leveraging both its internal competencies and favorable external conditions.

Nevertheless, for this trajectory of expansion to be sustainable, it is critical that the weaknesses identified in Table 5 are addressed as a matter of priority. Table 6 outlines a proposed order of priority for addressing these internal weaknesses, which should be considered as a strategic action plan for improvement.

On the other hand, the analysis of environmental awareness among employees revealed a significant knowledge gap. The prevalence of incorrect or incomplete responses in this area suggests a limited understanding of environmental and sustainability issues. To remedy this, it is recommended that the company organize a certified environmental training program—ideally lasting two to three days—focusing on key topics such as climate change, carbon footprint reduction, and sustainable business practices. Such an initiative would not only strengthen the company's internal capacity in line with double materiality principles but also support long-term ESG compliance and stakeholder trust

Table 8. Table captions should be placed above the tables.

Question No.	Weakness Definition	Priority	Recommended Process
45	Do you think the organizational chart is complete?	1	A new organization chart should be prepared, and the job descriptions of the directorates should be prepared
51	Do you think the occupational safety measures are sufficient?	1	A work safety department should be established
52	Are the internal training given to blue-collar workers sufficient?	1	The company should prepare a training program and implement it urgently
7	Being in a province where the normal forest area percentage is 44 in 2021 and in a district where the agricultural area is 20% and the industrial area is 5%	4	There is no action to be taken at the moment. The situation should be re-evaluated as a result of the Izmir investment.
30	Adequacy of the number of MC CO. white-collar employees	3	A new job description should be prepared and the need for white collar workers should be determined
50	Should an industrial engineering department be established in MC CO.?	1	A new organization chart should be prepared, and the job descriptions of the directorates should be prepared
53	Are the internal trainings given to white-collar workers sufficient	2	The company should prepare a training program and implement it urgently
26	Lack of assistant general managers	3	The issue should be discussed in the Board of Directors and a new organization chart should be prepared
31	Adequacy of the number of MC CO. blue-collar employees	1	A new job description should be prepared and the need for blue collar workers should be determined
32	Adequacy of the number of MC CO. female employees	1	The hiring of female employees should be accelerated
46	Are the job descriptions sufficient?	1	New job descriptions should be prepared by consultants
	Adequacy of MC CO. facilities in terms of indoor space	2	The Board of Directors should decide
55	Do you think the current white-collar and blue-collar distinctions are correct?	2	New job descriptions should be prepared by consultants
58	Are the website in English/foreign languages and its design complete?	1	The English website should be prepared by professionals
12	According to İŞKUR figures, 23.3% of the registered employees at the end of 2021 were women; on the other hand, the rate of female	1	The hiring of female employees should be accelerated

	employees in MC CO. was very low;		
33	Adequacy of MC CO. facilities in terms of infrastructure	3	The Board of Directors should decide
42	Works of OHS-Environment coordination department	1	A work safety department should be established
6	Continental climate, average annual rainfall (764 mm) being above the Turkish average (574 mm)	4	There is no action to be taken at the moment. The situation should be re-evaluated as a result of the Izmir investment.
29	Adequacy of distribution of MC CO. services in the local market, domestic and international activities	3	The Board of Directors should decide
21	Not being within the borders of the nearest passenger port and its distance	4	There is no action to be taken at the moment. The situation should be re-evaluated as a result of the Izmir investment.
54	Is there a training plan for personal development for white-collar workers other than internal training and is it implemented?	2	The company should prepare a training program and implement it urgently
56	Do you think that the education level should be considered in distinguishing between white-collar and blue-collar workers?	2	New job descriptions should be prepared by consultants

6 Conclusion

The findings of the SWOT analysis underscore MC Co.'s robust strategic positioning, marked by considerable internal strengths and favorable external opportunities. This alignment suggests that the company is well-equipped to pursue sustainable growth under a Maxi–Maxi strategic posture. Nonetheless, addressing the identified weaknesses—particularly those concerning environmental coordination and awareness—remains crucial for ensuring the organization's long-term resilience. The observed gap in environmental literacy among staff highlights the urgent need for targeted training initiatives and institutional capacity building. Taken together, the findings of this analysis underscore the strategic value of applying SWOT within the framework of double materiality, offering a structured yet adaptable approach for aligning internal strengths with sustainability objectives and evolving stakeholder expectations.

Double materiality represents a significant advancement in how corporate performance is evaluated. It encourages companies to adopt a more comprehensive, transparent, and accountable stance toward sustainability. When used in tandem, SWOT analysis and the double materiality principle provide a practical means of navigating this dual responsibility. By systematically identifying impacts, risks, and opportunities from both financial and societal perspectives, organizations can meet new regulatory requirements, strengthen their brand identity, and cultivate a more resilient and sustainable business model.

Ultimately, the integration of double materiality and SWOT analysis serves as a cornerstone for forward-looking companies striving to generate lasting value—for both them and the broader society. It is important to recognize, however, that the success of such an approach hinges on the presence of an informed and capable workforce. In this regard, the implementation of focused seminars, hands-on training, and applied learning programs can empower employees while simultaneously reinforcing the company's sustainability agenda.

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Assessment of Wind Forecasting over the Aegean Sea with WRF Simulations

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Abstract. This study evaluates the performance of the Weather Research and Forecasting (WRF) model for wind forecasting over the Aegean Sea, a region with high potential for offshore wind energy production in Türkiye. WRF simulations at 3-km and 1-km resolutions are validated against Advanced Scatterometer (ASCAT) satellite data and in-situ measurements from 10 coastal stations between January and April 2025. Results show that WRF accurately captures wind direction patterns, achieving a mean absolute error of 20.85° in open-sea regions and closely predicting predominant directions at in-situ sites (e.g., 121° vs. 112° at Dikili). On average, WRF underestimates wind speeds compared to ASCAT (-0.41 m/s bias) and overestimates them at in-situ stations (average bias: 1.40 m/s). Increasing resolution to 1 km reduces speed bias but does not fully address coastal error variability. Challenges in simulating air-sea interactions, partly due to coarse resolution of ERA5 sea surface temperature data, suggest a need for refined parameterizations and turbulence-resolving approaches, such as Large Eddy Simulation or high resolution CFD models coupled with WRF predictions.

Keywords: Computational Fluid Dynamic, Remote Sensing, Weather Research Forecast Model, Wind Measurement.

1 Introduction

According to the Global Wind Energy Council's (GWEC) 2023 Global Offshore Wind Report, the global offshore wind energy capacity reached 64.3 GW by the end of 2022, accounting for approximately 6.7% of the total wind energy capacity [1]. Although offshore wind currently contributes less than onshore wind, the sector is experiencing significant growth, with a 15.4% increase in capacity from 2021 to 2022. In Türkiye, where no offshore wind farms are yet operational, technical studies commenced in 2024 to explore potential sites along the coasts of Bandırma, Bozcaada, Gelibolu, and Karabiga. The National Energy Plan, published by the Ministry of Energy and Natural Resources, sets a target of 5 GW of offshore wind capacity by 2035 [2]. Given the high wind energy potential of the Aegean Sea, accurate wind forecasting using models like the Weather Research and Forecasting (WRF) system is critical for planning and optimizing offshore wind energy projects in this region.

Accurate wind speed and direction data are critical for identifying optimal offshore wind farm sites and ensuring efficient operation. Long-term wind measurements (at least one year) are typically required to assess resource potential and minimize planning costs. Coastal and offshore winds, influenced by complex land-sea-atmosphere interactions, exhibit high variability, particularly in regions like the Aegean Sea with intricate coastlines and islands. Sparse meteorological observations in such areas necessitate comprehensive wind resource assessments through direct measurements or computational models [3].

Offshore wind measurements are conducted using in-situ and remote sensing techniques, each with distinct advantages and limitations. In-situ methods, such as meteorological masts and buoy stations, provide accurate data but face logistical challenges. Masts offer high precision but are costly and limited to fixed locations [4], while buoys are more affordable but less accurate due to wave motion [5]. Remote sensing tools, like Light Detection and Ranging (LiDAR), deliver high-resolution wind data but are expensive and weather-sensitive [6]. Satellite-based scatterometers, such as the Advanced Scatterometer (ASCAT) on ESA's MetOp satellites, estimate wind speed and direction from sea surface roughness, covering 500-km swaths at a 0.125° resolution (approximately 10.5 km in mid-latitudes) [7, 8]. ASCAT data show strong correlations (0.7–0.9) with in-situ measurements for wind speeds between 2 and 25 m/s [9], but their coarse resolution and limited temporal coverage (up to four daily measurements) restrict their use for detailed coastal applications.

Numerical Weather Prediction (NWP) models, such as WRF [10], address these limitations by providing high-resolution wind field simulations over complex coastal regions. However, WRF's accuracy must be validated against reliable observations to ensure its suitability for wind energy applications. This study evaluates WRF's performance in forecasting wind speed and direction over the Aegean Sea, focusing on its ability to capture coastal and offshore wind patterns critical for Türkiye's offshore wind energy development. By comparing WRF outputs with ASCAT and in-situ measurements, we assess the model's accuracy and potential to support wind farm planning.

2 Methodology

This study focuses on the Aegean Sea (37.0°N–40.5°N, 24.0°E–29.0°E), with a particular emphasis on the Aliağa Gulf (38.1°N–39.3°N, 26.0°E–27.5°E), a potential site for offshore wind energy development in Türkiye. The region's complex coastline and islands create intricate wind patterns driven by land-sea-atmosphere interactions. Figure 1 illustrates the study area, WRF model domains, and the locations of in-situ measurement stations.

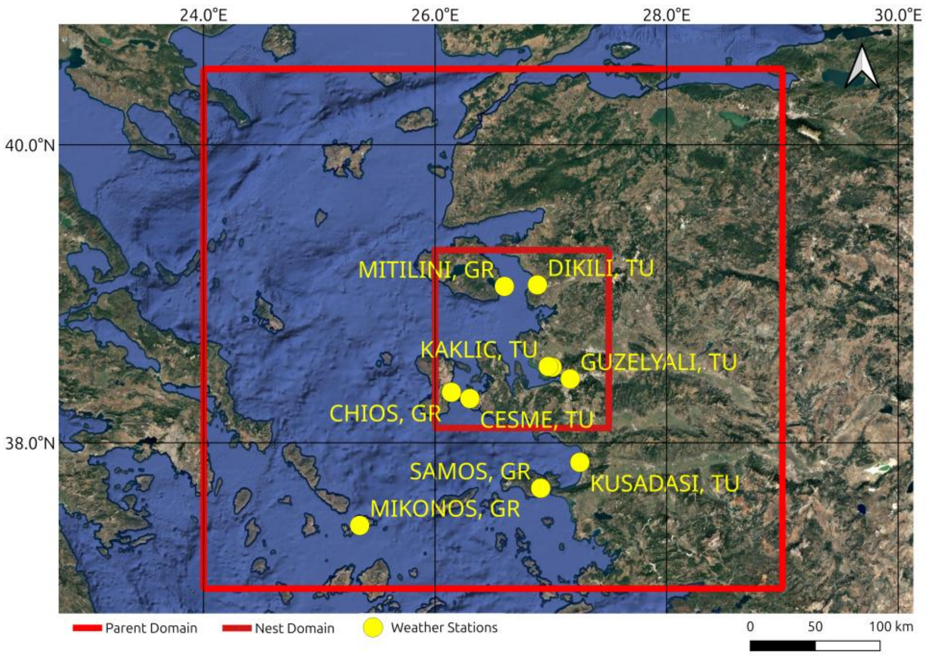

Fig. 1. The map of the Aegean Sea study area, WRF nested domains, and in-situ measurement stations.

Wind fields are simulated using WRF version 4.5, configured with two nested domains: a 3-km resolution Parent Domain and a 1-km resolution Nested Domain centered on the Aliağa Gulf. Initial and boundary conditions are derived from ERA5 reanalysis data [11] at 0.25° resolution, obtained hourly for the study period (e.g., January 1–April 19, 2025). The dataset included pressure-level variables (e.g., temperature, wind components, relative humidity) and surface-level parameters (e.g., 10-m wind, sea surface temperature, surface pressure). The model is run with the CONUS physics suite, incorporating the WSM6 microphysics scheme, Kain-Fritsch cumulus parameterization, RRTMG radiation schemes, and YSU planetary boundary layer scheme. A Lambert conformal projection centered at 38.75°N, 26.5°E is used, with a time step of 18 seconds and 35 vertical levels.

The wind speed and direction data are sourced from ASCAT measurements and in-situ meteorological stations. The ASCAT L2 data from MetOp-B and C satellites, collected from January 1 to April 19, 2025, included 46 measurements across 17 days, representing calm (<3 m/s), moderate (3–10 m/s), and strong (>10 m/s) wind conditions (Table 1). ASCAT provides 10-m wind estimates at a 0.125° resolution (~10.5 km in mid-latitudes) [7].

Table 1. Selected days for WRF-ASCAT comparisons

Date	Wind Category	Number of ASCAT Measurements
2025-01-01	Calm (<3 m/s)	3
2025-01-13	Strong (>10 m/s)	3
2025-01-18	Moderate (3–10 m/s)	3
2025-01-25	Moderate (3–10 m/s)	3
2025-01-30	Moderate (3–10 m/s)	3
2025-02-06	Strong (>10 m/s)	2
2025-02-18	Moderate (3–10 m/s)	3
2025-02-23	Moderate (3–10 m/s)	4
2025-03-02	Calm (<3 m/s)	2
2025-03-07	Moderate (3–10 m/s)	2
2025-03-14	Moderate (3–10 m/s)	3
2025-03-19	Strong (>10 m/s)	3
2025-04-01	Moderate (3–10 m/s)	2
2025-04-06	Moderate (3–10 m/s)	2
2025-04-07	Strong (>10 m/s)	4
2025-04-13	Moderate (3–10 m/s)	3
2025-04-19	Calm (<3 m/s)	1

The in-situ data from the NOAA Integrated Surface Dataset (ISD) are obtained from 10 coastal stations within 2 km of the sea: Mitilini, Chios, Samos, Mikonos (Greece), and Dikili, Çiğli, Kaklıç, İzmir Güzelyalı, Çeşme, Kuşadası (Türkiye), with Dikili and Kuşadası data from marine platforms (Table 2).

The WRF predictions are compared against the ASCAT data and the in-situ measurements to assess model accuracy. The validation process involves spatial and temporal alignment of model outputs with observational data, followed by statistical analysis to quantify errors in wind speed and direction. Coastal and open-sea regions are analyzed separately to account for distinct wind characteristics, using a classification derived from high-resolution geographical data (Figure 2).

Table 2. In-situ measurement stations, their coordinates, data frequencies and platform types.

Station Name	Country	Latitude (°N)	Longitude (°E)	Data Frequency	Platform
Mitilini	Greece	39.057	26.598	Half-hourly	Land
Chios	Greece	38.343	26.141	Hourly	Land
Samos	Greece	37.690	26.912	Half-hourly	Land
Mikonos	Greece	37.435	25.348	Half-hourly	Land
Dikili	Türkiye	39.067	26.883	Hourly	Marine
Çiğli	Türkiye	38.513	27.010	Hourly	Land
Kaklıç	Türkiye	38.518	26.977	Half-hourly	Land
Güzelyalı	Türkiye	38.433	27.167	Hourly	Land
Çeşme	Türkiye	38.300	26.300	Hourly	Land
Kuşadası	Türkiye	37.867	27.250	Hourly	Marine

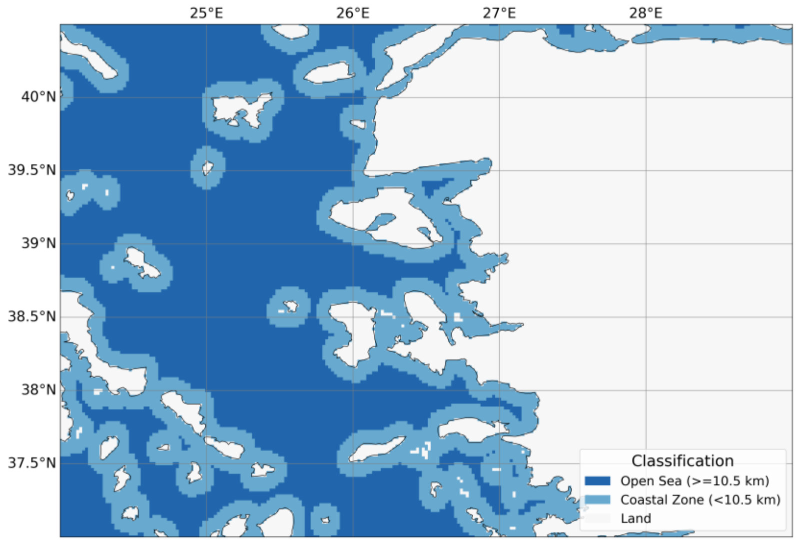

Fig. 2. Classification of the Aegean Sea into open-sea and coastal zones (10.5 km buffer).

WRF simulations from the 3-km Parent Domain and 1-km Nested Domain are compared with ASCAT measurements from January 1 to April 19, 2025. WRF outputs are interpolated to the ASCAT grid (0.125°) using bilinear interpolation. Simulations are initialized with ERA5 data at least two hours before ASCAT measurement times, with outputs saved at exact measurement times. A land mask from Natural Earth [12] 50m data excluded land-based grid cells. Metrics for wind speed included Mean, Bias, Mean Absolute Error (MAE), MAE Percentage, Root Mean Square Error (RMSE), and Standard Deviation. Wind direction metrics used circular statistics, yielding Circular Mean, Circular MAE, Circular RMSE, and Circular Standard Deviation. Coastal and open-sea regions are classified using a precomputed dataset with ASCAT grid cells are defined as open-sea if they include ≥90% open-sea pixels (>10.5 km from land). Separate error statistics are computed for each region, including mean error, MAE, RMSE, and median error for both speed and direction. Results are visualized through spatial difference maps and boxplots to compare error distributions across domains and regions.

WRF outputs are compared with in-situ measurements from 10 coastal stations for five 24-hour periods (January 1, January 30, February 18, March 19, April 7, 2025). In-situ data retained original timestamps (hourly/half-hourly), with wind direction in meteorological conventions. WRF simulations, with 5-minute output intervals, are interpolated to station coordinates using bilinear interpolation in the 3-km Parent Domain. Metrics included Bias, RMSE, and Pearson correlation for wind speed, and circular Bias, RMSE, and correlation for wind direction. Time series and wind roses visualized temporal and directional agreement, using ten speed bins (0–20 m/s) and 16 directional sectors.

3 Results and Discussion

Nested WRF simulations are performed over the Aegean Sea to forecast wind fields, with a focus on the Aliağa Gulf. The simulations utilized two nested domains: a Parent Domain at 3 km resolution covering the most of the Aegean Sea and a Nested Domain at 1 km resolution centered on the Aliağa Gulf. These simulations, spanning January 1 to April 19, 2025, are initialized and driven by ERA5 reanalysis data at 0.25° resolution, providing hourly boundary conditions. The WRF model is configured with the CONUS physics suite to capture complex land-sea-atmosphere interactions. Model outputs, including 10-m wind speed (U10, V10) and direction, are compared against the ASCAT satellite data and the in-situ measurements from 10 coastal stations. Validation metrics, such as Mean Absolute Error (MAE), Root Mean Square Error (RMSE), and circular statistics for direction, are computed separately for coastal and open-sea regions to assess the model's performance across different spatial scales.

WRF slightly underestimates the wind speeds compared to the ASCAT data, with larger discrepancies in coastal areas than open-sea regions, and shows a slight clockwise bias in the wind direction. Table 3 summarizes these findings, showing a mean wind speed bias of -0.41 m/s in the Parent Domain and -0.87 m/s in the Nested Domain. Within the Nested Region, increasing resolution from 3 km (-1.10 m/s bias) to 1 km (-0.87 m/s bias) reduces the speed bias, indicating improved coastal predictions at higher resolution, consistent with Mediterranean WRF-ASCAT comparisons [13]. For wind direction, the MAE is 22.0° in the Parent Domain and 28.1° in the Nested Domain, with a slight improvement in the Nested Region (29.0° to 28.1°). However, persistent coastal error variability suggests resolution alone is insufficient to address all discrepancies.

Table 3. Summary of WRF-ASCAT error metrics for parent and nested domains.

Metric	Parent Domain (Res: 3km)	Parent in Nested Region (Res: 3km)	Nested Domain (Res: 1km)
WRF Speed Mean (m/s)	7.58	6.37	6.60
ASCAT Speed Mean (m/s)	7.99	7.47	7.47
Speed Bias (m/s)	-0.41	-1.10	-0.87
Speed MAE (m/s)	1.39	1.86	1.83
Speed MAE Percentage (%)	19.8	27.6	27.2
Speed RMSE (m/s)	1.82	2.34	2.30
Speed StdDev (m/s)	1.65	1.75	1.76
WRF Direction Mean (°)	98.3	91.2	92.7
ASCAT Direction Mean (°)	92.7	118.3	117.9
Direction MAE (°)	22.0	29.0	28.1
Direction MAE Percentage (%)	6.1	8.1	7.8
Direction RMSE (°)	33.1	38.6	36.9
Direction StdDev (°)	28.7	33.0	31.2

Figure 3 illustrates the spatial distribution of wind speed and direction differences, confirming larger speed underestimations near the coast. Higher resolution in the Nested Domain improves coastal speed predictions but has minimal impact on direction differences. Figure 4 presents boxplots of error distributions, summarized in Table 4, revealing higher speed error variability in coastal regions (Parent Domain: 2.09 m/s, Nested Domain: 2.40 m/s) than open-sea areas (Parent Domain: 1.73 m/s, Nested Domain: 2.01 m/s). Direction errors also vary more in coastal areas (Parent Domain: 39.21°, Nested Domain: 41.25°) than open-sea regions (Parent Domain: 30.05°, Nested Domain: 33.27°). Higher resolution reduces MAE for speed (coastal: 1.96 m/s, open-sea: 1.62 m/s) and direction (coastal: 30.74°, open-sea: 23.69°), but standard deviations remain largely unchanged (e.g., speed: 2.40 m/s, direction: 41.25° in coastal Nested Domain). Terrain effects, sea surface temperature (SST) variations, or model physics may contribute to these errors. For instance, ERA5's 0.25° SST data may fail to capture fine-scale coastal gradients, impacting air-sea interactions that drive local wind patterns, such as sea breezes [14].

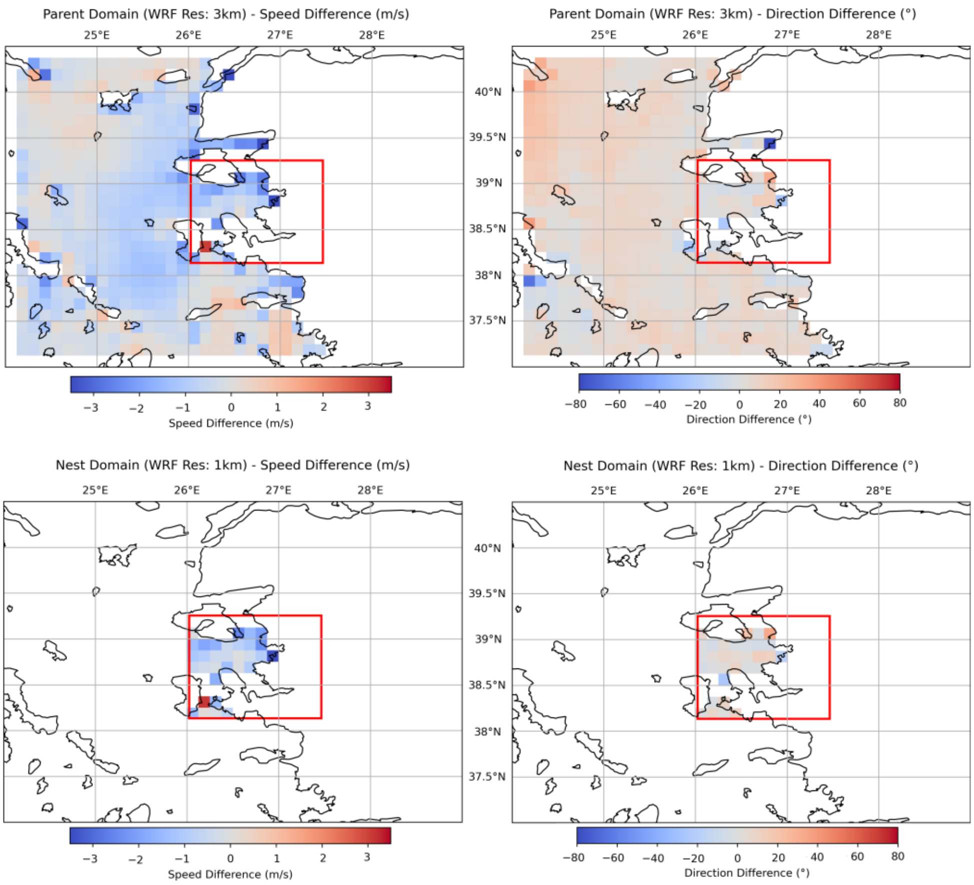

Fig. 3. Spatial comparison of WRF-ASCAT speed and direction differences for January 1 - April 19, 2025, averaged across all ASCAT measurement times.

Table 4. Summary of WRF-ASCAT error metrics for coastal and open-sea regions.

Metric	Parent Domain (3km) Coastal	Parent Domain (3km) Open sea	Parent in Nested Region (3km) Coastal	Parent in Nested Region (3km) Open sea	Nested Domain (1km) Coastal	Nested Domain (1km) Open sea
Magnitude Mean Error (m/s)	-0.46	-0.41	-1.19	-0.85	-0.93	-0.71
Magnitude StdDev (m/s)	2.09	1.73	2.33	1.94	2.40	2.01
Magnitude MAE (m/s)	1.60	1.31	2.02	1.61	1.96	1.62
Magnitude RMSE (m/s)	2.14	1.78	2.62	2.11	2.57	2.13
Magnitude Bias (m/s)	-0.45	-0.40	-1.19	-0.85	-0.93	-0.71
Direction cMean (°)	5.07	6.49	2.73	1.86	2.25	2.12
Direction cStdDev (°)	39.21	30.05	41.73	35.35	41.25	33.27
Direction cMAE (°)	28.00	20.85	31.09	24.98	30.74	23.69
Direction cRMSE (°)	43.53	34.04	46.04	38.67	44.53	36.11

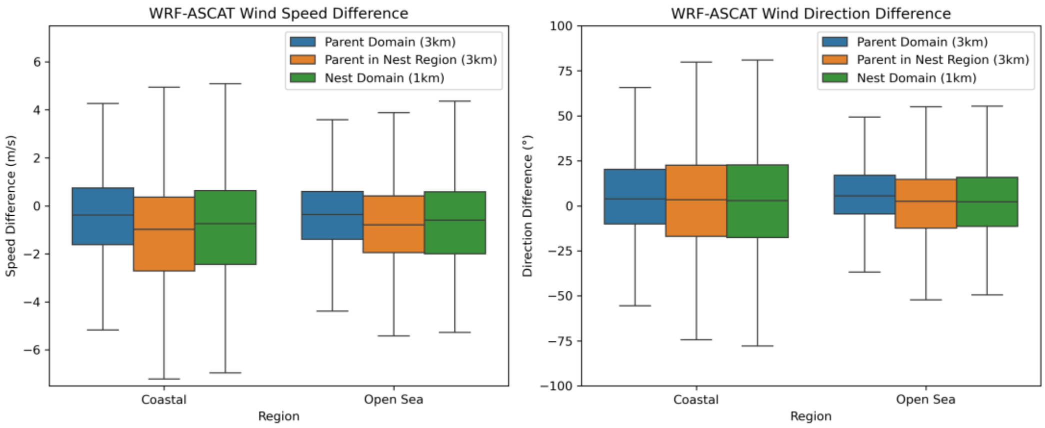

Fig. 4. Boxplot of WRF-ASCAT speed and direction errors for coastal and open-sea regions, aggregated over January 1- April 19, 2025.

WRF's performance is further validated against in-situ measurements from 10 coastal stations (Table 5). WRF overestimates wind speeds by an average of 1.40 m/s, with an RMSE of 2.51 m/s and a correlation of 0.73, while wind direction has a mean bias of 34.81°, an RMSE of 51.29°, and a correlation of 0.73. Performance is weaker at marine stations (e.g., Dikili: speed bias 1.72 m/s, direction bias 35.82°; Kuşadası: speed bias 2.00 m/s, direction bias 43.16°) compared to terrestrial ones (e.g., Mikonos: speed bias 0.44 m/s), indicating challenges in simulating air-sea interactions [15, 16]. Accounting for ASCAT's documented overestimation of wind speed (+0.5 to +1.0 m/s) relative to in-situ measurements [17], WRF's predictions show promising accuracy despite these biases. Figure 5, a time series for Dikili on January 1, 2025, shows WRF capturing general trends but with speed discrepancies. Figure 6, a five-day wind rose for Dikili, indicates WRF predicts the predominant direction (121°)

close to in-situ (112°) but overestimates speed (WRF: 4.3 m/s, in-situ: 2.6 m/s), confirming directional accuracy but highlighting speed overestimation challenges. The limited representation of small-scale turbulence in the YSU boundary layer scheme may contribute to speed biases at marine stations, as turbulent eddies influence momentum transfer [18].

Table 5. Validation metrics for WRF-In-Situ wind speed and direction comparisons.

Station Name	Speed Bias (m/s)	Speed RMSE (m/s)	Speed Correlation	Direction Bias (°)	Direction RMSE (°)	Direction Correlation
Mitilini. GR	1.06	2.04	0.84	39.52	60.76	0.66
Chios. GR	1.34	2.66	0.85	29.18	48.81	0.78
Samos. GR	2.12	3.03	0.75	22.91	38.06	0.84
Mikonos. GR	0.44	1.81	0.89	20.77	33.71	0.86
Dikili. TU	1.72	2.66	0.33	35.82	57.02	0.70
Çiğli. TU	0.61	2.00	0.76	32.32	47.96	0.79
Kaklıç. TU	0.76	1.87	0.83	27.10	37.82	0.82
Güzelyalı. TU	1.05	2.20	0.67	47.30	62.89	0.57
Çeşme. TU	2.91	3.63	0.83	49.99	67.14	0.60
Kuşadası. TU	2.00	3.19	0.56	43.16	58.76	0.64
Average	1.40	2.51	0.73	34.81	51.29	0.73

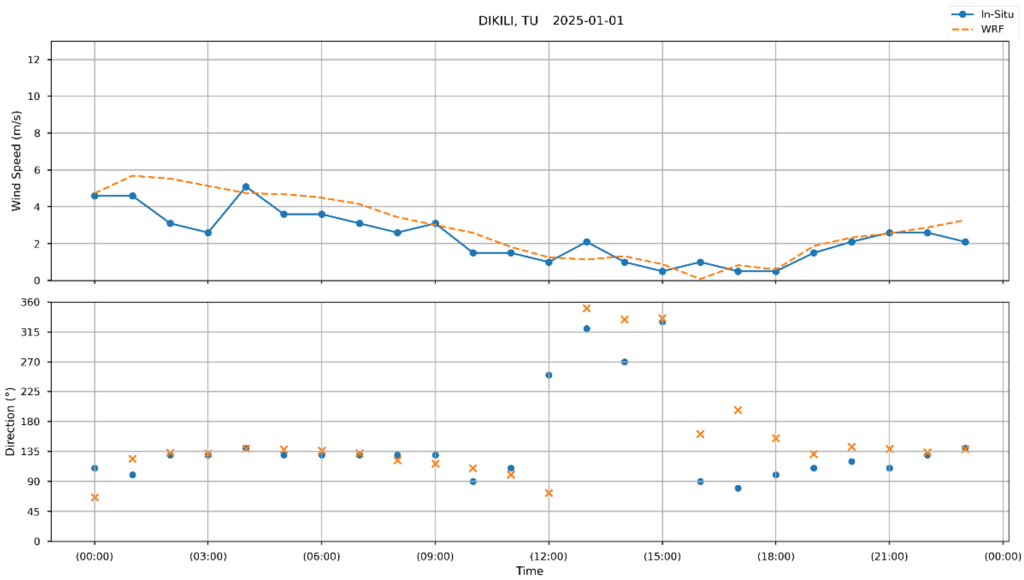

Fig. 5. Time series of wind speed and direction for WRF and in-situ measurements at Dikili (January 1, 2025)

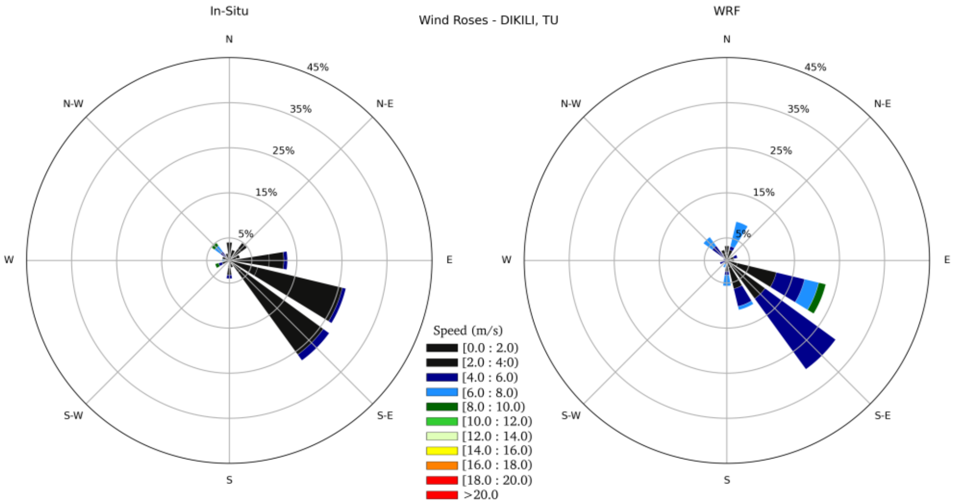

Fig. 6. Wind roses comparing WRF and in-situ wind distributions at Dikili.

These findings provide insights into WRF's wind forecasting capabilities. WRF accurately simulates wind direction patterns, achieving a direction MAE of 23.69° in open-sea regions and closely predicting predominant directions at in-situ stations (e.g., 121° predicted vs. 112° observed at Dikili). However, the model's underestimation of wind speeds compared to ASCAT, particularly in coastal areas, and overestimation compared to in-situ measurements at marine sites, align with known challenges in WRF's coastal wind predictions due to surface fluxes and boundary layer dynamics [15, 16]. Future research should focus on refining surface roughness and boundary layer parameterizations, incorporating high-resolution SST data to better capture coastal gradients, and exploring turbulence-resolving approaches like Large Eddy Simulation (LES) within WRF or coupled computational fluid dynamics (CFD) models to improve local turbulent flow predictions, particularly in coastal areas like Aliağa [13, 14, 19]. Expanding in-situ validations at marine sites will further enhance WRF's reliability for wind energy applications.

4 Conclusion

These nested WRF simulations for wind forecasting over the Aegean Sea are successfully assessed using ASCAT and in-situ measurements from 10 coastal stations. The WRF predictions effectively capture wind direction patterns, achieving a direction mean absolute error (MAE) of 20.85° in open-sea regions. However, WRF underestimates wind speeds compared to ASCAT (average bias: -0.46 m/s) and overestimates them at weather stations (average bias: 1.40 m/s). Higher resolution (1 km vs. 3 km) in the Nested Region reduces speed bias (-1.10 m/s to -0.87 m/s) and slightly improves direction accuracy, highlighting the value of fine-scale modeling.

WRF's accuracy is promising, particularly when accounting for ASCAT's wind speed overestimation (+0.5 to +1.0 m/s) [17]. Challenges in speed predictions at marine sites suggest a need for improved parametrization of surface roughness, momentum fluxes, and boundary layer turbulence representation [14, 15]. Future work should incorporate high-resolution SST data, optimize model physics, and explore turbulence-resolving approaches, such as WRF's Large Eddy Simulation (LES) mode or coupled computational fluid dynamics (CFD) models with WRF, to better capture local air-sea interactions [18, 19]. Such enhancements are needed to strengthen WRF's accuracy for wind energy forecasting.

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From Sustainable Energy and Climate Action Plans (SECAPs) to Action: MLP4Climate for Local Climate Leadership in Türkiye

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Abstract. The EU4 Energy Transition: Covenant of Mayors in the Western Balkans and Türkiye (EU4ETTR) project supports municipalities in turning Sustainable Energy and Climate Action Plans (SECAPs) into measurable, actionable outcomes. This Multi Donor Action is jointly co-financed by the European Union and the German Federal Ministry for Economic Cooperation and Development and implemented by GIZ in the Western Balkans and the Lithuanian Central Project Management Agency (CPMA) in Türkiye. In Türkiye, the project established the Multi-Level Governance Platform for Climate (MLGP4Climate), now connecting over 70 municipalities and more 60 associations, including 37 women cooperatives, national institutions and international partners. The platform enables structured collaboration, expert working groups, and access to a digital portal offering more than 700 resources, including funding calls, guides, and SECAP tools. Through MLGP4Climate, municipalities receive tailored support to develop or revise their SECAPs, secure climate financing, and launch impactful mitigation and adaptation projects—closing the gap between strategy and implementation. The platform also supports alignment with national policy and EU climate frameworks, contributing to Türkiye's 2053 net-zero target. MLGP4Climate illustrates how institutionalized multi-level governance can transform local governments into proactive climate actors—and serves as a replicable model for accelerating municipal climate action across diverse governance contexts.

Keywords: multi-level governance, municipal climate action, energy transition, Covenant of Mayors, SECAPs, Türkiye.

1 Introduction

Türkiye faces urgent challenges from climate change due to its geographical vulnerability, including increased heatwaves, droughts, and severe flooding, which significantly impact agriculture, urban infrastructure, and public health. Rapid urbanization exacerbates these vulnerabilities, placing additional stress on water resources and urban energy systems (cf. Demircan et al. 2017). In 2021, Türkiye ratified the Paris Agreement and committed to achieving net-zero greenhouse gas emissions by 2053. This commitment represents a fundamental shift towards sustainable economic growth, signaling alignment with global climate mitigation efforts and emphasizing Türkiye's dedication to reducing its carbon footprint.

Cities have a crucial role in reaching these ambitious national targets due to their significant contributions to overall emissions and their potential for effective local-level interventions (UNDP 2024). Local governments directly influence key sectors such as energy, transportation, and waste management, making them central actors in achieving decarbonization and enhancing climate resilience. Despite this, municipalities in Türkiye face challenges including limited technical capacities, insufficient funding, fragmented governance structures, and varying levels of awareness and commitment among local leaders (Bulkeley 2010, Gouldson et al., 2016).

Under initiatives like the Global Covenant of Mayors (GCoM), municipalities are strongly encouraged to prepare and implement Sustainable Energy and Climate Action Plans (SECAPs), which sets ambitious voluntary targets for signatory cities to reduce CO_2 emissions by at least 40% by 2030 and enhance climate resilience. SECAPs provide structured roadmaps that guide municipalities in systematically lowering emissions, increasing renewable energy usage, adapting to climate impacts, and addressing energy poverty. These action plans are essential tools for translating broad climate commitments into tangible local actions.

Recognizing these gaps, the *EU4 Energy Transition: Covenant of Mayors in the Western Balkans and Türkiye (EU4ETTR)* project was launched in 2021, funded by the European Union and the German Federal Ministry for Economic Cooperation and Development (BMZ). Implemented by the German Association for International Cooperation GIZ in the Western Balkans and the Lithuanian Central Project Management Agency (CPMA) in Türkiye, the project supports municipalities by providing technical assistance for SECAP development and encouraging supportive governance networks. Its primary aim is to help CoM cities effectively achieve their pledged climate and energy targets, thus contributing to the broader energy transition and climate action in the region. Central to this initiative is the *Multi-Level Governance Platform for Climate (MLGP4Climate)*, an innovative approach to coordinating climate action between local, regional, and national stakeholders in Türkiye.

This article focuses specifically on Türkiye's experience with MLGP4Climate under the EU4ETTR project. It describes the platform's inception, testing, and nationwide expansion, highlights key achievements, explores encountered challenges and lessons learned, and evaluates the platform's replicability for promoting climate action in other contexts.

2 Establishing a Multi-Level Governance Platform in Türkiye

2.1. Concept and Inception (2021-2022)

The concept of a multi-level governance platform (MLGP) for climate emerged from the recognition that effective climate action requires coordinated efforts of various stakeholders—national ministries, municipal unions, local governments, academia, NGOs, and the private sector (Di Gregorio et al., 2019). In the project's first year (2021), an institutional analysis identified 18 key institutions at national, regional, and local levels that would be relevant to such a platform. Through a series of round-table consultations with municipal associations and stakeholders, the project formulated a roadmap for establishing a governance structure to support local energy and climate action. These discussions underscored two priority needs: (i) strengthening the capacity of municipalities to develop and implement SECAPs, and (ii) creating coordination mechanisms under the umbrella of major municipal unions (specifically the Union of Municipalities of Türkiye, UMT, and the Marmara Municipalities Union, MMU). In other words, the groundwork suggested that empowering local authorities had to go hand-in-hand with building a platform that connects cities through their associations for collective climate action.

During 2022, extensive research and stakeholder engagement refined the MLGP concept. Data was gathered via two online surveys and one in-person survey (at a SECAP training event) with inputs from over 200 respondents including city officials, ministries, NGOs, and experts. The survey results revealed a critical factor: many municipalities initially had limited knowledge of what a multi-level governance platform entailed, highlighting the need for a clear and accessible definition of the platform's purpose and value. In response, the project team prepared a comprehensive MLGP Structure Report, which outlined definitions of multi-level governance, mapped over 30 stakeholder groups and their roles, and proposed an organizational design. A detailed institutional mapping of Türkiye's administrative system was also conducted to ensure the platform aligned with existing government structures (national government, provinces, metropolitan and district municipalities, etc.). This helped clarify how different levels of government and civil society would interface through the MLGP.

By late 2022, the project had developed a draft MLGP model and action plan. A stakeholder meeting at MMU's headquarters in November 2022 presented the proposed governance structure and a phased implementation roadmap. The roadmap consisted of three phases: *Preparation* (late 2022 – early 2023) to finalize the platform design and select pilot municipalities; *Implementation & Monitoring* (2023) to pilot test the platform on a limited scale; and *Expansion* (2024) to scale up the platform nationwide. As part of the preparation, seven pilot municipalities were identified (including Istanbul Metropolitan Municipality (IMM) and Bağcılar as initial project partners, plus municipalities like Sakarya, Edirne, Çorlu, Pendik, and Avcılar) and engaged through meetings to secure their commitment. Two major municipal unions, UMT and MMU, formally endorsed the initiative by signing Letters of Confirmation of Cooperation, cementing a partnership between the project and these key institutions. By the end of 2022, the foundation was laid for a collaborative, multi-stakeholder platform tailored to Türkiye's context. The preparatory work stressed several design principles that anticipated future challenges: ensuring broad stakeholder buy-in, providing technical support to cities, establishing working groups on SECAP implementation, and planning for the continuity of the platform beyond the initial pilot.

2.2. Pilot Phase: Testing the MLGP in 2023

2.2.1. Launching the Test Platform In early 2023, the project moved into the pilot implementation phase (the "Implementation & Monitoring" phase of the roadmap). The MLGP pilot platform was officially launched with a kickoff meeting in March 2023, hosted by the Marmara Municipalities Union in Istanbul. This marked the start of a year-long test of the multi-level governance approach on a regional scale (focused on the Marmara region) under MMU's facilitation. The governance structure proposed in theory was now put into practice. A Secretariat was established at MMU to handle day-to-day coordination of the platform. A Steering Committee (SC) of 14 members was convened, bringing together high-level representatives from key stakeholders (including national ministries, UMT/MMU leaders, and pilot city mayors). In parallel, an Advisory Committee (AC) with 24 members was formed, comprising experts from government agencies, universities, NGOs, and other partners to provide technical. Two Working Groups (WGs) were created to delve into specific topics. One working group focused on "Challenges & Solutions" for SECAP implementation, providing a forum for municipalities to identify obstacles (such as funding, data collection, or policy gaps) and collectively brainstorm solutions (https://mlgp4climate.com/mlgp-activities/wg-1-challenges-and-solutions). The second working group concentrated on "International Cooperation and Project Development," aiming to link cities with financing opportunities and external partnerships (this group helped municipalities prepare joint projects and tap into climate funds, https://mlgp4climate.com/mlgp-activities/wg-2-international-cooperation-partnership-development-and-finance). In total, about 25 experts and municipal representatives participated in these WGs during the pilot.

Over the course of 2023, the MLGP pilot was actively managed through regular meetings and collaborative tools. The Secretariat set up an online collaboration platform (initially a shared Google Drive and mailing groups) to facilitate document exchange among all members. Governance meetings were held frequently: the Steering Committee, Advisory Committee, and WGs convened in a combined 11 meetings during the year. These meetings were instrumental in maintaining momentum and accountability. Through the WGs, municipal practitioners and national experts jointly worked on outputs such as SECAP implementation guidance and identification of policy needs. One tangible outcome was the production of Working Group reports and a "Blue Paper" – a document summarizing key findings and recommendations from the pilot (e.g. proposals for improving intergovernmental coordination on climate policy). By the end of the pilot, the project team had also drafted an MLGP Action Plan for 2024 and beyond, which outlined how the platform could be scaled up nationally based on lessons from the test run.

2.2.2. Participation and Multi-level Engagement

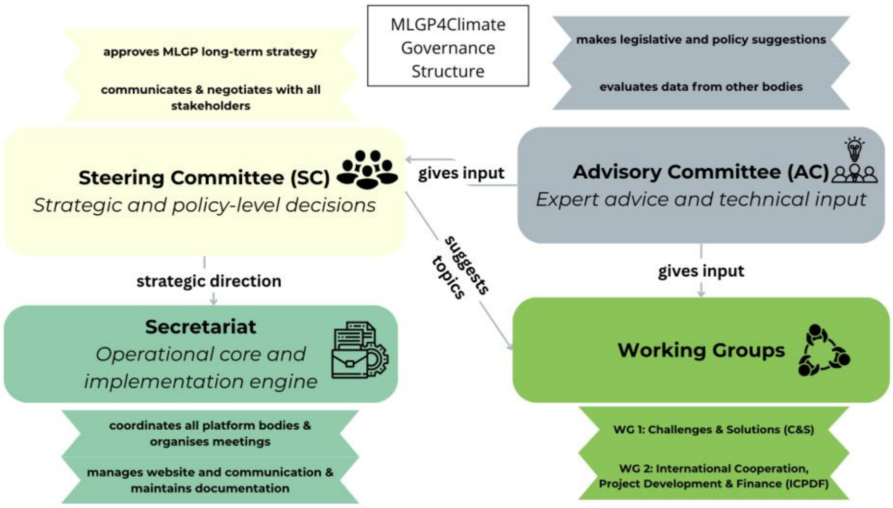
The pilot phase successfully brought together a broad coalition of actors, validating the multi-level approach. Initially, 7 municipalities had committed to the test; this number grew to 10 pilot municipalities actively participating by mid-2023. These included a mix of large metropolitan cities and smaller district municipalities, mostly from the Marmara region (such as Istanbul, Edirne, Sakarya, Bağcılar, Çorlu, Pendik, Avcılar, etc.). In addition to the core pilot cities, 10 observer municipalities were invited to follow the process and attend events. The observers allowed wider sharing of lessons beyond the pilot circle and prepared the ground for future expansion. Crucially, national government involvement was ensured: by the end of 2023, three ministries (including, for example, the Ministry of Environment, Urbanization and Climate Change, and the Ministry of Energy) were actively engaged in the Steering Committee deliberations. Both municipal unions UMT and MMU participated in the platform governance, symbolizing joint ownership by the key city networks in Türkiye. This close collaboration between UMT (national union) and MMU (regional union) was a strategic decision – it provided political support and legitimacy, and it eased the eventual transition of the platform from a regional test to a national initiative. Indeed, throughout 2023 the project facilitated strategic consultations between UMT and MMU to define how the platform would be co-owned and managed after the pilot. By fostering trust and clarity between these institutions, the pilot phase addressed potential governance ambiguities early on.

The multi-level composition of the platform proved invaluable in identifying and addressing challenges of SECAP implementation. For example, during pilot working group discussions, city officials highlighted difficulties in obtaining emissions data and financing projects. These issues were elevated to the Steering Committee, where national policymakers could consider solutions such as standardizing data collection protocols or mobilizing funds. The “Challenges & Solutions” Working Group created a feedback loop: it gathered common obstacles faced by municipalities (like integrating energy poverty concerns or aligning SECAP methodologies with national standards) and fed them into higher-level discussions. As a result, even during the test phase, the platform began influencing policy. A summary list of identified challenges and proposed solutions was compiled for the consideration of the Steering and Advisory Committees. One notable focus area was the synchronization of SECAP processes with national climate planning – the platform recommended steps to standardize SECAP templates and align them with Türkiye’s emerging climate strategy, ensuring local plans would collectively support national targets. Another focus was addressing cross-cutting issues such as energy poverty and data harmonization, which the working group recognized as critical for effective local climate action. By the end of 2023, the pilot MLGP had thus not only tested a governance model but also generated concrete insights for improving multi-level collaboration on climate policy.

2.2.3. Pilot Outcomes

The test phase concluded successfully, achieving all planned activities and hitting performance targets. The active engagement of 20 municipalities (pilot + observers), two municipal unions, and multiple ministries over the year demonstrated the feasibility of the MLGP approach at a small scale. The platform fostered a new dialogue channel between local and national actors: for the first time in Türkiye, municipal climate action stakeholders had a structured forum to regularly confer with each other and with central government representatives on equal footing. Key outputs from the pilot included the aforementioned Blue Paper and draft scale-up plan, as well as enhanced capacity of the participating cities. For instance, municipal staff involved in the WGs gained experience in multi-level negotiations and project development, which would benefit their SECAP efforts. The pilot also tested the digital tools and administrative procedures needed for the platform. By using simple tools (email groups, shared drives) and regular virtual meetings, the Secretariat kept participants connected without large resource requirements. This was an important proof of concept for later scaling, indicating that a lean coordination mechanism can be effective.

Perhaps most importantly, the pilot phase fulfilled its role as a learning exercise to “identify and eliminate challenges” before scaling up. The trial run surfaced several lessons: it confirmed strong interest among cities to engage (exceeding the initial pilot group), it revealed the necessity of continuous communication to maintain momentum, and it highlighted the value of having a neutral facilitator (MMU) to convene stakeholders. Minor adjustments were made along the way – for example, the frequency of some meetings was tweaked to avoid fatigue, and additional training was provided when gaps in understanding were noticed. By December 2023, the positive results and feedback from stakeholders gave confidence to proceed to the expansion phase. In summary, the pilot established a working multi-level governance framework for climate action in the Marmara region, setting the stage for a nationwide rollout.



2.3. Nationwide Scale-Up: Launch of MLGP4Climate (2024–2025)

Building on the pilot’s success, the platform transitioned in 2024 from a regional test into a permanent national initiative. Early in 2024, efforts were made to institutionalize the platform at the national level, reflecting a commitment to ensuring its long-term sustainability. The platform was rebranded as “MLGP4Climate” to emphasize its focus on climate action and to mark its evolution from pilot stage. The core governance structure remained the same—Steering Committee, Advisory Committee, Secretariat, and two Working Groups—providing continuity and stability in operations. However, the scale and outreach of activities were greatly amplified to cover all of Türkiye and to incorporate a wider array of stakeholders.

2.3.1. Official National Launch

The national phase kicked off with a high-level launch event on 30 April 2024 in Ankara, hosted by UMT with support from the project. This event gathered 81 participants, including senior officials from multiple ministries, mayors and experts from municipalities across Türkiye, leaders from UMT and MMU, as well as representatives from international organizations and EU institutions. The presence of such a broad audience underscored that MLGP4Climate had gained recognition as a flagship initiative for climate governance in the country. At the launch, the strategic vision and objectives of MLGP4Climate were presented, and endorsements were given by national authorities, signaling political support for the platform's continuation. The event also served as an opportunity to demonstrate the progress made during the pilot year, thereby rallying additional municipalities and partners to join the platform.

By the time of the launch, the project team and UMT had prepared a suite of strategic documents to guide the platform's national rollout. These included an Annual Work Plan for 2024 outlining scheduled meetings, trainings, and deliverables; updated Terms of Reference for all platform bodies (SC, AC, WGs) clarifying roles and decision-making processes at the larger scale; a set of technical specifications for an IT platform to support the expanded membership; and a finalized Scale-up Strategy aligning MLGP4Climate's goals with Türkiye's climate policy framework and the EU Green Deal orientation. With these documents, the platform entered its operational phase with clear governance and an actionable roadmap.

Digital Platform and Resources: One of the notable achievements in the national phase was the development of a dedicated MLGP4Climate web portal (www.mlgp4climate.com) as the central hub for all platform activities and knowledge sharing. The website, launched in April 2024 in tandem with the physical kickoff event, significantly enhanced the platform's functionality and reach. By April 2025, the portal hosted an extensive digital library of almost 700 resources, ranging from climate action guidelines, case studies, and webinar recordings to templates and tools (many resources were provided in both English and Turkish, to ensure accessibility, https://mlgp4climate.com/mlgp-library). The site featured interactive components such as event calendars, member directories, and discussion forums. A dedicated funding opportunities section was included to disseminate information on relevant climate financing calls (for instance, announcements about EU programs or national grants for which cities could apply). This was directly inspired by the needs identified during the pilot – cities often lack timely information on funding, so the platform took on the role of an information broker. Additionally, the portal introduced standardized member profiles for each participating municipality and association (over 80 profiles were published). These profiles showcased each member's commitments, key projects, and areas of expertise, facilitating peer learning and matchmaking for partnerships. The investment in an online platform greatly improved communication: all MLGP4Climate members could now easily access materials, follow progress, and engage with each other virtually, reducing the barriers of distance in a nation as large as Türkiye. The website quickly became a living repository of Türkiye's local climate action efforts, enhancing transparency and institutional memory.

Membership Expansion: With the platform open to all interested local authorities and relevant organizations, membership grew rapidly through 2024. By April 2025, more than 70 municipalities and 35 associations had formally joined MLGP4Climate. This represents a remarkable scaling from the initial 10 pilot cities. Members spanned the entirety of Türkiye – from major metropolitan areas like İstanbul, Ankara, İzmir, Konya to smaller cities and districts that were new to the climate action scene. The inclusion of diverse municipalities (urban and rural, large and small) broadened the platform's representativeness and ensured that perspectives from different regions (e.g., coastal areas concerned with sea-level rise, inland areas facing heatwaves and drought) were brought to the table. In terms of population, the member municipalities collectively represent a significant portion of Türkiye's urban residents, indicating substantial coverage of the country's climate efforts via MLGP4Climate.

The 35 associations and organizations in the platform added another layer of richness. These included national agencies, regional development organizations, NGOs, and professional associations with expertise in energy and climate. For example, specialized bodies like the Energy Efficiency Association (ENVER), the Turkish Energy Cities Union (EKB), and the Green Buildings Association (ÇEDBİK) were among those invited and signed cooperation agreements to participate. Engaging such entities provided technical depth (e.g., experts in building efficiency or renewable energy) and facilitated capacity building for municipalities. Early in 2024, the project reached out to several of these associations through introductory meetings, inviting them to contribute to MLGP4Climate's activities. The response was positive, and cooperation letters were signed formalizing the partnerships. The platform thus evolved into a multi-actor coalition, not only of governments but also of supportive institutions that can drive innovation and disseminate best practices.

Efforts were also made to bring new municipalities into the Covenant of Mayors framework via the platform. Recognizing that some cities had not yet joined the Global Covenant of Mayors (GCoM), MLGP4Climate used outreach as a tool for advocacy. For instance, as a result of platform engagement, Kuşadası Municipality (previously not a CoM signatory) received an invitation and agreed to join the initiative, and Konya Metropolitan Municipality officially became a GCoM member in February 2024. These examples show how the platform not only worked with existing CoM cities but also expanded the circle of local authorities committing to climate targets. This expansion is critical for scaling impact: the more municipalities pledge to cut emissions and adapt to climate change, the closer Türkiye gets to meeting its national targets. The MLGP4Climate provided an entry point and support system for newcomer cities embarking on climate action planning.

Throughout 2024 and into 2025, MLGP4Climate activities maintained high momentum. The Steering Committee and Advisory Committee met quarterly to review progress and make strategic decisions (a total of 3 joint SC/AC meetings were held in the reporting period). The Working Groups convened even more frequently, totaling 7 meetings on their specific topics. Impressively, participation in these meetings grew compared to the pilot phase: each session was attended by between 80 and 124 participants, reflecting the broad interest and engagement of the enlarged membership. This level of attendance—dozens of stakeholders on regular calls—indicates that MLGP4Climate became a focal point for climate action discourse in Türkiye. Stakeholders who previously might operate in silos (e.g., a city energy manager, a university researcher, and a ministry official) were now regularly interacting and collaborating via the platform. The inclusive, nation-wide scope of the platform also meant that best practices and challenges from one region could be shared with others, accelerating learning. For example, a successful building retrofit program in one city could be presented to peers from another city across the country during a WG meeting, potentially spurring replication.

By April 2025, the MLGP4Climate platform had engaged over 600 individual stakeholders in its various activities (cumulatively counting participants in events, trainings, and meetings). This broad reach significantly elevated the profile of climate action at the local level. Local decision-makers became more aware of national policies and EU initiatives, and conversely, national policymakers gained better insight into on-the-ground realities. MLGP4Climate had effectively become a nationally recognized and inclusive governance platform, enhancing municipalities' capacities to plan and deliver climate and energy actions. Its early successes even began to attract attention from outside Türkiye—there were inquiries and interest from other countries in the region about how a similar multi-level platform could be established elsewhere. The stage was set for deeper integration of local climate action into Türkiye's national strategy, leveraging the MLGP4Climate as a permanent mechanism for multi-level coordination.

3 Strengthening Local Capacity and Regional Cooperation

While the MLGP4Climate platform was one of the centerpieces of Türkiye's approach under EU4ETTR, the project also implemented complementary activities to build capacity, enhance cooperation, and connect cities to external support. These initiatives bolstered the platform's effectiveness by ensuring that local officials had the knowledge and resources to act on their climate commitments, and by linking municipal action in Türkiye with broader regional and global efforts.

Covenant of Mayors Support and Training: Recognizing that many municipalities needed technical guidance to develop and implement SECAPs, the project established a National Covenant of Mayors Helpdesk for Türkiye. This helpdesk (accessible via a dedicated email, TRhelpdesk@globalcovenantofmayors.eu) became operational to provide on-demand advice on SECAP preparation, greenhouse gas inventory methodologies, climate risk assessment, and the formal CoM reporting process. Over the project duration, the helpdesk responded to more than 200 inquiries from Turkish municipalities. Common inquiries ranged from questions about how to conduct a Baseline Emissions Inventory to guidance on funding sources for SECAP actions.

The high volume of requests underscored the strong interest among cities to engage in climate action, as well as the gaps in capacity that the helpdesk helped to fill. This facility ensured that even municipalities not directly in the pilot could benefit from the project's expertise, thereby broadening impact. In addition to one-on-one support, the project produced a bilingual (Turkish-English) Covenant of Mayors and MLGP4Climate introduction brochure. Thousands of copies of this brochure were disseminated, including at major events such as the World Urban Forum 12 (WUF12) in Cairo in 2024, where it reached over 500 participants from around the world. By raising awareness of Türkiye's municipal climate efforts on international stages like WUF12, the project helped put Turkish cities on the global map of climate action.

Capacity-building workshops and training sessions were a regular feature of the project. For example, between January and March 2025, a series of twelve SECAP Masterclasses and four Project Proposal Preparation Trainings were delivered, each attracting around 200 participants on average. These virtual trainings covered topics such as emissions modeling, climate adaptation planning, and preparing bankable project proposals. All training materials (presentations, toolkits, Q&A from sessions) were later published on the MLGP4Climate website for reference. By providing structured learning opportunities, the project significantly increased the technical proficiency of local teams. In a similar vein, specialized workshops addressed cross-cutting priorities. In line with the EU Green Deal's emphasis on inclusivity, an "Empowering Women for SECAP Implementation" workshop was organized on 7 May 2025 in Istanbul, convening over 50 participants (including women leaders of local cooperatives and municipal staff) to discuss the role of women's initiatives in driving climate projects. This event, among others, ensured that gender equality and social inclusion were woven into the climate action narrative, encouraging municipalities to consider vulnerable groups in their plans. It also exemplified the project's holistic approach to capacity building – not just technical training, but also empowering underrepresented groups to participate in climate solutions.

Networking and Regional Collaboration: Recognizing the relevance and importance of networking for municipal climate action (cf. Busch et al., 2018), the EU4ETTR project placed strong emphasis on networking both within Türkiye and internationally. The MLGP4Climate platform itself was a form of network institutionalization; beyond that, the project team organized and participated in numerous events to spur knowledge exchange and partnerships.

At the national level, the project supported or co-organized over 15 events and conferences dedicated to climate and energy topics. For instance, the project experts attended a climate-focused panel at IRENEC 2024 (International 100% Renewable Energy Conference) in Istanbul, where municipal representatives shared their experiences and explored solutions to common challenges in renewable energy deployment. Similarly, a City Climate Finance Workshop was held in collaboration with the City Climate Finance Gap Fund in late 2024, helping more than 75 municipal officials from Türkiye learn about financing instruments for climate projects. These events often featured matchmaking sessions between cities and financial institutions, and some led to follow-up mentoring for cities on developing project proposals.

The project also brokered partnerships and formal agreements to cement inter-city and inter-agency cooperation. For example, partnerships were established with Edirne, Kartal, and Istanbul Metropolitan Municipalities to pilot innovative approaches (like climate-smart budgeting and green procurement) which could be later scaled out via MLGP4Climate. In January 2025, a high-profile Covenant of Mayors Türkiye–Mediterranean (CoM Med) workshop was held, bringing together Turkish municipalities and peers from the Mediterranean region. During this event, an important Memorandum of Understanding (MoU) was signed that laid the groundwork for structured collaboration between CoM Türkiye and CoM Med networks. This MoU signified Türkiye's commitment to share knowledge with and learn from neighboring regions, and it created a formal bridge between MLGP4Climate and the wider Covenant of Mayors Mediterranean initiative.

Additional cooperation activities targeted specific themes or audiences. For instance, the Konak Climate Summit in İzmir, the UCLG-MEWA (United Cities and Local Governments Middle East & West Asia) meeting, the Çine SECAP Signing Ceremony in Aydın, and Şanlıurfa's CLIMAAX launch were all supported by the project. Each of these events engaged different stakeholders – from metropolitan mayors to rural district officials to youth groups – thereby broadening the coalition for climate action. The Cities Meet Cities exchange program in Antalya (November 2024) is another example: it hosted delegates from Amman Municipality (Jordan) to share Türkiye's experiences in municipal climate governance. This exchange not only benefited the visiting city but also allowed Antalya and other Turkish cities to gain insights into climate adaptation measures practiced in a different context, fostering South-South cooperation.

On the international front, study tours were organized to expose Turkish officials to European best practices, a method supported by recent literature, which highlights that study visits can increase the credibility of policies within municipal administrations and serve as strategic instruments for mentor cities (Haupt 2021). In 2024, two study visits to Lithuania took place (in July and December) with over 30 Turkish delegates including mayors, city energy managers, and union representatives. Lithuania was chosen as it has a strong track record in multi-level climate governance and community energy projects. The delegates visited institutions like the Lithuanian Energy Agency and municipal sites, learning about innovative approaches such as energy communities and advanced SECAP monitoring systems. These visits yielded tangible outcomes: for example, a bilateral project application was jointly developed between Bandırma (Turkey) and Akmenė (Lithuania) as a result of connections made during the exchange. This indicates how the project facilitated not just knowledge transfer but actual project development collaborations. In March 2025, a delegation of Turkish mayors and MLGP4Climate members traveled to Brussels for meetings with the European Commission's DG CLIMA and DG ENER, and the Committee of the Regions. This Brussels workshop introduced Turkish municipalities to new EU initiatives like the CHAMP (Community Action Platform for Net Zero) initiative and connected them with key EU officials. It was a valuable opportunity to integrate Turkish cities into European climate networks and discussions, essentially building a bridge between local authorities in Türkiye and EU climate governance structures.

Through these myriad capacity-building and networking activities, the project significantly enhanced cooperation among Turkish municipalities and between Turkish and international climate actors. The combination of a formal platform (MLGP4Climate), an active helpdesk, training programs, and networking events created a robust support ecosystem. As a result, by early 2025, the municipal climate movement in Türkiye was far more coordinated and knowledgeable than at the project's start. Over five formal cooperation agreements (MoUs or partnerships) had been facilitated by the project among cities and institutions, and at least four SECAPs were launched or substantially advanced with project support. Taken together, these efforts have strengthened Türkiye's contribution to global climate mitigation and adaptation. Importantly, they also align local actions with national and EU-level objectives, ensuring coherence. For example, information flowing through the helpdesk and platform means that municipalities are preparing SECAPs that reflect the EU's 2030 climate targets and feed into Türkiye's own "Net Zero 2053" vision. Likewise, by engaging in regional networks (like CoM Med) and EU dialogues, Turkish cities are contributing to and benefiting from international climate cooperation. In summary, the EU4ETTR project in Türkiye fostered not just a governance platform but also a community of practice, whereby cities are learning from each other and jointly pushing the envelope of climate action. This community is well-poised to continue beyond the project, anchored by the institutionalized MLGP4Climate and sustained through the partnerships forged.

4 Driving Local Climate Action through SECAPs and Pilot Projects

At the core of local climate action is the development and implementation of Sustainable Energy and Climate Action Plans (SECAPs). Under the Covenant of Mayors framework, each signatory city commits to preparing a SECAP that typically includes a Baseline Emissions Inventory, climate risk assessment, and an outline of actions to reduce emissions and adapt to climate change by a target year (2030 or beyond, Scorza and Santopietro 2024). Türkiye's experience in EU4ETTR placed heavy emphasis on accelerating SECAP development for key municipalities and ensuring those plans translate into real projects and emissions cuts. The project provided structured technical assistance, facilitated peer learning on SECAP preparation, and even funded pilot implementations to kick-start SECAP execution.

Technical Assistance and Integration of New Themes: Two of the largest municipalities in Türkiye's cohort, Istanbul Metropolitan Municipality (IMM) and Bağcılar Municipality, received intensive technical support through a dedicated working group mechanism. Over the course of 2023-2024, more than 40 working group meetings and coaching sessions were held with IMM and Bağcılar's teams, focusing on enhancing their SECAPs. One innovative aspect was the integration of energy poverty and energy access considerations into these plans. With rising energy costs and socio-economic disparities, energy poverty emerged as a key issue linking climate action with social justice. The project organized specialized energy poverty training – one session trained 23 staff from IMM in June 2024, and another two-day training in December 2024 built capacity for Bağcılar's newly established Energy Support Desk. These trainings covered methods to identify vulnerable households, measures to reduce energy bills (like home insulation and efficient appliances), and ways to incorporate these measures into SECAP action lists. As a result, Bağcılar updated its SECAP to include a third pillar on "Energy Access and Poverty Alleviation", making it one of the first SECAPs in Türkiye to explicitly address this issue. This addition broadened the scope of climate action to ensure no one is left behind, aligning with EU priorities on a just transition. It also served as a model for other cities – the lessons from Bağcılar were shared via MLGP4Climate so that other municipalities could consider similar approaches.

In parallel, the project developed new guidance documents and tools to assist all cities in SECAP preparation. A comprehensive SECAP Preparation Guide was produced and launched on the MLGP4Climate website in 2024. This guide, tailored to the Turkish context, walks municipalities through each step of developing a SECAP, from conducting emissions inventories to setting targets and identifying actions. It draws on international Covenant of Mayors guidelines but includes local examples and tips based on the project's experiences. Furthermore, recognizing the increasing importance of climate adaptation, the project authored an Urban Climate Adaptation Guide along with an Adaptation & Mitigation Synergy Brochure. These resources were introduced in a dedicated Climate Adaptation Workshop in late 2024, which brought together city planners and environmental engineers to discuss climate risk assessments and how to integrate adaptation measures (like flood management or urban greening) into SECAPs. The dissemination of these tools via the MLGP4Climate library means that even municipalities outside the direct project beneficiaries can benefit, raising the overall quality of SECAPs across Türkiye.

SECAP Progress and Quantified Outcomes: By early 2025, several major municipalities had either completed or substantially advanced their SECAPs with project support. Notably, Istanbul Metropolitan Municipality's SECAP, which targets a 40% reduction in greenhouse gas emissions by 2030, has started to yield measurable results. Within the first three years of implementation, IMM achieved a reduction of about 225,848 tons of CO_2, corresponding to 14.6% of its baseline emissions. In terms of energy, IMM's actions led to an estimated 1.93 million MWh of energy savings over three years – a significant stride towards its goal of saving 644,771 MWh annually by 2030 . Similarly, Bağcılar Municipality's SECAP set an ambitious target of 53.25% emissions reduction by 2030 (roughly 2.88 million MWh in energy savings). By 2025, Bağcılar had already cut approximately 358,417 tons of CO_2 in the past three years and saved around 960,450 MWh of energy. These early achievements indicate that the SECAPs are not just plans on paper, but living documents driving concrete action and yielding emissions cuts. Another pilot city, Çorlu, illustrates progress among medium-sized cities: its SECAP targets a 40.4% emissions reduction by 2030, equivalent to 870,205 tons of CO_2 avoided, alongside a renewable energy generation target of 717,329 MWh (through solar and wind installations). With project guidance, Çorlu completed its risk and vulnerability assessment and is on track to meet its renewable energy milestones. These results demonstrate the potential impact of scaling up local climate actions: aggregated across dozens of cities, they make a meaningful contribution to national emissions reductions and energy efficiency goals.

Beyond these large municipalities, the project extended technical support to a cohort of other cities across Türkiye to jump-start their SECAPs. Cities such as Bandırma, Safranbolu, Karatay, Diyarbakır, Kuşadası, Uzunköprü, Narlıdere, Selçuklu, and Şanlıurfa were among those receiving expert assistance. The support ranged from training workshops in those locales to one-on-one consultancy to help municipal teams conduct greenhouse gas inventories or stakeholder consultations. Each city had unique challenges – for example, Safranbolu (a smaller city) needed guidance on data collection with limited staff, while Diyarbakır (a larger province) required alignment of its climate planning with its metropolitan governance structure. The EU4ETTR team's flexible assistance ensured that each city made progress according to its context. By the end of the project, at least four SECAPs had been officially adopted or were in final draft stage as a direct outcome of this technical support, and several others were in the pipeline. This acceleration of SECAP adoption is a critical outcome: prior to the project, only a handful of Turkish cities had comprehensive climate action plans, whereas now a growing number do – and they are of higher quality and ambition thanks to the infusion of expertise.

Pilot Implementation Projects: A distinctive feature of the Türkiye component was the allocation of grant support for pilot projects that implement SECAP actions. Rather than stopping at planning, the project took the extra step of funding and showcasing real investments on the ground, to demonstrate what SECAP implementation looks like and what benefits it can deliver. Following a competitive selection in 2022, three municipalities were awarded grants to execute priority projects from their SECAPs. These municipalities were Melikgazi (a district of Kayseri), Bağcılar (in Istanbul), and Çorlu (in Tekirdağ), each focusing on renewable energy and energy efficiency actions.

In Melikgazi, the project supported the "Solar City Project," which involved installing solar photovoltaic (PV) systems on municipal facilities. By mid-2024, Melikgazi had completed a 171.72 kWp solar power plant on the roof of a municipal service building. Within just six months (April–October 2024), this installation generated over 1,230 MWh of clean electricity, leading to an avoidance of 66.6 tonnes of CO_2 emissions. To put this in perspective, the emissions savings were equivalent to planting over 30,800 trees, a fact publicized to raise community awareness. The project also funded supplementary measures: Melikgazi procured an electric vehicle for municipal use and installed two EV charging stations, showcasing a shift to cleaner transportation. By the end of 2024, Melikgazi further expanded its solar capacity with an additional 115 kWp PV system at another site, expected to produce ~235 MWh annually. This project turned Melikgazi into a local pioneer of solar energy, inspiring neighboring cities about the feasibility and benefits of such investments.

In Bağcılar, the grant was used to implement energy efficiency and solar PV installations as part of its SECAP measures. The municipality installed solar panels on the rooftops of public buildings, yielding about 203.9 MWh of renewable electricity generation capacity. Additionally, public lighting systems were retrofitted with LEDs, and an energy management system was introduced in municipal facilities. Bağcılar's project targeted a CO_2 reduction of 100.3 tons per year, contributing directly to its SECAP emission goals. The process of implementation was documented in an evaluation report to capture lessons, noting for example that the municipality decided partway to outsource some technical aspects (hiring a consultant for SECAP drafting and proposal writing) to accelerate progress. Despite minor adjustments, Bağcılar maintained regular coordination meetings with the project team to monitor implementation and ensure knowledge transfer. By early 2025, the installations were operational, and Bağcılar held public awareness campaigns to share the results, including demonstrations of the solar system to local schools to promote climate education.

Çorlu's pilot project, completed in early 2025, focused on a combination of rooftop solar PV and energy-efficient street lighting. The grant funded the installation of solar panels on several municipal buildings and the replacement of old street lamps with LED fixtures in key areas of the city. The project culminated in a local event on 9 April 2025 to inaugurate the new systems, attended by city officials and community members. The expected annual output from Çorlu's solar installations was on the order of tens of MWh (with one site targeting ~240 MWh/year), and together with the LED upgrades, the project's combined impact was estimated at reducing emissions by ~120 tons CO_2 per year . While modest relative to the city's overall emissions, these interventions have high replicability and visibility. Already, the knowledge gained (e.g., procurement processes for solar panels, technical standards for LED retrofits) is being shared with other mid-sized cities through MLGP4Climate workshops.

Each of these pilot projects served a dual purpose: demonstration and capacity building. Technically, they demonstrated that local climate investments can be executed within a short timeframe and yield quantifiable benefits. Institutionally, they provided the municipal administrations with hands-on experience in project management, from design to procurement to implementation and monitoring. This experience is invaluable for scaling up; those municipalities are now better prepared to undertake larger projects or to apply for external funding (such as the EU's Climate Fund or Green Climate Fund resources). Indeed, the MLGP4Climate website's funding section, which regularly posted calls like the EBRD's Green Cities program or the EU's Horizon Europe opportunities, saw increased interest from municipalities after they had a successful pilot under their belt. Moreover, the pilot cities became local champions – Melikgazi's mayor, for example, presented the results of the Solar City Project at a national energy summit, advocating for more cities to invest in renewables.

By driving SECAP development to completion and seeding initial projects, the EU4ETTR project ensured that Türkiye's local climate action moved from planning to practice. The combination of better plans and real projects means municipalities are now contributing credible efforts to climate mitigation. These local actions, when aggregated, help move the needle on national indicators. For example, the energy savings and renewable generation achieved in Istanbul, Bağcılar, Melikgazi, and others directly feed into Türkiye's national energy efficiency and renewable energy targets (which are part of its strategy to peak emissions by 2038 and reach net zero by

2053). The experiences also provide a rich repository of case studies for the country. They highlight what is achievable in a short time with political will, community support, and technical guidance – lessons that can be shared through MLGP4Climate to inspire more municipalities to follow suit.

5 Key Achievements and Impact

Over the four-year project period, Türkiye's participation in the EU4 Energy Transition initiative yielded significant achievements that strengthened local climate action and advanced multi-level governance. Some of the key accomplishments include:

- **Institutionalizing Multi-Level Climate Governance:** Türkiye established its first Multi-Level Governance Platform for Climate (MLGP4Climate), engaging a vast network of stakeholders. By 2025, the platform brought together more than 70 municipalities and 35 partner organizations in an ongoing dialogue with national ministries. More than 600 individuals (mayors, city staff, experts, etc.) took part in MLGP4Climate activities, making it a cornerstone of climate governance in Türkiye. The platform's inclusive structure ensured representation and input from all levels, creating a sustainable mechanism to align local actions with national policies.
- **Enhanced Municipal Capacities and SECAP Adoption**: The project directly supported the development or update of numerous Sustainable Energy and Climate Action Plans. At least 4 major SECAPs (including Istanbul and Bağcılar) were completed with higher ambition and technical robustness, and several others are underway. Training programs reached hundreds of municipal officers, equipping them with skills in GHG inventorying, climate adaptation planning, and project financing. As a result, cities are now better prepared to design and implement effective climate strategies. Notably, pioneering integration of energy poverty alleviation into SECAPs was achieved, setting a precedent for combining climate and social goals.
- **Tangible Emissions Reduction and Energy Savings:** Local actions facilitated by the project have already led to measurable reductions in greenhouse gas emissions and energy consumption. Collectively, the pilot cities reported emissions cuts on the order of hundreds of thousands of tons of CO_2 within just a few years of SECAP implementation (e.g., IMM and Bağcılar together reduced over 584,000 tCO_2 in 3 years). Energy efficiency measures and renewable energy projects supported by the project have saved roughly 2.9 million MWh of energy in the same period across those two cities. These figures demonstrate the impact potential as more municipalities implement their SECAPs. In the longer term, if all member cities meet their 2030 targets, it would represent a substantial contribution toward Türkiye's national climate milestones (particularly the 2030 NDC goals and the 2053 net-zero path).
- **Pilot Projects and Innovation:** Through grant funding and technical aid, the project enabled 3 pilot infrastructure projects (solar PV and energy efficiency) in municipalities, totaling around 500 kWp of solar capacity installed and deliver-

ing several thousand MWh/year of clean energy. These pilots not only cut emissions (nearly 200 tCO_2/year combined) but also serve as showcases of innovation – introducing technologies like EV charging infrastructure, LED smart lighting, and municipal solar plants in their locales. The successful execution of these projects has built confidence and know-how at the local level, demonstrating that even mid-sized cities can quickly adopt renewable energy solutions.

- **Networking, Partnerships, and Visibility:** The project significantly boosted networking and cooperation both within Türkiye and internationally. It facilitated 5 formal cooperation agreements (e.g., between CoM Türkiye and CoM Med, city-to-city MoUs), and organized exchanges with cities abroad (e.g., study tours to Lithuania, hosting Amman in Antalya) that have led to joint project proposals and enduring relationships . Through high-profile events (WUF12, IRENEC, UCLG forums, etc.) and targeted workshops, the project gave Turkish municipalities a platform to voice their efforts globally and to learn from others. The creation of a national CoM Helpdesk and resource center made Türkiye's local climate community more interconnected and informed than ever before.
- **Policy Integration and Recognition**: MLGP4Climate has begun to influence national policy discussions. Insights and data from the platform have informed the national government's approach to supporting local climate action – for example, the Ministry of Environment has taken note of the platform's outputs when drafting the upcoming Climate Change Law, ensuring provisions for local action coordination. The platform's model of multi-level collaboration has gained recognition as a best practice, with interest expressed by other countries in the Western Balkans and beyond in possibly replicating it. International bodies, including the EU Covenant of Mayors Office, have acknowledged Türkiye's MLGP4Climate as a unique example of translating the multi-level governance concept into reality. This recognition is evidenced by invitations for the project team to present the approach in regional CoM meetings and European climate governance forums.
- **Inclusivity and Social Co-benefits:** The project strived for an inclusive approach, reflected in gender-balanced participation and attention to vulnerable groups. Women's representation in platform committees was strong (e.g., women held around 40–45% of working group seats, according to project monitoring), and dedicated initiatives empowered women and youth in climate action. Additionally, by explicitly tackling energy poverty in SECAPs, the project linked climate action with social equity, ensuring that the benefits of the energy transition (such as lower energy bills and cleaner air) will reach underprivileged communities. This approach aligns with findings that equitable climate adaptation should consider the diverse vulnerabilities and capacities of different social groups, promoting transparent, accountable, and participatory decision-making processes that directly involve marginalized communities (Chu & Cannon, 2021). Such a holistic vision enhances the public acceptance and sustainability of climate measures.

In essence, the EU4ETTR project in Türkiye achieved both quantitative outcomes (in terms of plans, emissions reductions, participants engaged) and qualitative outcomes (new governance models, increased trust between government levels, mainstreaming of climate considerations). The country now has a replicable framework (MLGP4Climate) that can continue to scale up action and an empowered network of municipalities that are actively contributing to national and EU climate objectives. The groundwork is laid for further progress; the challenge moving forward will be to maintain and build on this momentum.

6 Challenges and Lessons Learned

Implementing a multi-level governance approach for climate action in Türkiye was not without its challenges. Over four years, the project encountered and addressed various issues, each offering valuable lessons for future efforts. Key challenges and corresponding lessons include:

1. **Initial Low Awareness and Engagement**
   At the outset, many municipalities had limited understanding of multi-level climate governance and were uncertain about the Covenant of Mayors commitments. This made it challenging to secure buy-in for the platform concept.
   Lesson learned: Invest heavily in early-stage stakeholder engagement and clarity of communication. The project overcame this by conducting stakeholder analyses, surveys, and round-tables that clarified the roles and benefits of the MLGP. By co-creating the platform design with input from cities and other actors, the project built a sense of ownership. The takeaway is that new governance frameworks must be communicated in familiar terms and demonstrate clear value to each stakeholder group to gain traction.
2. **Coordination across Diverse Stakeholders**
   Aligning priorities and schedules among national ministries, a national municipal union, a regional union, dozens of municipalities, and various NGOs was inherently complex. Differences in institutional culture and potential overlaps with existing initiatives posed coordination challenges.
   Lesson learned: Formalize the structure and processes, but allow flexibility. The creation of defined committees (SC, AC, WGs) with terms of reference provided a clear coordination mechanism and division of labor. Regular meetings (set well in advance in the Work Plan) kept everyone on track. At the same time, the platform maintained flexibility to expand (adding observer cities, inviting new associations) and to adjust focus based on member feedback. A structured yet adaptive coordination model can manage complexity by giving everyone a seat at the table and a clear agenda.
3. **Balancing Regional Pilot and National Scale**
   There was some uncertainty during the transition from the MMU-led pilot to the national platform – e.g., how to ensure continuity and avoid duplication of

efforts. Regional actors feared losing momentum or influence when scaling up.
Lesson learned: Use the pilot as a learning and trust-building phase, and plan the transition from the start. By involving key stakeholders early on (including those present in the pilot's Steering Committee) and by demonstrating pilot success, the project facilitated a smoother path for national adoption. A formal roadmap with a defined "Expansion phase" was instrumental. This experience shows the importance of phasing: a contained pilot can test the waters, but a clear strategy to institutionalize successful elements at higher levels should be crafted from the beginning to maintain continuity.

4. **Data and Technical Barriers**
   Many municipalities struggled with technical aspects of SECAP development – from data collection for emissions inventories to economic analysis of action plans. Discrepancies in data (especially in provinces where multiple authorities hold pieces of data) and lack of standardized methodologies were problematic.
   Lesson learned: Provide common tools and facilitate data harmonization. The project's SECAP Guide and training were a direct response, but equally important was the Working Group on Challenges & Solutions, which tackled issues like data harmonization at a systemic level. One outcome was the recommendation to develop a national SECAP reporting template compatible with both CoM and national greenhouse gas inventory systems. This is being taken up by the Ministry for future integration. Thus, a combination of capacity building and structural alignment is needed to overcome technical barriers in a multi-level context.
5. **Financing and Resource Constraints**
   Identifying funding for climate actions was a challenge for municipalities, particularly smaller ones with limited budgets. Even though planning is crucial, without financing, plans can stall.
   Lesson learned: Integrate financing strategies and support into the capacity-building process. The project addressed this by including project financing modules in training, connecting cities with funders (e.g., Gap Fund, EBRD, national grants) through events, and by highlighting financial opportunities on the MLGP4Climate portal (https://mlgp4climate.com/financial-calls). Several municipalities, for instance, learned about and applied to the EU City Facility and CLIMAAX calls via information shared on the platform. The grant-funded pilots also served as examples that relatively small investments can unlock bigger projects (Melikgazi's solar project helped them then apply for a larger solar farm funding). The lesson is that multi-level climate initiatives must go beyond policy coordination to actively address financing – acting as a bridge to funding sources or building local capacity to prepare bankable projects.
6. **Organizational Changes**
   During the project, Türkiye experienced significant events like national elections in 2023 and upcoming local elections in 2024, which could change local

leadership and priorities. Additionally, normal municipal administration turnovers meant that contact points in some cities changed.
Lesson learned: Institutionalize knowledge and widen the engagement to reduce dependency on individuals. The platform's approach of involving technical staff, not just mayors, in working groups ensured that capacity and commitment were spread across the organization. The MLGP4Climate portal and documentation of all meetings created a knowledge repository that survives personnel changes. While political shifts are inevitable, having broad-based support (across different parties, levels, and both politicians and civil servants) increases resilience. Indeed, MLGP4Climate managed to maintain bipartisan appeal as it was framed around common interests like economic savings from energy efficiency, rather than any partisan agenda.

7. **Managing Stakeholder Expectations**
Different stakeholders had different expectations – some municipalities were keen to immediately get project funding, while others wanted policy changes from the national government. Balancing quick tangible benefits with long-term policy dialogue was delicate.
Lesson learned: Deliver a mix of short-term wins and progress on long-term processes. The project did this by implementing the quick pilot projects (to show immediate results) while also working on slower-moving elements like the multi-level governance agreement and integration into national plans. Communicating clearly what the platform can and cannot do was also important. For example, it was communicated that MLGP4Climate is not a funding program per se, but a facilitation mechanism that can help cities find funding. Setting realistic yet ambitious expectations kept stakeholders motivated and committed.

In conclusion, the challenges faced in establishing Türkiye's MLGP4Climate and associated activities underscore that process matters as much as product in multi-level climate governance. By proactively identifying challenges (even dedicating a working group to that purpose) and iteratively improving the approach, the project turned many challenges into learning opportunities. A critical lesson from Türkiye's experience is that multi-level collaboration is a continuous journey of negotiation and adaptation. What has been achieved is a strong starting point; but maintaining trust and effectiveness will require ongoing effort and responsiveness to new challenges, such as scaling up implementation and perhaps incorporating new topics like green jobs or nature-based solutions in the future. Türkiye's case provides a roadmap for others: start with inclusive planning, test on a manageable scale, institutionalize broadly, link actions to support, and always loop back to address challenges transparently.

7 Replicability

Türkiye's multi-level governance platform for climate (MLGP4Climate) offers a model that can be adapted and replicated in other contexts, especially in countries or regions seeking to strengthen the link between local climate action and national goals. It thereby aligns with scholarly perspectives that emphasize the importance of vertical and horizontal coordination in climate policy implementation (Betsill & Bulkeley, 2022). As the EU4ETTR project concludes, several factors point to the replicability and sustainability of the approach:

Institutional Model: The MLGP4Climate approach – leveraging existing municipal associations as anchors for a climate platform – resonates with the concept of utilizing established institutional frameworks to facilitate policy integration across governance levels (Jordan & Huitema, 2014) and is thereby relevant beyond Türkiye. Many countries have associations of local governments (national municipal leagues or regional unions) that could perform a similar convening role. The lesson is to build on structures that municipalities already trust and participate in. Türkiye's use of UMT and MMU was key; other countries can similarly utilize their municipal networks to host multi-level dialogues. Moreover, the platform's multi-tiered committee structure (Steering Committee, Advisory Committee, Working Groups) offers a modular design that can be tailored to specific contexts, reflecting the flexibility advocated in MLG frameworks (Peters & Pierre, 2004). For example, smaller countries might merge Steering and Advisory functions, whereas larger ones might have multiple regional chapters under a national umbrella. The concept of Letters of Cooperation between government levels (like those signed in Türkiye) can also formalize commitments in other settings. Indeed, following Türkiye's example, some Western Balkan countries in the EU4ETTR project are already exploring establishing their own multi-level climate working groups under their national municipal associations.

Policy Environment: Türkiye's platform aligned with its national climate policy trajectory (Paris Agreement ratification, net-zero 2053, etc.), which was conducive to support. For replicability, it helps if the national government is looking for ways to engage municipalities in meeting NDCs or other targets. The MLGP can be presented as a solution to that need. For instance, as the EU promotes climate governance through initiatives like the European Climate Pact and demands local inclusion in National Energy and Climate Plans (NECPs), countries in the neighborhood (Western Balkans, Caucasus, etc.) could adopt MLGP4Climate-like systems to channel local inputs into national plans. The success in Türkiye – where the platform has started to be recognized by national ministries – demonstrates how bottom-up initiatives can gain top-down endorsement when interests align.

Digital Infrastructure: The MLGP4Climate web platform has been a game-changer for scalability and transparency. Its contents (guides, templates, bilingual resources) can be shared and localized for other countries. In fact, the digital library's 700+ resources include many generic materials (like how to do a GHG inventory) that are applicable internationally. A replicability idea is to create a template MLGP portal that can be quickly customized for different regions, reducing the time to set up similar knowledge hubs. The existence of an online platform also allows a replicating region to draw on Türkiye's experience by perhaps linking libraries or having inter-platform exchanges (for example, MLGP4Climate Türkiye could connect with a potential "MLGP4Climate Balkans" platform to exchange news and resources). This digital approach supports replication by providing a ready-made blueprint for knowledge management, aligning with studies that highlight the role of digital infrastructure in enhancing organizational capacity for climate action (Susskind et al., 2017).

Peer Learning and International Interest: The project's networking outcomes laid a foundation for regional replication. The MoU between CoM Türkiye and CoM Med, as well as interactions with EU bodies, means that knowledge of the Turkish model has disseminated. There have been international inquiries regarding replication – for instance, some municipalities in neighboring countries have reached out to learn how they can advocate for a similar platform at home. The Western Balkans, being part of the same EU4ETTR project, are natural next adopters. The project in those countries ran in parallel with some similar elements, but they can benefit from the lessons documented by Türkiye's more detailed platform experience. Additionally, global city networks such as ICLEI and UCLG, which were aware of the MLGP4Climate's progress, could help promote the concept across their member cities. The platform could be featured as a best practice in international forums (as it was in WUF and likely in future COP side events), sparking further interest. This aligns with research emphasizing the significance of peer learning and transnational networks in diffusing climate governance innovations (Bulkeley et al., 2014).

8 Future Outlook in Türkiye

In Türkiye, the journey of MLGP4Climate is expected to continue beyond the EU4ETTR project's end in mid-2025. There is strong advocacy from participating cities to keep the platform alive because it directly supports them in achieving their climate commitments. Looking ahead, one can anticipate annual work plans that continue the cycle of capacity building, policy dialogue, and project support. The platform may also expand thematically. For example, as Türkiye updates its climate policies, new working groups might be introduced on topics like Climate Finance or Monitoring, Reporting and Verification (MRV) to assist with tracking progress towards the net-zero goal. Given the interest from the Ministry of Environment, MLGP4Climate could be formally linked to the national Long-Term Climate Strategy process – e.g., the platform could be tasked to gather local inputs

for Türkiye's upcoming strategy revisions or act as a consultation body for the planned Climate Law. Such formal roles would further entrench it in governance.
Another avenue is regional expansion within Türkiye. While MLGP4Climate is nationwide, there could be sub-networks (perhaps building on MMU's regional pilot model) focusing on specific areas or provinces where climate issues are more acute or where more localized coordination is beneficial (for instance, a network for South-Eastern Anatolia municipalities dealing with extreme heat and water stress). These could operate under the overall MLGP framework. The platform's flexibility allows for such scaling out.
On the implementation side, the momentum gained in launching pilot projects is set to accelerate. Many member municipalities, seeing the success of Melikgazi or Bağcılar, are preparing their own project proposals. Through MLGP4Climate's financial opportunities section, they are staying informed of calls like the EU's Mission Cities programme, Horizon Europe Green Deal calls, and national green funds. With enhanced capacity, more Turkish cities are expected to secure funding for climate projects in the next few years – a direct legacy of the project's investment in capacity building. This will, in turn, feed more success stories back into the platform, creating a virtuous cycle of ambition and implementation. This reflects the understanding that capacity building is essential for enabling effective and inclusive governance of emerging climate interventions (Durakçay, 2023).

Western Balkans and Regional Replication: The Western Balkan countries involved in EU4ETTR (Albania, Bosnia and Herzegovina, Kosovo, Montenegro, North Macedonia, Serbia) have observed Türkiye's MLGP development closely. Each has its own context, but many share the challenge of coordinating various governance levels for climate action. A possible next step (supported by donors or regional bodies like the Energy Community Secretariat) could be to establish a Western Balkans Climate Governance Network, perhaps initially as an informal coalition of national municipal associations, taking inspiration from MLGP4Climate. Given that these countries often look to EU candidate peers for successful models, Türkiye's example could be influential. Notably, Türkiye's bridging of local action to EU climate goals (despite not being an EU member) resonates with Western Balkan states which are in the EU accession process and expected to align with EU climate acquis. The MLGP concept could help them meet EU expectations for multi-level climate dialogue.

Upscaling the Impact in Türkiye: As MLGP4Climate continues, one can envisage it playing a pivotal role in helping Türkiye reach its "Net Zero by 2053" target. The platform can act as the conduit through which local contributions to emission reduction are quantified and aggregated. For instance, by 2030, if say 100 municipalities under MLGP4Climate each reduce emissions by an average of 25-30%, that could collectively achieve a significant fraction of the national target for that period. The platform could also help localize the Sustainable Development Goals (SDGs), particularly SDG 11 (Sustainable Cities) and SDG 13 (Climate Action), by tracking and reporting city-level progress. Furthermore, MLGP4Climate can evolve to address emerging areas like climate adaptation in a more concerted way – possibly establishing a national risk and resilience forum for cities under its umbrella, especially as climate impacts intensify.

In summary, the future outlook for Türkiye's MLGP4Climate is robust: it is expected to become a permanent fixture of the country's climate governance landscape, continuing to grow in membership and influence. Its replicability prospects are promising, given the interest it has generated and the compatibility of its approach with broader trends in climate governance (like the push for multi-level action in the Paris Agreement framework and the EU's emphasis on subsidiarity in the Green Deal implementation). By sharing lessons and offering a template for success, Türkiye's experience under the EU4 Energy Transition project can inform and inspire other nations aiming to bolster their climate action through effective multi-level collaboration.

9 Conclusion

Türkiye's journey under the EU4 Energy Transition: Covenant of Mayors in Western Balkans and Türkiye (EU4ETTR) project illustrates how multi-level governance can transform climate action from concept to concrete results. In just four years, the country moved from fragmented local efforts towards a coordinated national platform – MLGP4Climate – that connects municipal action with national strategy and European initiatives. Through this platform and associated support activities, Turkish cities have been empowered to plan better, act faster, and collaborate smarter on climate and energy goals. Local governments are now not only implementing Sustainable Energy and Climate Action Plans, but doing so in a harmonized way that collectively advances Türkiye's contribution to global climate mitigation and adaptation targets.

The success of Türkiye's approach lies in its hybrid nature: it combined academic insight (applying principles of governance, capacity building, and policy integration) with a practical, policy-oriented narrative that made sense to on-the-ground decision-makers. Mayors and ministers alike saw their interests reflected – cities gained knowledge and resources to improve services and meet citizen expectations (cleaner air, lower energy costs), while the national government gained a reliable partner network to deliver on international climate commitments. This alignment of local and national priorities was facilitated by the MLGP4Climate which acted as a bridge, ensuring two-way communication and feedback. For example, local innovations like Bağcılar's energy poverty initiative can inform national social policy, and conversely, national programs like building retrofitting are disseminated to cities through the platform.

The project's integrative approach also tied EU climate goals to local action in a seamless narrative. Even though Türkiye is not an EU member, its cities voluntarily committed to EU-aligned targets (40% emissions reduction by 2030) through the Covenant of Mayors, and the project provided the means to pursue those targets. In doing so, it created a model for how EU climate objectives (under the Green Deal and Neighbourhood policies) can be operationalized in partner countries via local governments. The presence of an EU-funded initiative certainly provided impetus and technical backing, but the ownership and enthusiasm generated ensure that the process outlives the project's funding cycle. As of mid-2025, Türkiye has a self-sustaining Multi-Level Governance Platform, dozens of active SECAPs, a pipeline of climate projects, and a cadre of trained local climate leaders. These are durable outcomes.

Türkiye's experience yields several broader insights. First, it affirms that local action is indispensable for meeting national and global climate goals; cities are where policies meet reality, and engaging them early and often multiplies impact. Second, it shows that multi-level governance is not just a buzzword – when given structure and support, it can tangibly improve policy coherence and resource utilization. Third, capacity building and stakeholder empowerment are long-term investments that pay off by enabling sustained action beyond a single project or political term. Fourth, peer learning and networks amplify success – Turkish cities learned from European peers and now are in a position to mentor others, exemplifying the virtuous cycle of knowledge exchange.

In conclusion, Türkiye's MLGP4Climate under the EU4 Energy Transition project stands as a compelling case of connecting the dots from local to national to global. It highlights how a well-designed multi-level governance platform can accelerate climate action in line with EU initiatives and international agreements, even in a developing economy context. The achievements in emissions reduction, energy savings, and policy innovation over a short period showcase what is possible when there is commitment at all levels and a mechanism to bring those levels together. As the world moves toward implementing the Paris Agreement and the SDGs, the lessons from Türkiye can inform replication in other regions, whether in the Western Balkans, Eastern Europe, or beyond. The climate crisis demands collaborative governance models; Türkiye's MLGP4Climate provides a blueprint of one such model in action – academic in its rigor, yet profoundly pragmatic in its execution. It demonstrates that when local passion and national vision converge, supported by international partnership, the results are a win for all, from the smallest community all the way to our global climate.

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